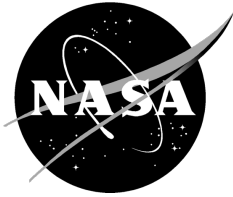


NASA/TM-20205007032



# **Small Unmanned Aircraft System Communications and Navigation Performance**

## **Results and Analysis from NASA's Unmanned Aircraft Systems Traffic Management Technical Capability Level 4 Demonstration**

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AUGUST 2020

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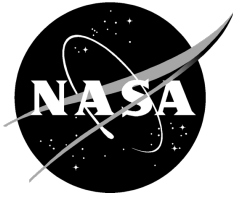
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This report is available in electronic form at  
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# 1. Abstract

NASA performed research and development of technologies and requirements for traffic management of small Unmanned Aircraft Systems (UAS). In this effort, four measures of performance (MOPs) were developed to understand the performance of small UAS communications and navigation systems in urban operations. This Technical Memorandum (TM) describes UAS Traffic Management (UTM) operational architecture, UTM Technical Capability Level 4 (TCL4) flight tests that took place in two different urban settings, the four MOPs, and the TCL4 MOP results.

## 2. UTM Operational Architecture

In UTM, a UAS Service Supplier (USS) provides appropriate operational data to the operator and other USSs. These data exchanges are defined by a set of Application Programming Interfaces (API) and UAS Service Supplier Specification [Rios 2019]. Figure 1 shows a high-level data exchange in UTM using the APIs. UTM is complementary to the FAA's Air Traffic Management (ATM) systems, and the interaction between the National Airspace System (NAS) and UTM takes place through Flight Information Management System (FIMS).

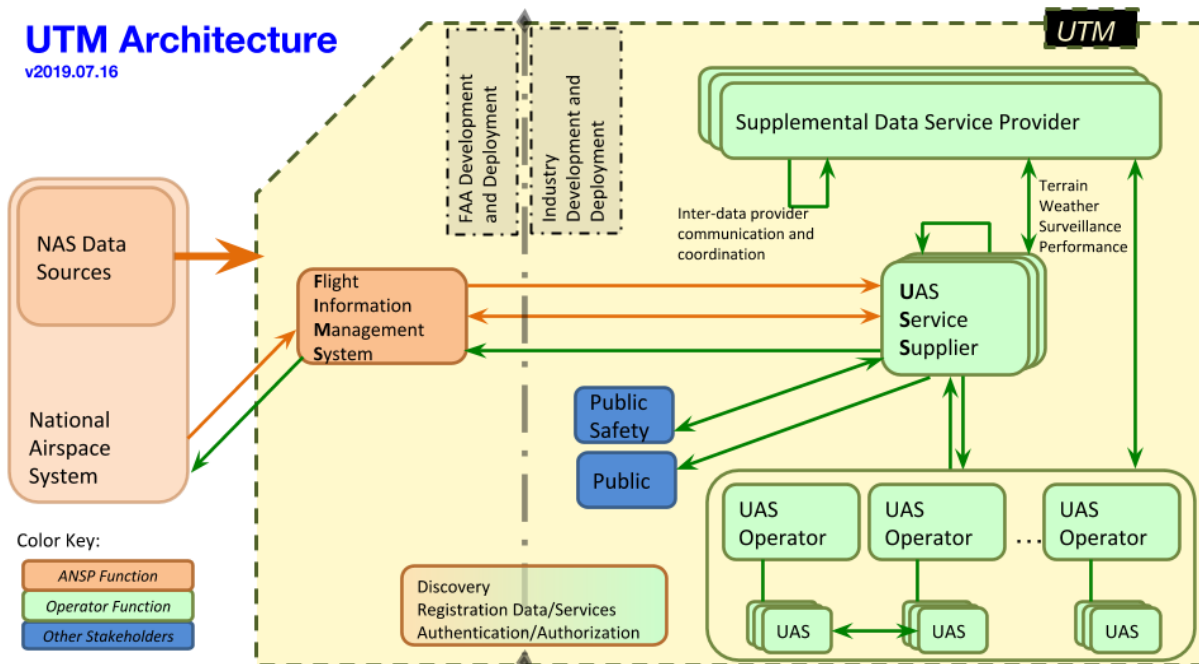


Figure 1. UTM Data Exchange Architecture

### **3. TCL4 Flight Test**

#### **Test Description**

NASA performed UTM research and development in four Technical Capability Level (TCLs). In TCL1 Visual Line-of-Sight (VLOS) operations such as agriculture, firefighting, and infrastructure monitoring were addressed with a focus on geofencing and operations scheduling [Rios 2016]. Technologies and requirements for Beyond Visual Line-of-Sight (BVLOS) operations in sparsely populated areas were examined in TCL2 and for operations over moderately populated areas in TCL3 [Johnson 2017], [Homola 2017], [Aweiss 2019]. TCL4 built on the earlier TCLs and focused on BVLOS operations in urban areas for tasks such as newsgathering and package delivery, and for managing large-scale contingencies. TCL4 is briefly described here and for more information see [Rios 2020].

The TCL4 demonstration in 2019 was a set of scenario-driven activities that integrated the UTM research and development objectives. Several scenarios were created focusing on different challenges associated with operations in a potential operational TCL4 environment, such as persistent, mixed tempo, and high-density BVLOS operations over an urban area. Two sets of operational tests were conducted at the Reno, NV test range and the Corpus Christi, TX, test range. A total of 144 live operations were flown from June 18-28, 2020, in the Reno flight test range for some of the scenarios, with nine live Unmanned Aircraft (UA) produced by three different manufacturers. These included one vehicle from AirRobot GmbH & Co. KG, five from Drone America, and three from SZ DJI Technology Co., Ltd. Five USSs, developed by AirMap Inc., AiRXOS (a GE venture), ANRA Technologies, Avision Inc., and Uber Technologies Inc., supported the operations. A total of 208 operations were flown from August 12-16, and August 19-23, 2020, in the Corpus Christi, Texas range for all scenarios, with nine UA from two manufacturers, including two from 3DR and seven from SZ DJI Technology Co., Ltd. Seven USSs developed by AirMap Inc., AiRXOS, ANRA Technologies, Avision Inc., Collins Aerospace (a unit of United Technologies Corp.), OneSky (Analytical Graphics, Inc.), and Uber Technologies Inc. supported the operations.

