Unmanned Aircraft System Loss of Link Procedure Evaluation Methodology

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Acknowledgements

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I. Executive Summary

Unmanned Aircraft Systems (UAS) are aircraft systems that are remotely piloted from ground stations via a real-time command and control (C2) data link. If the link between the ground station and UAS is lost, the Unmanned Aircraft (UA) utilizes pre-programmed contingency procedures until the link is re-established or the UAS ends the flight in a safe manner. Currently the various UAS manufacturers and operators utilize different procedures when the C2 link is lost, which reduces predictability of the UA's flight for Air Traffic Control (ATC).

Having standardized procedures for UAS during loss of link situations would increase the predictability of UAS behavior for ATC, making these events easier to handle. Standardized procedures could also assist in integrating UAS into non-segregated civil airspace in greater numbers.

To aid in the standardization of UAS loss of link procedures, the UAS Loss of Link (UL2) team's sponsor desired metrics and a methodology to evaluate the viability of various proposed contingency procedures from an ATC perspective. The sponsor desired a low-fidelity capability that could be executed quickly to support community efforts to develop standardized procedures.

The developed methodology includes a predictability model that uses a Monte Carlo simulation to estimate the probability that a controller can adequately predict the first maneuver of a UA's contingency procedure. For the purpose of this analysis, the team used a sponsor-provided sample procedure that allocated UA maneuver timing.

The team found that the model can provide the user with the determination of whether or not the controller was able to identify the UA as lost link before the UA performed the first maneuver of its contingency procedure. This model is repeatable and utilizes adjustable parameters so that different procedures can be analyzed. The user can determine whether the results (probability of when a loss of link situation was not identified in time) are appropriate based on his or her set threshold criteria and then further compare the results to other modeled procedures.

The methodology also includes a controller workload simulation using a MITRE-developed tool called *airspace*Analyzer. Although the tool was not created as a workload model, the team's sponsor recommended this tool to the team for the analysis. Three scenarios involving loss of link situations were designed to explore the functionality of the tool and to determine whether it could be used to evaluate a loss of link situation's impact on controller workload.

The team determined that there are some potential limitations in using *airspace*Analyzer as a model of controller workload. The largest limitation is that the software attempts to solve separation issues by maximizing forward progress of aircraft, and therefore may maneuver more aircraft than is necessary in order to avoid a major disruption to one aircraft's intended route. Because of this, a more thorough evaluation of *airspace*Analyzer should be performed in order to ensure that appropriate and interpretable controller workload metrics are capable of being produced by the tool.

II. Introduction

A. Background

An Unmanned Aircraft System (UAS) is an aircraft system that does not have an on-board pilot. UAS are piloted remotely from ground stations via a real-time command and control (C2) data link. Therefore, the risk of any type of contingency maneuver differs greatly from aircraft with a pilot onboard. If the link between the ground station and Unmanned Aircraft (UA) itself is lost, the aircraft utilizes pre-programmed contingency procedures until the link is re-established or the UAS ends the flight in a safe manner. This is known as a loss of link procedure. However, loss of link procedures differ depending on the manufacturer and operator of the UA. Loss of link procedures also have an impact on the operations of the UAS, ground stations, and Air Traffic Control (ATC).

ATC is responsible for managing air traffic on the ground and in the air in a safe and efficient manner. Their main objective is to separate air traffic and maintain this separation in order to avoid a potential conflict. Individual controllers are in charge of sectors, which are subdivisions of airspace defined by lateral and vertical bounds. Each sector is designed by the Federal Aviation Administration (FAA) and has a distinct radio frequency for communication between pilots and ATC. In order to visualize traffic within a particular sector, ATC uses radar scopes that display key information about an aircraft's call sign, position, altitude, speed, and transponder code. This information is displayed on the scope as part of an aircraft's data block as shown in Figure 1. A change in transponder code will show RDOF (radio failure) within the data block, which is often used to indicate that a UAS has lost its C2 link.

Figure 1 - Example Aircraft Data Block

B. Sponsors and Stakeholders

This project was sponsored by the MITRE Corporation, a not-for-profit organization that manages Federally Funded Research and Development Centers (FFRDCs). The team worked directly with Andrew

Lacher, who is the UAS Cross-Center Coordinator and Research Strategist at MITRE's Center for Advanced Aviation System Development (CAASD).

In addition to the sponsor, this topic involves many members of the UAS community including ATC, UAS pilots, UAS manufacturers and operators, as well as UAS researchers. The team's sponsor facilitated meetings with a subset of these stakeholders so the team could gain an understanding of the various stakeholder views.

C. Problem Definition and Need

When an Unmanned Aircraft (UA) loses its C2 link, it becomes unpredictable to ATC due to the large set of possible loss of link procedures it may use. This unpredictability may result in an increase in controller workload if additional coordination with pilots or other controllers is necessary. For example, a neighboring aircraft may need to be rerouted in order to avoid the unresponsive UA. A reroute often requires additional controller-pilot transmissions on busy radio frequencies, and may result in additional communication with controllers responsible for neighboring airspace. Additionally, since a UA does not have the capability to sense-and-avoid, a loss of link situation also increases the risk of a loss of separation or collision, which is a critical safety hazard.