For all flight operations, arrangements were made to allow only participants in the defined range. Extended VLOS operations were used to emulate BVLOS operations. That is, the UA was in sight of designated visual observers when the operator was unable to see it due to obstruction (e.g., UA behind a building) or distance, and the observers and the operators maintained a line of communication among them to keep track of the operation.

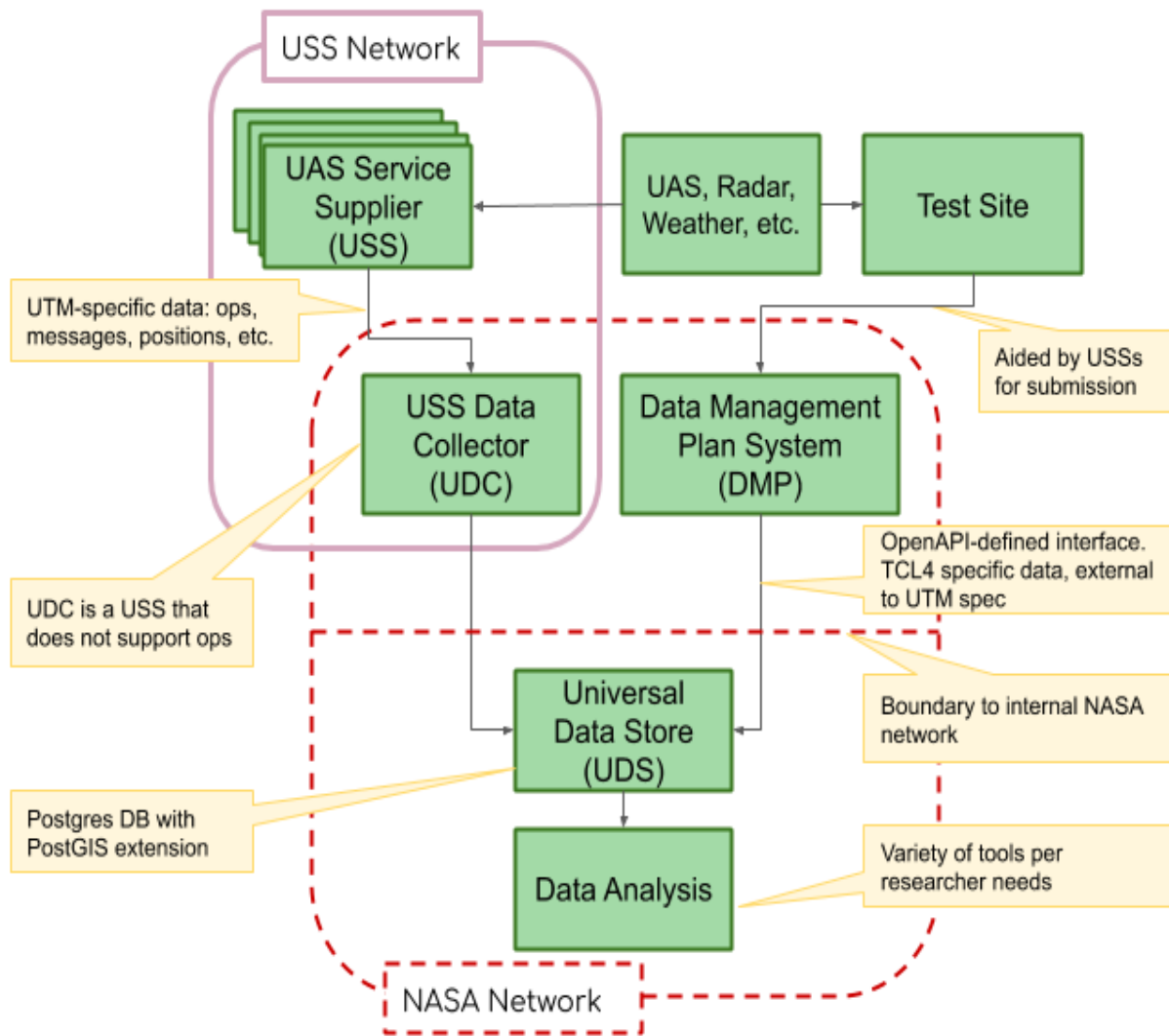
Since TCL4 focused on operations in urban areas, it is important to understand UAS communications and navigation performance in an urban setting that would enable safe and efficient operations. For this purpose, data were collected from UA, the Ground Control System (GCS) and the USS, and the collected data were processed to calculate MOPs for the performance assessment.

#### **Data Collection**

The TCL4 data collection architecture evolved with the lessons learned from previous TCLs where the NASA UTM team worked with internal and external stakeholders to execute flight tests and collect data. In the TCL4 test, there were two flows of data into NASA from the stakeholders. First was the data exchanged as part of the operational concept [FAA 2018], [NASA 2016], such as operation plans, UA positions, and other operational UTM messages. All of these data were collected during testing with a designated USS Data Collector (UDC) that interacted with the other USSs as if it were a USS. The other flow of data came via the system set up by NASA's Data

Management Plan (DMP) team. The DMP data were for research purposes and not part of the operational concept. These data were collected during and after testing.

Both data flows ended up in a Universal Data Store (UDS), a single source of truth for all TCL4 data. The UDS within this architecture ensured consistencies across numerous data visualization and analysis efforts. Figure 2 summarizes the TCL4 data collection architecture [NASA 2020].



**Figure 2.** TCL4 Data Collection Architecture

#### 4. Communications and Navigation Measures of Performance

The NASA UTM team defined four MOPs to assess the performance of small UAS communications and navigation systems in the TCL4 settings. Table 1 shows a summary of the MOPs addressed in this TM. The following two subsections describe data preparation and reduction steps for the MOP calculations.

**Table 1.** Summary of Communications and Navigation MOP

MOP	Description	Minimum Success	Target Success
Rate of loss of Command and Control (C2)	This MOP calculates the percentage of time across all operations that an operation was without complete C2.	< 4%	< 1%
Rate of C2 loss during a Conflict	This MOP calculates the percentage of operations in a conflict that experienced a loss of C2 during the conflict.	< 4%	0%
Rate of Navigation Degradation during a Conflict	This MOP measures the rate of navigation performance degradation per airborne time during conflicts.	≤ 15% of the time of conflict	0% of the time of conflict
Rate of Safe Landing	This MOP measures the percentage of a safe landing.	≥ 25%	≥ 75%

### Data Preparation

The data needed to perform the analysis in this TM was sourced from data exchanges within the USS Network and data collected by the Test Site and provided directly to NASA via the DMP system. From the USS Network Data, operation plans were used to identify the airspace that the operator intends to use for the operation, described as a series of 4D volumes. UTM messages were used to keep track of state changes to the operation, including any priority or contingency status changes.

From the DMP data, the following models<sup>1</sup> were used:

1. **ConPreRunOp** provided planned landing locations, such as safe landing locations, rooftop landing locations, visual line of sight and beyond visual line of sight locations.
2. **ConActualLanding** provided the actual landing location(s) and time(s).
3. **AuxiliaryUASOperation** provided another source for actual landing location(s) and time(s).
4. **FlightEssentialTelemetryAndUasStates** provided data taken from the vehicle's logs which included location, communication status, and navigation status data.

<sup>1</sup> All TCL4 DMP data models are available at <https://github.com/nasa/utm-docs/tree/master/TCL4%20Data%20Management>



## Data Reduction

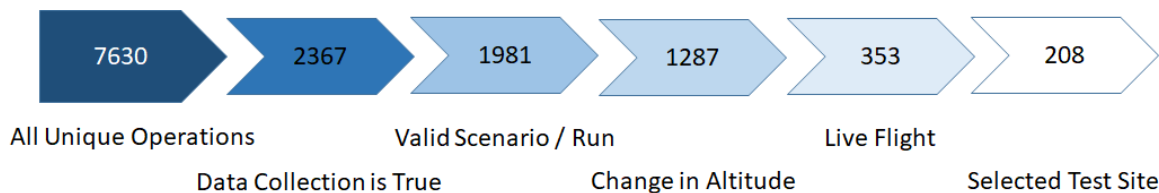
### Operations for Analysis

All data were collected during each run of each scenario. However, not all data that end up in the TCL4 datastore were intended or appropriate for the calculation of each MOP. To determine valid operations for analysis, the metadata of each model is filtered as follows:

1. Only models identified by the submitter as valid via a metadata flag
2. Only valid demonstration scenarios, with corresponding valid run numbers. Some scenarios are for testing or shakeout of the operations or various subsystems and are not intended for data analysis.
3. Only operations that changed altitude by 75ft, which is based on the standard GPS error model of  $\sim 2$  sigma
4. Only live flights (i.e. not simulated)

All operations not intended for data analysis are excluded from the results.

Upon completion of these initial reductions, and review of the quantity and quality of the other DMP data models submitted for those operations, it was determined that only one of the two test sites provided enough of the data sufficient for analysis. As a result, only the operations from the Texas test site were considered.



### Determining Landing Locations

For this analysis, the valid operations identified in the 'Operations for Analysis' section were used as the preliminary filter. This list is then further reduced to only operations with landing location(s) and time(s). These values were received via the DMP, the ConActualLanding and AuxiliaryUASOperation models, as discussed in the 'Data Preparation for MOP Calculations' section.

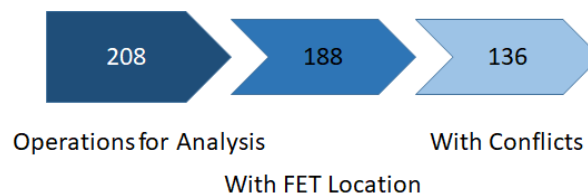


Using this method, 184 distinct operations were identified. From these operations, there were a total of 219 distinct landings for analysis. Distinct landings were defined as landings with a unique location (i.e. latitude and longitude) and time. Since this data was taken from two sources, it is possible that a single 'actual landing' is represented by two or more landings in the analysis. If, for example, the same 'actual landing' was submitted in the ConActualLanding model, and the AuxiliaryUASOperation model with a slightly different timestamp or location, they would be considered two different landings in this analysis.

### **Determining Conflict Occurrences**

For this analysis, the valid operations identified in the 'Operations for Analysis' section were used as the preliminary filter. This list of operations was then further reduced to only operations with FlightEssentialTelemetryAndUasStates location data (i.e. Latitude, Longitude, and Altitude).

To identify the operations 'in conflict', the FlightEssentialTelemetryAndUasStates location data for each operation were compared against the data for all other relevant operations (i.e. operations in the same scenario and run). If at a given time, two operations were within 700ft laterally and 200ft vertically, the two operations were considered 'in conflict'. From these 'in conflict' occurrences, the duration of a given conflict could be determined. An operation pair could possibly have multiple conflict occurrences (i.e. the operations go within the conflict distance bounds, move further apart than the bounds, and return to within the bounds). To account for such conditions, if the operations were 'out of conflict' for longer than 20 seconds, the next time they were 'in conflict' would count as the start of a new conflict occurrence.

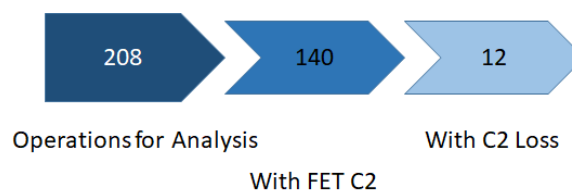


Using this method, 136 distinct operations were identified. Between those operations, a total of 172 conflicts occurred.

### **Determining Loss of Command and Control (C2) Occurrences**

For this analysis, the valid operations identified in the 'Operations for Analysis' section were used as the preliminary filter. This list of operations was then further reduced to only operations with FlightEssentialTelemetryAndUasStates communication data. For communication data, NASA asked the test site and partners to provide the metrics that they would use to identify a loss of C2. These metrics would then be added as 'sensors' in the FlightEssentialTelemetryAndUasStates model. The metric provided was identified as 'CONNECTED\_TO\_RC\_DJI'.

For the MOP calculation, any occurrence of that sensor with a value of '0' for longer than 5 seconds is identified as a loss of communication.



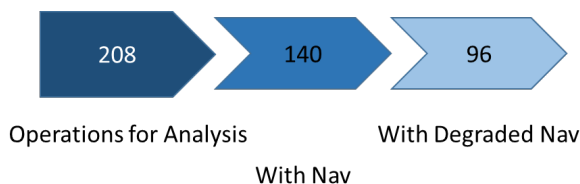
Using this method, a total of 140 operations were identified that included C2 status data. Of those 140 operations, 12 experienced a loss of C2.