Standardized procedures for loss of link situations are necessary to make the UA's flight path more predictable and easier to manage for ATC. The standardization of procedures could also assist in commercializing the use of UAS.

In order to achieve this, there must be agreement within the UAS community in defining a standardized procedure. Therefore, a means of evaluating and ranking candidate standardized loss of link procedures is necessary. The purpose of this project is to satisfy the sponsor's need for metrics and a methodology for evaluating loss of link procedures in order to facilitate community development of standardized procedures. The sponsor can use the metrics and methodology to select the most promising loss of link procedures and perform further analysis using human-in-the-loop (HITL) simulations.

D. The UL2 Team

1. Sahar Sadeghian

Sahar Sadeghian is a Senior Systems Engineer at The MITRE Corporation. She started working at MITRE in 2010 when she graduated from George Mason University with a Bachelor's Degree in Systems

Engineering. At MITRE, she works at the Center for Advanced Aviation System Development (CAASD) focusing on Aviation Safety. She will be graduating with her Master's Degree in Systems Engineering from George Mason in May 2012.

2. Steven Lubkowski

Steven Lubkowski has worked at The MITRE Corporation since 2006, currently working in MITRE's Center for Advanced Aviation System Development (CAASD) as a Senior Systems Engineer. He received his Bachelor's Degree in Systems Engineering specializing in Aviation Systems from George Mason University in 2010 and is currently pursuing his Master's Degree in Systems Engineering, graduating in May 2012.

3. Rob Dean

Rob Dean has worked at The MITRE Corporation since 2007 when he graduated from the University of Virginia with a Bachelor's Degree in Mathematics. While working at MITRE, he has earned a second Bachelor's Degree in Airport Management from Vaughn College of Aeronautics and Technology, and is pursuing his Master's Degree in Systems Engineering from George Mason University. He expects to graduate in May of 2012.

4. Rohit Paul

Rohit Paul graduated from George Mason University with a Systems Engineering Bachelor's degree in 2009. He has worked at the Federal Aviation Administration as a Technical Engineer for the En Route and Oceanic Service Unit. Currently, he works at the MITRE Corporation as a Systems Engineer and Enterprise Architect in support of the Next Generation Air Transportation System (NextGen) and is planning to graduate with his Master's Degree in Systems Engineering in May 2012.

III. Scope

A. In Scope

The UL2 team collected metrics and developed a preliminary methodology to be used when evaluating UAS loss of link procedures. The focus of the project was on UAS flying within non-segregated civil airspace in the National Airspace System (NAS). The team focused on evaluation of loss of link procedures for UA operating in Class A airspace (above 18,000 feet Mean Sea Level (MSL)). In addition, the team's methodology focuses on loss of link situations with a duration of at least 30 seconds.

B. Out of Scope

The team was not responsible for the identification of an optimal procedure in loss of link situations. Any optimal solution would have to be discussed and agreed upon within the UAS community and is dependent on the many stakeholders. Because of this, allocation of weights to the identified metrics was out of scope. The sponsor emphasized that the methodology and metrics were the important elements in this project. The team did not include evaluation of loss of link procedures during takeoff and landing in terminal airspace.

IV. Requirements

A. Requirements

Requirements were developed to document the team's understanding of the sponsor's needs. The Project Requirements defined the team's required work for the duration of the project period. The Functional Requirements defined the expectations for the UAS loss of link procedure evaluation methodology.

B. Project Requirements

- The UL2 team shall solicit input from UAS Subject Matter Experts (SMEs) including Air Traffic Controllers, UAS Pilots, and MITRE UAS experts.
- The UL2 team shall define the required criteria to be used in the evaluation of UAS loss of link procedures.
- The UL2 team shall define appropriate metrics for each of the critical evaluation criterion.
- The UL2 team shall develop a methodology that uses the defined criteria and metrics to evaluate a sponsor-provided sample UAS loss of link procedure.
- The UL2 team shall demonstrate the applicability of the developed metrics and methodology on a sample UAS loss of link procedure.
- The UL2 team shall prepare a final report detailing the work performed throughout the duration of the project period, the final evaluation criteria, metrics, and the evaluation methodology that is developed.
- The UL2 team shall prepare a final presentation that explains the work to George Mason University Systems Engineering and Operations Research (SEOR) faculty and the project sponsor.

C. Functional Requirements

- The developed evaluation methodology shall provide a means for ranking UAS loss of link procedures.
- The developed evaluation methodology shall be capable of incorporating new evaluation criteria that may become important after the initial project period.
- The developed evaluation methodology shall be repeatable.

- The developed evaluation methodology shall include modeling and simulation of at least two of the defined evaluation criteria.
- The developed evaluation methodology shall be adaptable to include future modeling and simulation.

V. Project Approach

The team followed a three-tier approach in order to identify the metrics important to the UAS community and develop a methodology for analyzing the adequacy of loss of link procedures. This approach included a qualitative analysis to identify important criteria, an analysis of absolute conditions, and a quantitative analysis using models and simulations to evaluate the defined criteria.