### **Determining Degraded Navigation Occurrences**

For this analysis, the valid operations identified in the 'Operations for Analysis' section were used as the preliminary filter. This list of operations was then further reduced to only operations with data that could be used to determine a degraded navigation condition, which came from the FlightEssentialTelemetryAndUasStates DMP model.

Similar to the communication data, NASA asked the test site and partners to provide the metrics that they would use to identify degraded navigation. These metrics would then be added as

'sensors' in the FlightEssentialTelemetryAndUasStates model. The metric provided was identified as 'NAVIGATION\_ACCURACY\_CATEGORY\_POSITION'. Any occurrence of 'NAVIGATION\_ACCURACY\_CATEGORY\_POSITION' with a value less than 10 for longer than 5 seconds indicated degraded navigation.



Using this method, a total of 140 operations were identified that included navigation status data. Of those 140 operations, 96 experienced a degraded navigation condition. The following four subsections describe the four MOPs in detail.

## Rate of Loss of C2

### Background

The small UAS operators are expected to perform missions within constraints and directives that can change over time (e.g., a Temporary Flight Restriction). Therefore, operators must know whether they can communicate or not with their UA to adhere to dynamic constraints and directions [Jung 2020a]. For the TCL4 environment, the UTM team targeted <1% of the accumulated operational time to experience Loss of C2, with <4% as a minimum success. During the TCL4 demonstration, the operators used commercial off-the-shelf communications systems using Industrial Scientific, and Medical (ISM) frequency bands and also Long-Term Evolution (LTE) devices for communications.

### Results

Of the 140 operations with the data necessary for this MOP calculation, 12 experienced a loss of C2. Those 12 operations had a total of 1807 seconds in a loss of C2 condition. The total duration of the 140 operations was 103,067 seconds, resulting in a C2 loss occurring in about 2% of the total duration. This meets the minimum success criteria.

### Discussion

Of the 12 operations that experienced a loss of C2, 11 experienced loss of C2 near the beginning or the end of the operation; 7 experienced the loss within one minute of the operation starting or ending and 4 experienced the loss within 10 meters of the starting or ending position. Such a trend implies that there was a high level of Radio Frequency Interference (RFI) near the takeoff and landing locations in these 11 cases. In the 12<sup>th</sup> case, loss of C2 occurred between 199 meters and 232 meters from the GCS location, as shown in Figure 3 where green indicates where the operation flew with C2 capability, yellow indicates where C2 was lost, and the star icon indicates the GCS location. In this case, RFI from an unknown source or the loss of radio line of sight could have disrupted the C2 link. These findings enforce an earlier recommendation to the operator for monitoring the RF characteristic of the intended operation area and examine the radio noise floor during operations [Jung 2019]. The UA in Figure 3 continued flying the programmed route with the loss of C2. This implies a few possibilities. One is that the conditions used to identify loss of C2 for the MOP calculation did not trigger the UA's loss of C2 handling procedure such as return to its launch location. Another is that the UA recovered C2 before activating the UA's loss of C2 handling procedure. For future studies, it is recommended that the actual parameters used by UAs to identify loss of C2 condition to be logged both at UA and the GCS, along with the

associated thresholds and conditions. This would help researchers and operators gain further insights into understanding the loss of C2.

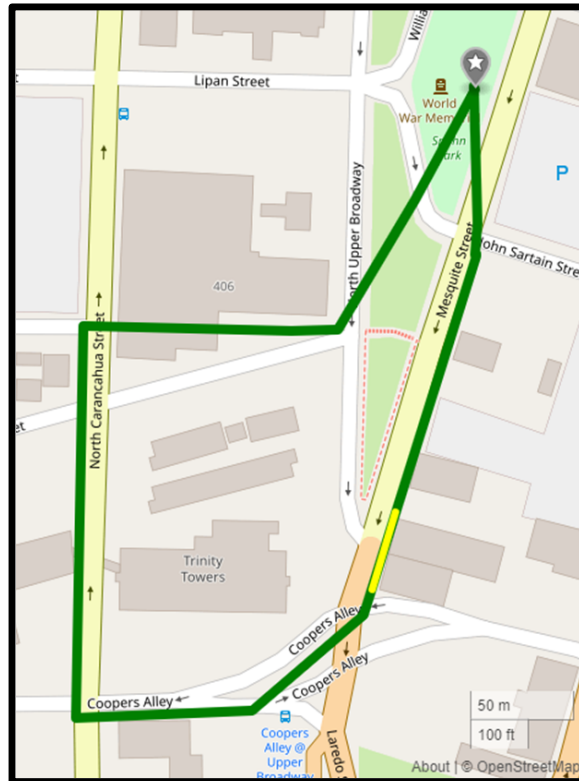


Figure 3<sup>2</sup>. Top-Down View of an Operation with Loss of C2

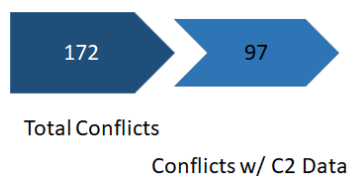
### Rate of C2 Loss during a Conflict

#### Background

For operations in the TCL4 environment, it is expected that UA to UA conflict is resolved with UA onboard, and/or ground-based, Detect and Avoid (DAA) functionality. C2, in particular UA telemetry, is necessary for the operator to be informed of a conflict and its resolution (e.g., UA heading away from each other). The UTM Project established a minimum success criterion of less than 4% rate of C2 loss during a conflict, and a target success of 0% for this MOP.

#### Results

Results identified in the ‘Determining Conflict Occurrences’ and ‘Determining Loss of C2 Occurrences’ sections in the Appendix are combined to determine the number of operations which had a loss of C2 occurrence during a conflict. Only conflicts with C2 data for both operations are considered.



<sup>2</sup> Underlying map data is © OpenStreetMap contributors. <https://www.openstreetmap.org/copyright>

Of the 97 conflicts where both operations had C2 status data, only 1 of the 97 conflicts had an operation that experienced a loss of C2 during the conflict. The 97 conflicts resulted in a total conflict duration of 12,553 seconds, and only 28 seconds where at least 1 of the operations experienced a loss of C2. This resulted in a less than 1% rate, which met the minimum success criteria.

### Discussion

At the time of the TCL4 demonstration, DAA solutions were not available and for safety, all operations were procedurally separated. For example, one UA was programmed to fly at higher altitudes than another UA in the same area. For analysis, a conflict was designated after the demonstration with the following threshold; two UA within 700 ft laterally and 200 ft vertically. Since conflicts are designated post-flight, they were passively resolved. That is, the two UA in the conflict did not maneuver to resolve the conflict but flew the routes as programmed.

Figure 4 shows the tracks of an example conflict. Note that the track figure is in 2D, whereas the conflict is determined in 3D. In the figure, the green lines indicate the full flight path, the yellow lines indicate the portion of the flight path where the operations were in conflict, and the red lines indicate the portion of the flight path where there was a loss of C2, which may have been caused by RFI or the loss of radio line of sight. The UA in Operation 1 continued flying the programmed route with the loss of C2. As previously mentioned, this implies a few possibilities. One is that the conditions used to identify loss of C2 for the MOP calculation did not trigger the UA's loss of C2 handling procedure, such as return to its launch location. Another is that the UA recovered C2 before activating the UA's loss of C2 handling procedure.

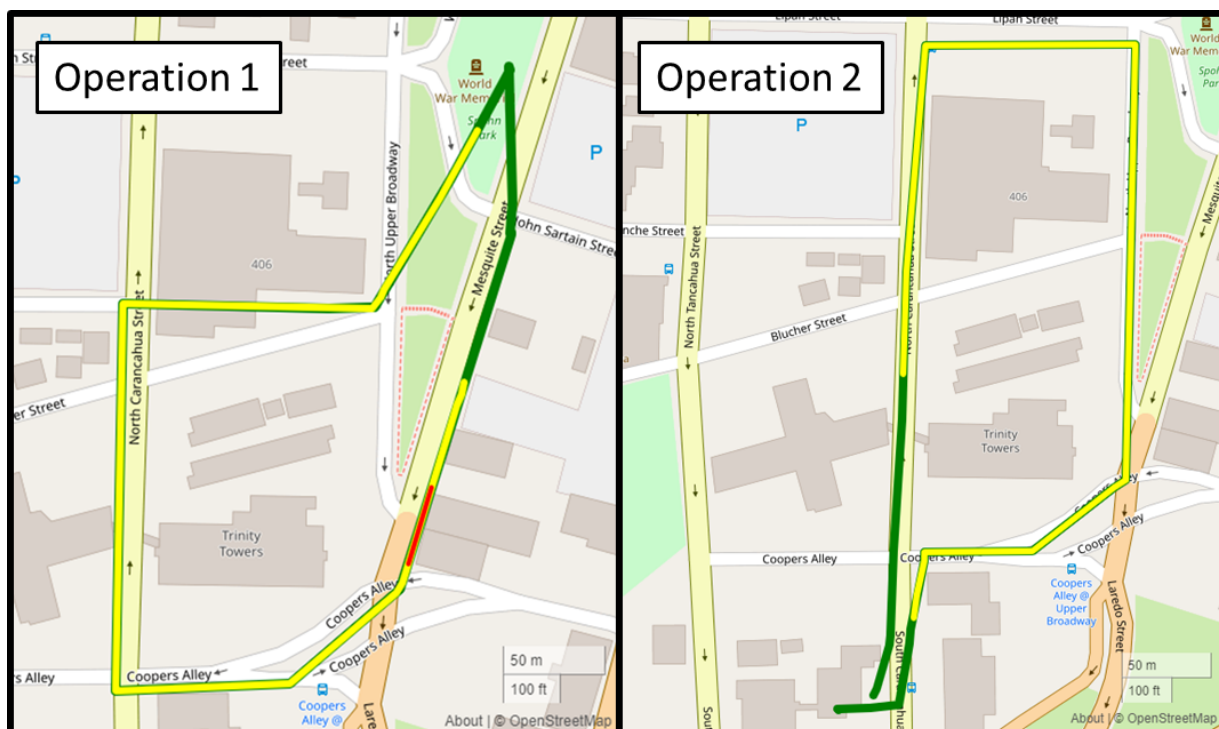


Figure 4<sup>3</sup>. Top-Down view of Conflicting Operations

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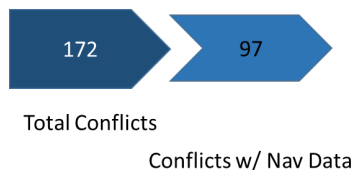
## Rate of Navigation Degradation during a Conflict

### **Background**

To safely resolve a conflict, a properly functioning navigation system is necessary. The UTM Project established a minimum success criterion of less than 15% rate of navigation degradation during a conflict, and a target success of 0% for this MOP.

### **Results**

Results identified in the ‘Determining Conflict Occurrences’ and ‘Determining Loss of Navigation Occurrences’ sections in the Appendix are combined to determine the number of operations which had a loss of navigation occurrence during a conflict. Only conflicts with navigation data for both operations are considered.



Of the 97 conflicts where both operations had navigation status data, in 86 of the conflicts (about 89%) at least one of the operations experienced degraded navigation. Of the 86 cases, 82 cases involved one or both operations experiencing degraded navigation performance for the entire duration of the conflict. Table 2 shows details of this MOP result.

The 86 conflicts resulted in a total duration of 11,252 seconds where at least 1 of the operations experienced navigation performance degradation, resulting in about 90% rate, far exceeding the success criteria of less than 15%.