A. Three Tier Approach

1. Qualitative

To determine the important criteria for evaluating UAS loss of link contingency procedures, the team conducted interviews with UAS stakeholders. The team met with the following Subject Matter Experts (SMEs) available at MITRE:

- Global Hawk UAS pilot (Chris Jella)
- ATC Human-in-the-Loop (HITL) experiment analyst (Jill Kamienski)
- UAS loss of link data analyst (Jane Whitely)
- Lead developer of automated ATC tool (Bill Niedringhaus)
- Traffic flow management lead architect (Andy Anderegg)
- Lead UAS Architect (Michelle Duquette)

The SMEs identified two important criteria of interest, controller workload and predictability of the UA.

2. Absolute Conditions

The team determined from discussions with the sponsor and SMEs that a loss of link procedure may be eliminated because it does or does not include a certain element or meet a specific qualification. Using certain thresholds that must be met by a procedure, the list of procedures can be narrowed.

3. Analytical

The team developed and identified simulations that allow the analysis of individual procedures based on two specific criteria: UA predictability and controller workload.

VI. Modeling Analytical Approach

Based on the team's discussions with the SMEs, two key criteria were identified: UA predictability and controller workload. Therefore, the team focused the project on analyzing these two criteria. Predictability was measured using a simulation model developed by the team. Controller workload was estimated using a MITRE-developed controller emulation tool named *airspace*Analyzer. The details of both models are described below.

A. Predictability Model

1. Background

The predictability model is designed to evaluate the predictability of a loss of link procedure. Since predictability is difficult to quantify, the model uses time as a pseudo-measure. Once a UA loses C2 link, it initiates a contingency procedure; this could be anything from following the original flight plan to hovering in a circle or flying its present heading. Since there are many possible contingency procedures depending on the manufacturer or operator of the UA, standardized procedures are necessary in order to make loss of link situations more predictable. The focus of the predictability model is to evaluate proposed standardized contingency procedures. The team used data from a sample loss of link procedure provided by the sponsor to test the model. The model has been formulated so that new data can be entered in order to evaluate different procedures or to account for more recent research.

2. Model Logic

The flow chart shown in Figure 2 illustrates the logic of the model, taking into account the events that take place when a UA loses C2 link. When a loss of link situation occurs, two different sets of events follow. In one set of events, the UAS pilot identifies that the UA has lost C2, waits a specific amount of time to ensure the loss of link is not a false alarm and then attempts to contact ATC in order to inform the controller of the situation and provide details on the UA's pre-programmed instructions. In the second set of events, the UA broadcasts its lost link status by changing its transponder code to 7600. The controller in charge of the sector containing the UA is informed of the loss of link via an indicator flashing RDOF on his or her radar scope. The broadcast is done by a radar transponder that replies back to secondary surveillance radar interrogation message with encoded information (e.g., aircraft identification, altitude, transponder code) that is independent of the C2 link.

These two sets of events can occur simultaneously and either can reach the controller. The decision module (dark blue diamond in Figure 2) identifies the length of time it takes for the controller to recognize the loss of link situation (whether from the pilot or from the UA broadcast). The decision module logs whether the response time was adequate. Adequacy in this case is defined by whether the controller was able to identify the loss of link situation before the UA performed its first contingency maneuver. The team used a sponsor-provided sample procedure in which the first maneuver of the contingency procedure is initiated three minutes after the loss of link broadcast starts.

If the UA performs its first maneuver before the controller recognizes the situation, then the model indicates that controller did not adequately detect the loss of link situation. If the controller recognizes the situation in time, there are two sets of events that can take place:

1. If the pilot contacts the controller first, the model assumes that the pilot will provide the controller with the maneuver information and the UA is now deemed "predictable."
2. If the controller recognizes the loss of link situation from the UA broadcast code, he or she would estimate the time at which the first maneuver will occur. When the maneuver occurs, the delta between the controller's estimated and actual maneuver initiation times is recorded.