**Table 2.** UA Navigation Performance during Conflicts

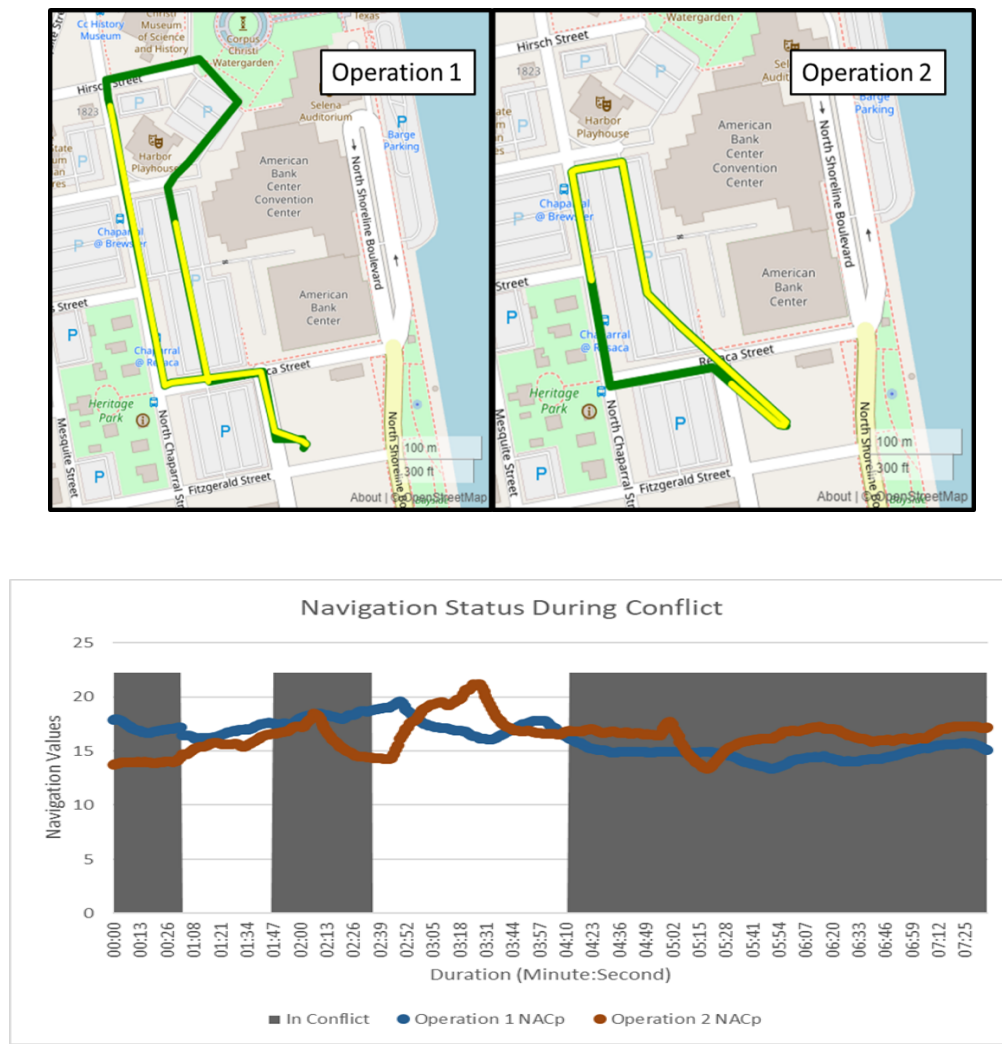
<u>Navigation Performance Status</u>	Number of Conflicts (97 total)	Degraded Nav Duration (sec)	Conflict Duration (sec)
Both UA degraded for the entire conflict duration	67	9605	9605
1 UA degraded for the entire conflict duration, 1 UA degraded for a portion of the conflict duration	1	141	141
1 UA degraded for the entire conflict duration, 1 UA Nominal	14	1391	1391
1 UA degraded for a portion of the conflict duration, 1 UA Nominal	4	115	249
Both UA Nominal	11	0	1167



## Discussion

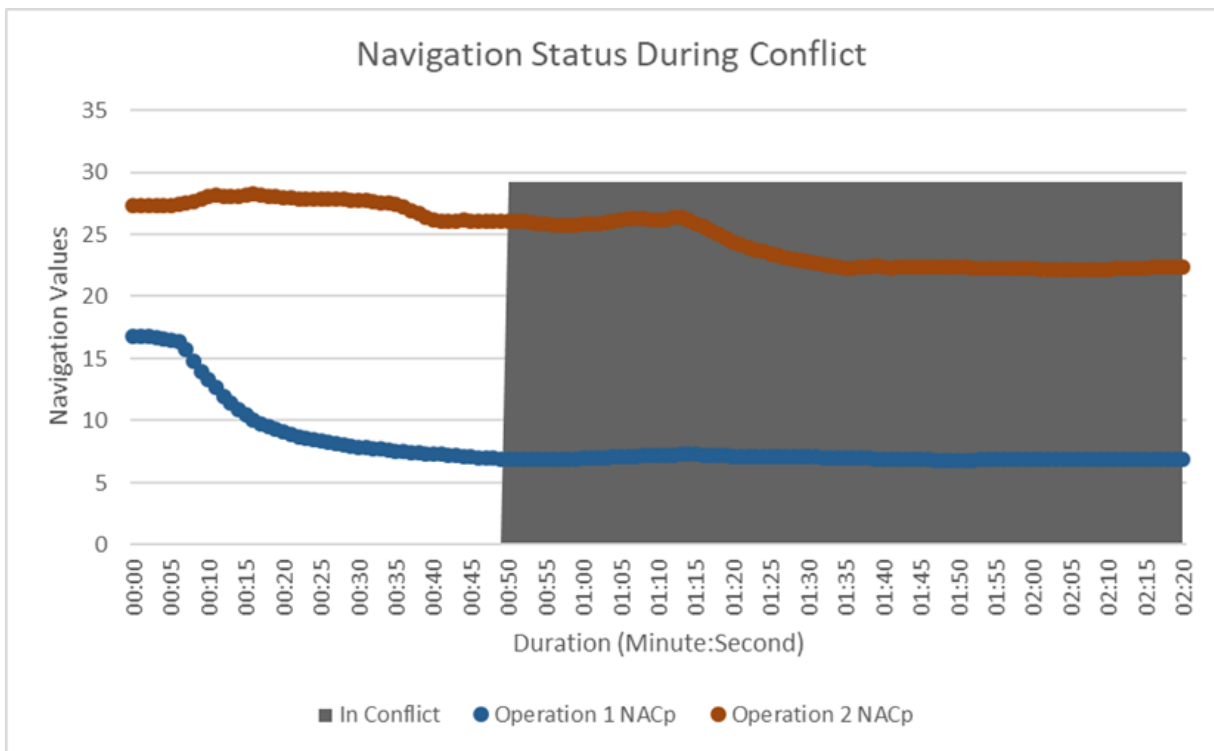
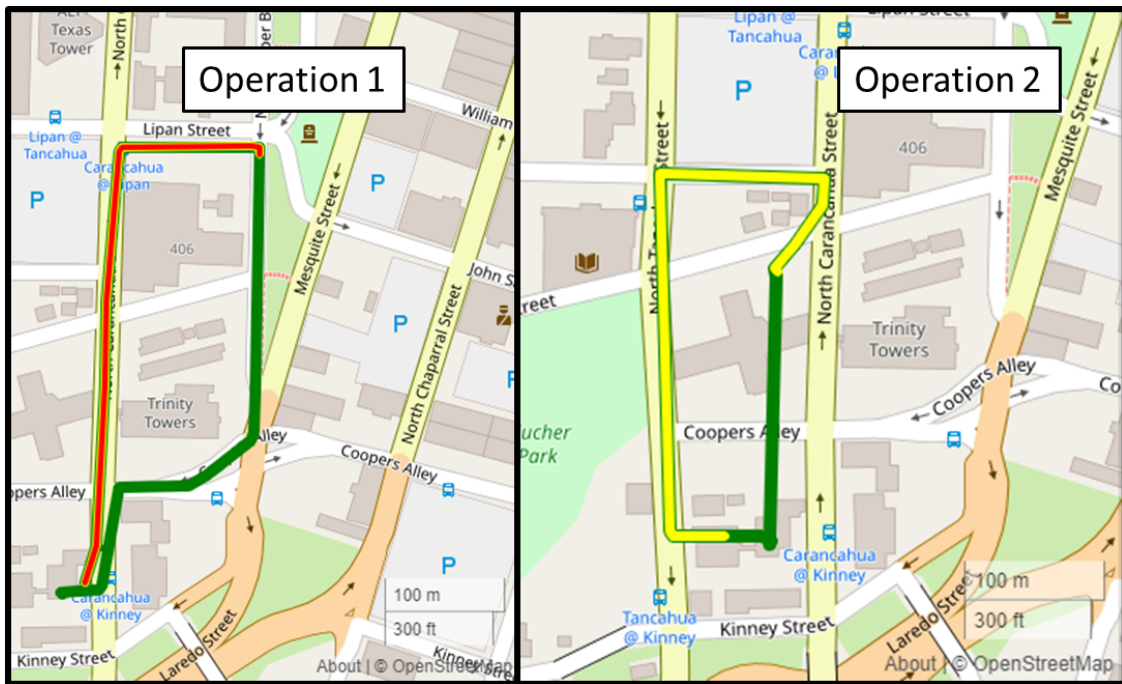
To calculate this MOP, the Horizontal Accuracy Category, NACp, of 10 is used as the minimum navigation performance. This category is associated with 10 meters or better horizontal accuracy bound (e.g., 9 meters) [RTCA 2011]. Figures 5, 6, and 7 show examples of nominal and degraded navigation performance during conflicts. In each figure, there are two sub-figures; one which shows the tracks of the two operations, and another which shows the navigation values with an indication of when the operations are in conflict (represented by the shaded region of the plots). Note that the track figure is in 2D, whereas the conflict is determined in 3D. In the track sub-figures, the green lines indicate the full flight path, the yellow lines indicate the portion of the flight path where the operations were in conflict, and the red lines indicate the portion of the flight path where there was degraded navigation.

In Figure 5, two operations enter conflict but do not experience degraded navigation. As the figure shows, the operations move within the ‘conflict’ distance several times during the operation, and the NACp values are always greater than the minimum (10) value. Figure 6 depicts a pair of operations where only one operation experiences a loss of navigation during the conflict. Figure 7 shows a pair of operations where both operations experience degraded navigation.



**Figure 5<sup>4</sup>.** Example: two operations which enter conflict but do not experience degraded navigation

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**Figure 6<sup>5</sup>.** Example: two operations which enter conflict and one experiences degraded navigation

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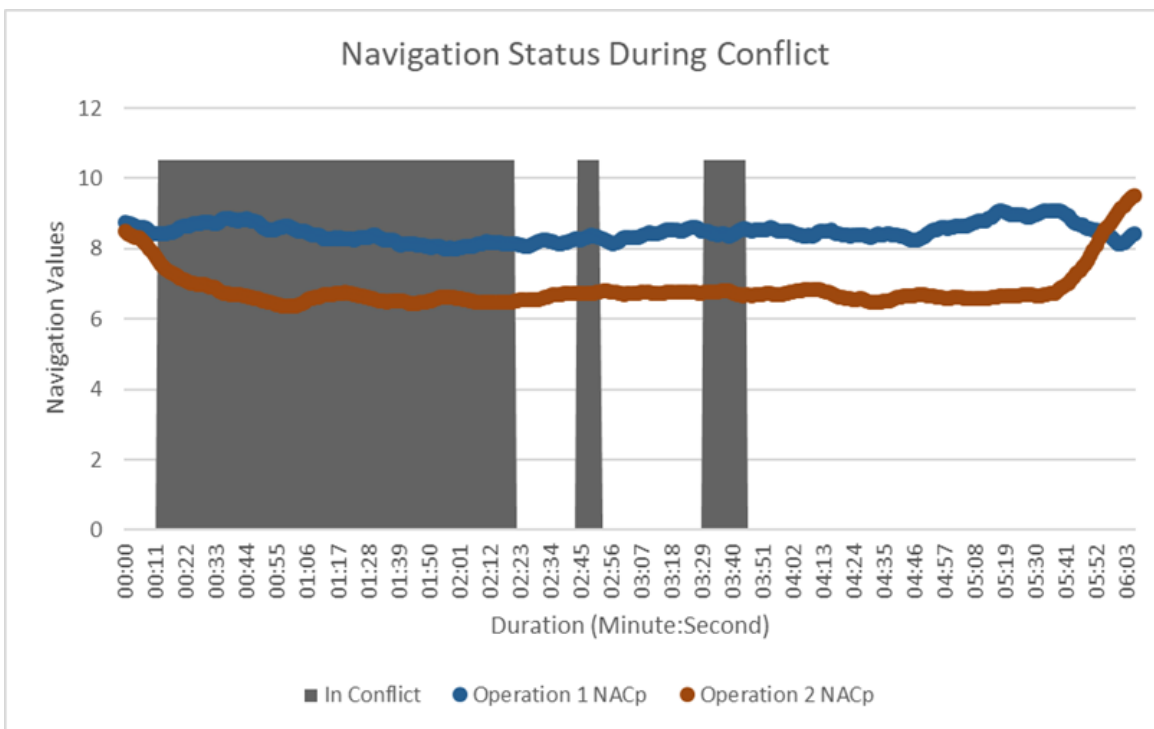
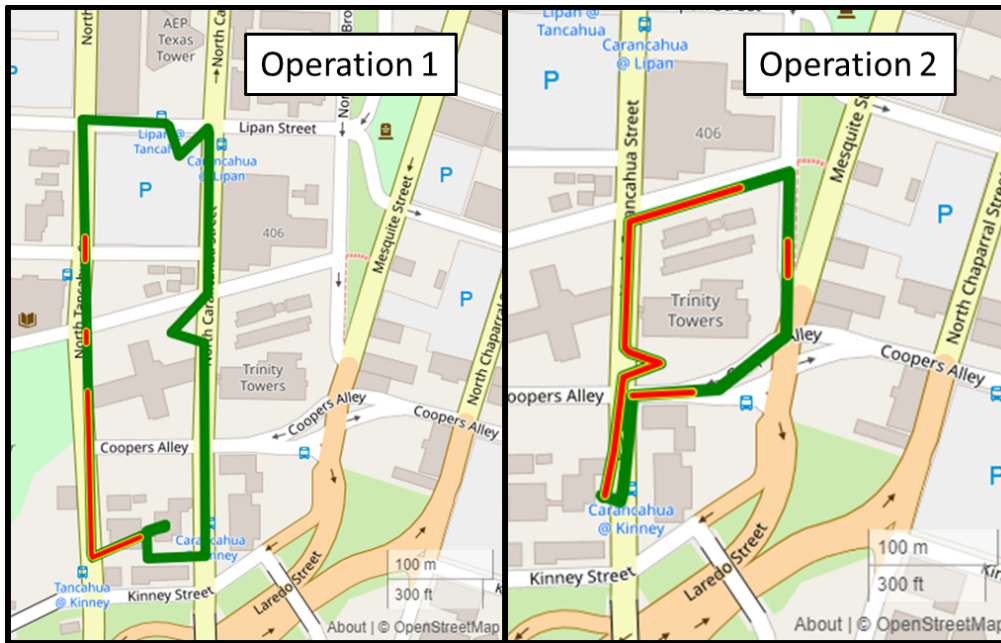