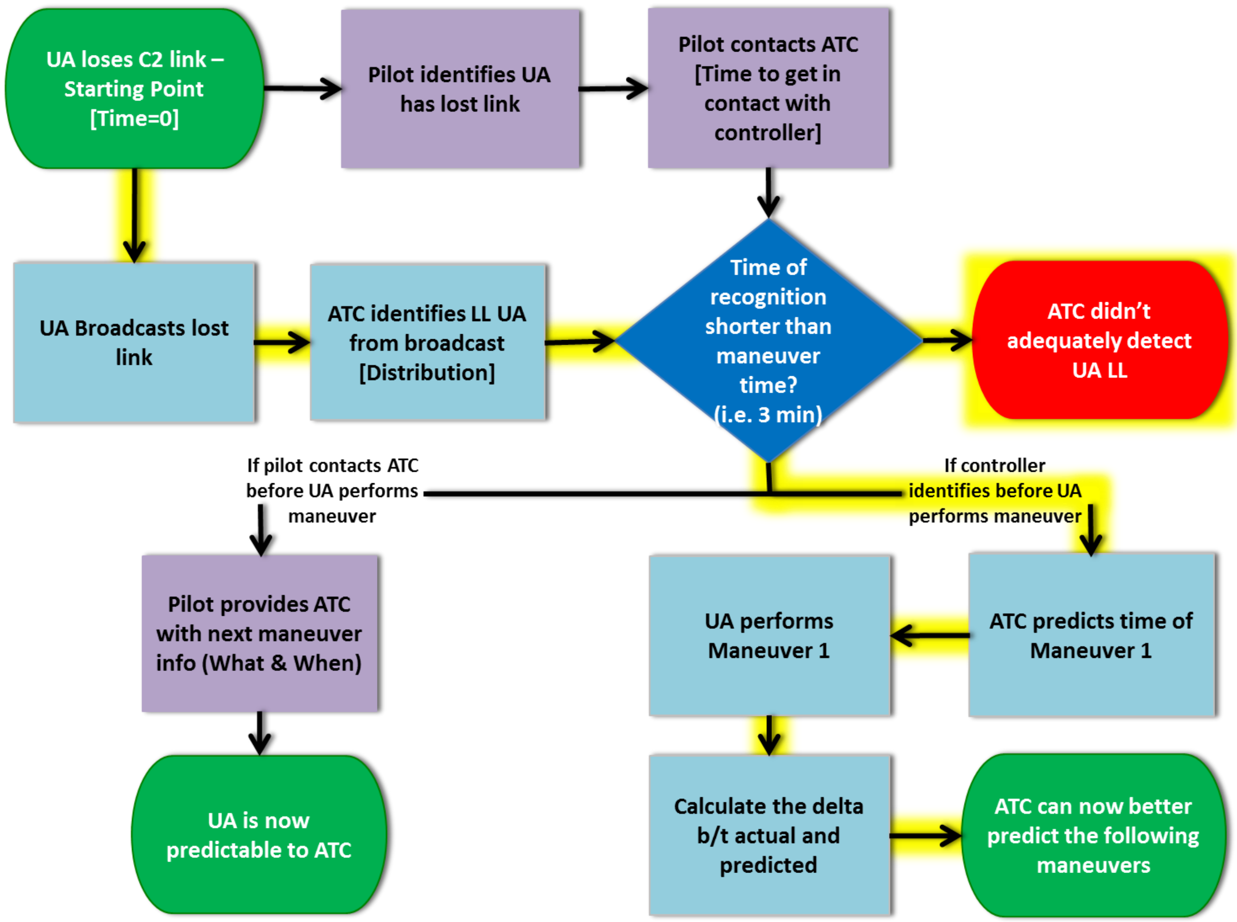


Figure 2 - Model Logic

For the purpose of this project, the model focused solely on the highlighted path in Figure 2. This path, unlike the path where the pilot contacts the controller, is more quantifiable in terms of time and therefore more interpretable as part of an initial modeling effort.

3. Data

Due to the relatively small number of UAS operations in non-segregated civil airspace, there is limited real data to define input parameters for modeling efforts. The block labeled "ATC identifies LL UA from broadcast" uses information taken from a HITL study conducted at The MITRE Corporation that recorded response times of controllers to RDOF signals displayed on an ATC workstation emulation. The predictability model leverages the limited data available. The distribution fit can be found in Appendix C - Predictability Model Data.

4. Assumptions

The team's assumptions for the predictability model are:

- All equipment and functions on the UA operate correctly aside from the C2 link.
- When the UA experiences loss of link, the controller knows what the UA's next maneuver will be.
- The controller plans sector movement ahead by two minutes, therefore there will be no potential for loss of separation between aircraft within the two-minute time frame after the UA experiences loss of link.
- Times of UA maneuvers are based on a sample procedure provided by the sponsor.
- Loss of link is indicated by a change in transponder code to 7600 indicating RDOF.
- If the pilot contacts the controller before the controller realizes the UA is experiencing loss of link, the pilot will inform the controller what the next maneuver is and when it will happen.

5. Tools and Models

To evaluate the time during these series of events, two tools were used. The team developed the model using a queuing and process modeling tool by Rockwell Automation called Arena. The team also used Microsoft Excel as a means to do a Monte Carlo simulation to verify and validate the Arena model.

a) Arena

Arena provides a means to analyze and define the best-fit curve for data. The team analyzed the input data on controller reaction times that were received from The MITRE Corporation (shown in Appendix C - Predictability Model Data). The controller reaction times best fit a Weibull distribution ($1 - e^{-\frac{x^{\alpha}}{\beta}} + \gamma$) with the values 1.14, 56.7, and 3 for α, β, and γ respectively. The best-fit curve can then be used in other tools such as Excel for further evaluation by extrapolating data. A model was also developed in Arena to depict the highlighted path in Figure 2 (this is also in Appendix C - Predictability Model Data).

b) Excel

This model also focused on the highlighted path mentioned above (Figure 2). The team produced a model that would allow the end user to tailor the inputs to meet his or her needs and perform a Monte Carlo simulation to evaluate a procedure. The model runs 200,000 trials to extrapolate the data for when a controller detects the UA's lost link status and when the UA performs its first maneuver. The user is able to enter three inputs (shown in Figure 3): The distribution for the controller reaction time, the distribution for probability of the potential for a loss of separation, and the time the UA initiates its first maneuver.

Input Sheet		
Procedure Name:	Test Procedure	
Input	**Function**	**Description**
Controller Inputs		
Controller Predictability Function	3+(56.7*(-LN(RAND()))^(1/1.14))	This input describes the inverse probability equation of when the controller will detect the UA.
UA Inputs		
Time before UA initiates the first maneuver	180	This describes the number of seconds before the UA initiates the first maneuver.
Other Inputs		
Time of Loss of Sepration formula	RAND()*200+120	This input describes the inverse probability equation for when there may be a loss of separation.