Figure 7<sup>6</sup>. Example: two operations which enter conflict, and both experience degraded navigation

For the TCL4 Demonstration, the operators used UAS built-in functions to monitor navigation performance, and no significant issues were reported throughout the operations [Jung 2020b]. This contrasts with the high rate of navigation degradation results, as represented by lower than

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10 NACp value. The discrepancy between the lack of actual navigation performance issues reported by the operators, and the MOP result, implies that whereas the 10-meter horizontal position accuracy was difficult to achieve during the TCL4 demonstration, the UTM was still able to maintain conformance. That is, UA operated without leaving their operation volumes.

## Rate of Safe Landing

### Background

For TCL4, the safe landing of UA was defined as the landing of UA at a planned location, with an assumption that this location was kept clear of people and properties not related to landing. The UTM Project established a minimum success criterion of greater than 25% rate of the UA achieving safe landing, with a target success of greater than 75% for this MOP.

### Results

For the actual landing locations, the ones identified in the 'Determining Landing Locations' section in the Appendix were used. For the planned landing locations, a designated landing position included in the operation plan was used. If an operation announced that a contingency was initiated, the contingency landing polygon was used as well. Note that the operation plan uses a position (i.e. point) and the contingency plan uses a polygon for indicating landing location. A 'safe' landing was determined when UA landed within 3 m, 5 m, or 10 m of a designated landing position, or when landed inside of the polygon defined in the contingency plan. The three distances reflect potential position error that can come from UA navigation system.

Of the 219 landings, 117 occurred within 3m of a planned landing location or within an identified polygon (53%), 26 (12%) were outside of 3m but within 5m of a planned landing location, and 35 (16%) were outside of 5m but within 10m of a planned landing location. As shown in Figure 8, 81% of landings were considered safe with the 10 m threshold, meeting the target success criteria for this MOP.

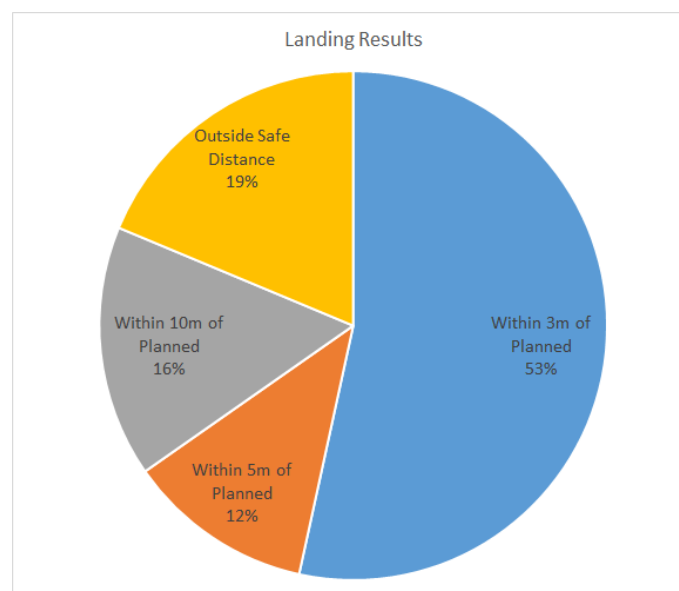


Figure 8. Rate of safe landing

## **Discussion**

Of the 219 landings, 41 (or 19%) landed more than 10 m away from the planned location. Whereas many of these operations were manually conducted by pilots, the data did not distinguish between the number of manual and automated landings. For the TCL4 demonstration, which used an Extended VLOS setting to emulate BVLOS operations, these landings did not have any actual safety implication as visual observers and the operator always had the UA in sight and made certain that there were no persons in the UA's landing path. For actual BVLOS operations, the UA should always land at the planned location that is properly prepared and maintained (e.g., a fenced platform that only allows operators to enter) and have the capability to avoid causing detrimental impact to people and property when it must land away from the planned location.

## **Summary**

Data collected from the TCL4 demonstration were used to assess small UAS communications and navigation performance in urban settings. Four MOPs, rate of loss of C2, rate of C2 loss during the conflict, rate of navigation degradation during the conflict, and rate of the safe landing, were calculated for this assessment. At the time of the TCL4 demonstration, the DAA capability was not implemented and this led to the procedural separation of concurrent operations preventing UA to UA conflict situations. Since two of the MOPs are associated with conflicts, reinvestigation of these MOPs with DAA solutions is recommended. For future studies on communication performance, it is recommended that the actual parameters used by UAs to identify loss of C2 condition be logged both at UA and the GCS, along with the associated thresholds and conditions. This would help researchers and operators gain further insights into understanding the loss of C2.

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