Figure 3 - Predictability Input sheet

The 200,000 trials are compiled into a chart for analysis. The final analysis consists of determining the probability that the controller will not be able to detect that the UA is in lost link status before it initiates its first maneuver. It also includes the probability of the potential for loss of separation (discussed in the next section) because the controller was not aware that the UA was in a loss of link situation. These measures can be used to determine the adequacy of a procedure for further evaluation.

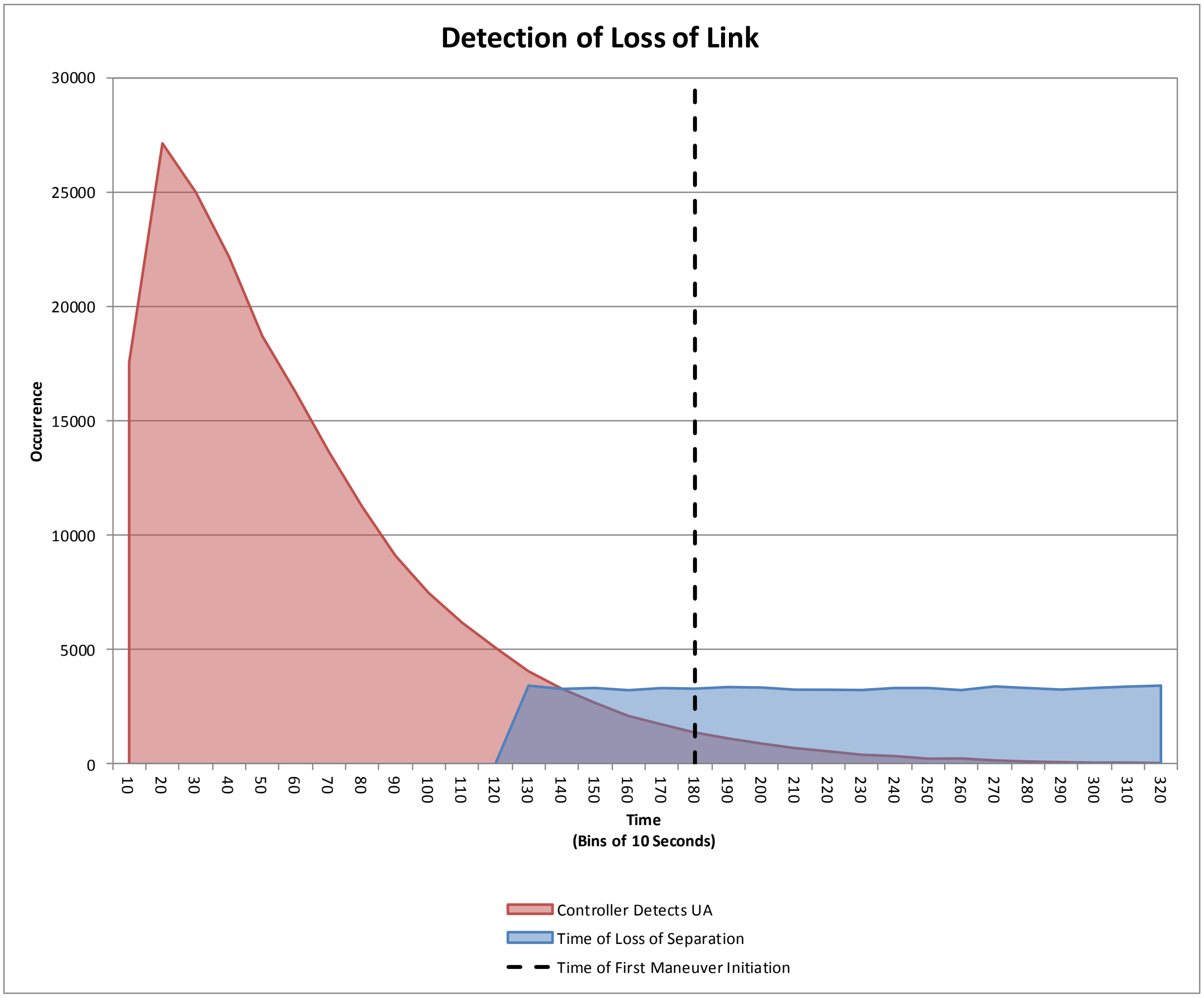
6. Outputs

Using the input data for the controller response times to a UA loss of link situation and the input data for the probability of loss of separation, the outputs are depicted in Figure 4. The red shaded area is the time at which the controller detects that the UA is in lost link status. The blue shaded area is the time at which there would be the potential for a loss of separation. The dotted line indicates when the UA initiates its first maneuver. The model calculates mean time of detection of the UA given the controller response time formula on the input sheet. This is representative of a possible bottom limit for when the UA can initiate a maneuver. The model also calculates the probability that the controller does not detect the UA's lost link status before the first maneuver is initiated. There is a possibility that the UA may lose separation with another aircraft before it is detected.

This model only estimates the potential for a loss of separation. This initial model does not take into account the probability of two aircraft being on courses that would bring them into conflict. Thus, the model outputs the probability that the UA has the potential for losing separation, given the controller does not detect its lost link status, and the probability of a potential for loss of separation before the UA initiates its first maneuver. Once the UA initiates its first maneuver, the risk of loss of separation significantly increases, therefore both measures are provided to allow better judgment of adequacy for the procedure.

Output Sheet

Procedure: Test Procedure



Mean time of detection (seconds)	**57.14**
Probability of detection after the initiation of first maneuver	**2.60%**
Estimated total probability of loss of separation with an undetected UA	**9.83%**
Estimated probability of loss of separation beofre the initiation of the first maneuver	**7.50%**

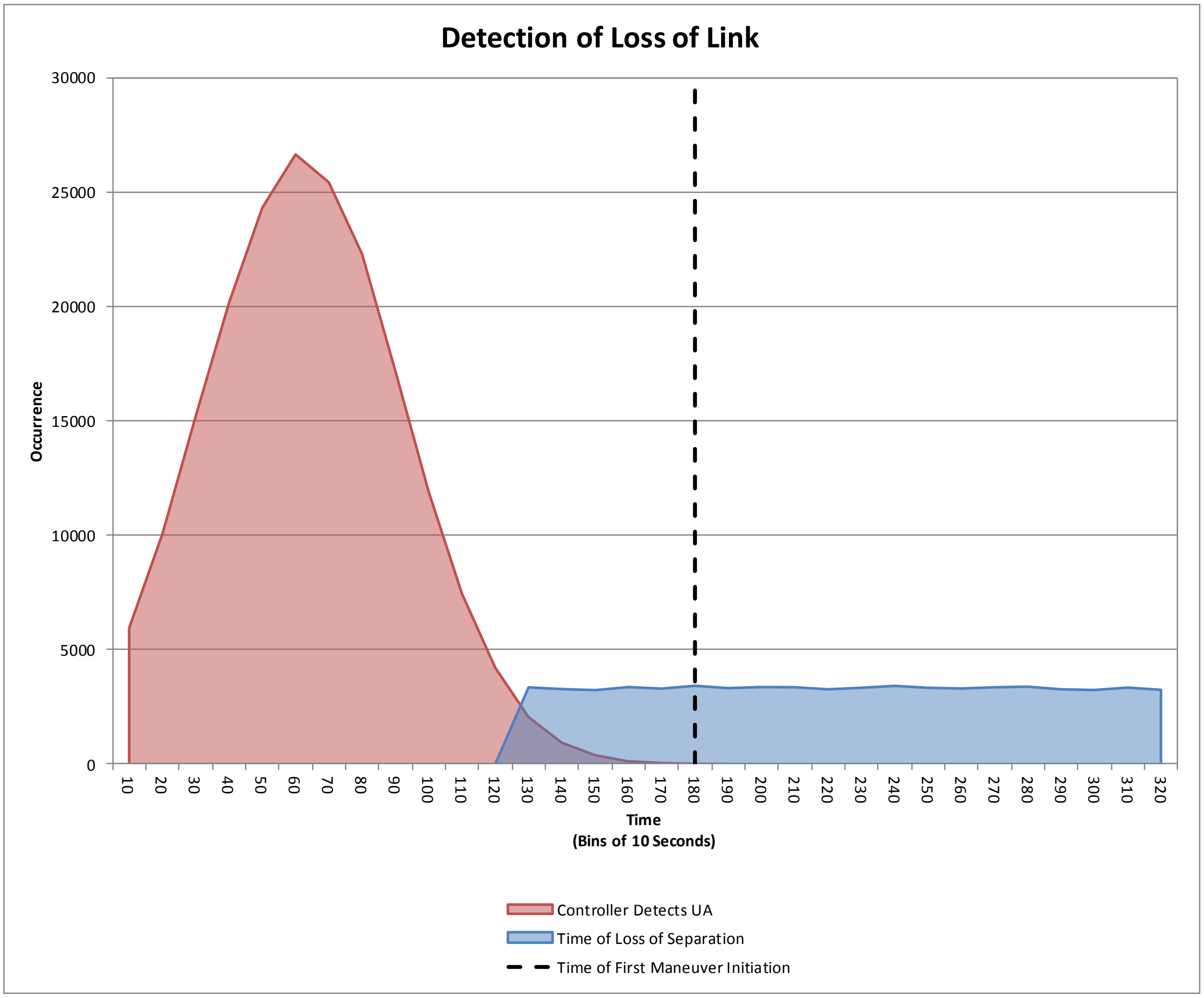
Figure 4 - Sample Procedure Output

After inputting the sample procedure provided by the sponsor and the sample formula for loss of separation (200x+120), the team analyzed the data outputs from the model shown in Figure 4. Based on the data entered for the controller reaction time, the mean time for detection was approximately 57 seconds. A controller would have approximately a 2.6% chance of not detecting the UA before it initiates its first maneuver.

In order to ensure that the model is valid, the team varied the inputs and analyzed the differences in the results. In Figure 5 below, the Weibull distribution was changed to a normal distribution to demonstrate the effect of different lost link status detection times. The detection parameter then changed to show a mean of 57 and standard deviation of 30 seconds. The probability of loss of separation within time of first maneuver changed to about 1.8% and the total probability of a potential for loss of separation changed to about 1.8%. These changes indicate that the model is adaptable to different input data.

Output Sheet

Procedure: Test Procedure 2



Mean time of detection (seconds)	**57.02**
Probability of detection after the initiation of first maneuver	**0.00%**
Estimated total probability of loss of separation with an undetected UA	**1.83%**
Estimated probability of loss of separation beofre the initiation of the first maneuver	**1.78%**

Figure 5 - Sensitivity Analysis - Test Procedure 2

7. Conclusions

Using the sample procedure provided by the sponsor (where the first maneuver of the contingency procedure occurs 3 minutes after loss of link), the model yielded the results discussed in the previous section. The team's sponsor will be able to use the results to determine whether a procedure meets the desired thresholds. In order to optimize the use of this model, the sponsor should do the following:

- Develop a threshold for what can be deemed "acceptable" in terms of the probability of the potential for loss of separation in a loss of link situation.
- Adjust the time to first maneuver to match the contingency procedure that the sponsor would like to analyze.
- Update the time of detection as more data becomes available.

B. Controller Workload Modeling with *airspace*Analyzer

1. Background

CAASD has developed a simulation tool named *airspace*Analyzer that models air traffic controller activities including separating, sequencing, and spacing aircraft according to a set of ATC separation standards that are defined by the user. Typical ATC separation standards in en route airspace require that two aircraft maintain at least five Nautical Miles (NM) of longitudinal separation or 1,000 feet of vertical separation. These requirements can be adjusted within the tool as needed by the user.

In order to use *airspace*Analyzer, the user must define the specific traffic conditions and ATC sectors that will be analyzed. The traffic is defined by associating a particular set of altitudes and locations for each aircraft during each time period of a scenario. The limits of a sector are defined both laterally and vertically.

Once the inputs of a scenario have been defined, a simulation is conducted and the tool reports a set of metrics that can be used to quantify the complexity of a particular scenario. Scenario complexity is a function of the amount of traffic in a sector as well as the trajectories of the aircraft that may simplify or complicate the ability of the software to safely maintain separation between pairs of aircraft. One reported metric, number of maneuvers, can be used as an indication of the level of effort required to keep the traffic separated. A maneuver occurs when an aircraft must deviate either laterally or vertically from its planned trajectory in order to maintain separation from another aircraft. As the number of maneuvers required to separate traffic increases, the controller level of effort increases, which directly translates to an increase in controller workload. Thus, for the purpose of this study, the number of maneuvers is used as a surrogate metric for controller workload.

The UL2 team has leveraged the functionality and metrics of *airspace*Analyzer to demonstrate the potential analyses of controller workload that can be conducted for a loss of link contingency procedure. Specific scenarios were developed to demonstrate how workload may increase when a UAS loses its link and is not maneuverable. These scenarios and their results are defined in the following sections.

2. Assumptions

The team's assumptions for the *airspace*Analyzer scenarios were:

- All equipment and functions on the UA operate correctly aside from the C2 link.
- The controller increases minimum longitudinal separation from the normal 5 NM to 15 NM around the UA when a loss of link occurs. Controller interviews suggested that a prudent controller will likely increase the amount of separation provided to a UA when it loses its C2 link due to uncertainty in the UA's potential trajectory.

3. Model

In order to model the potential increase in controller workload when a UA loses its C2 link, the team developed and simulated the following three scenarios:

1. **Responsive UA:** The UA responds to ATC commands exactly like a manned aircraft. The controller is in contact with the UA's pilot and the pilot and UA will respond to the controller's commands.
2. **Unresponsive but predictable UA:** The UA does not respond to ATC commands. The controller knows what the UA's next maneuver will be and when it will occur so the controller leaves separation at the default 5 NM.
3. **Unresponsive and unpredictable UA:** The UA does not respond to ATC commands. The controller does not know what the UA's next maneuver will be or when it will occur so the controller increases separation around the UA to 15 NM.

The team used a prepared UAS simulation (named "zoa_Uuas") built by the sponsor and lead developer of *airspace*Analyzer. The simulation code was modified to incorporate the three scenarios listed above. In the zoa_Uuas simulation, uMvB refers to the UA that was modified for the purposes of the scenarios. The team made the following modifications to the zoa_Uuas simulation code:

a) Scenario 1:

- UAS variable ("uas" in *airspace*Analyzer) for uMvB set to FALSE (UA set to respond to ATC commands)
- z_sep (vertical separation) variable for uMvB set to 1500 (vertical separation set to 2000* feet)

b) Scenario 2:

- uas variable for uMvB set to TRUE (UA set to not respond to ATC commands)
- z_sep variable for uMvB set to 1500 (vertical separation set to 2000* feet)

c) Scenario 3:

- uas variable for uMvB set to TRUE (UA set to not respond to ATC commands)
- z_sep variable for uMvB set to 3500 (vertical separation set to 4000* feet)
- sepMiles (lateral separation) variable for uMvB set to 15 (lateral separation set to 15 NM)

In addition, aircraft with tail numbers ASA252, ASA460, ASA423, and uMvB (Shown in Figure 6 as gray circles) were adjusted to be in level flight at Flight Level 350 (35,000 feet Mean Sea Level) and were adjusted to pass through the same section of airspace at roughly the same time, thus creating circumstances that would lead to a potential loss of separation between the four-aircraft as shown in Figure 8. The annotated red arrows indicate the direction of flight for each of the aircraft.

* Note that normal vertical separation for aircraft that do not have the avionics required for Reduced Vertical Separation Minima (RVSM) is 2000 feet. UAS are typically not capable of RVSM. airspaceAnalyzer's default vertical separation value is 500 feet, so in order to attain the desired separation of 2000 feet in Scenarios 1 and 2, the z_sep variable was set to 1500 feet (added to the default of 500). The z_sep variable was set to 3500 feet in Scenario 3 in order to achieve the desired increased vertical separation of 4000 feet.

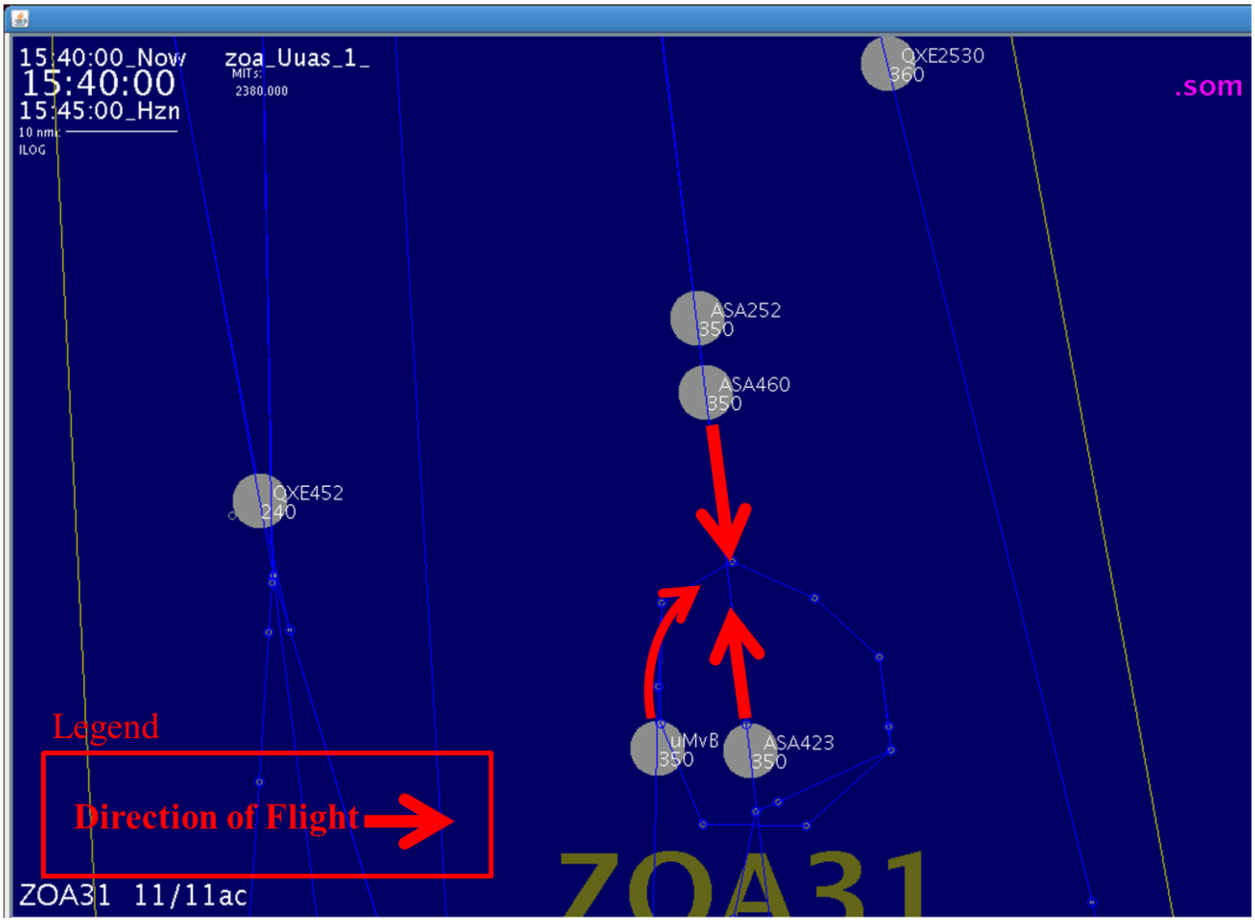


Figure 6 - UAS Workload Scenario Pre-Conflict

4. Results and Conclusions

In the generation of the three scenarios for testing *airspace*Analyzer's surrogate workload metrics, the team hypothesized that the workload experienced by the simulated controller would increase from Scenario 1 to Scenario 2 to Scenario 3. An unresponsive UA would require more of the controller's attention because the controller would be tasked with maneuvering aircraft around the UA, rather than the UA itself. An unresponsive UA that requires increased separation would require even more of the controller's attention because of the increased amount of airspace the UA occupies. In each scenario, the UA continued to fly its current flight plan once the loss of link event occurred. This represents one possible contingency procedure with which the UA may be programmed.

Two of *airspace*Analyzer's output metrics were analyzed as potential indications of controller workload. The first metric, maneuvers ("Maneuver" as displayed in *airspace*Analyzer), is a count of the total number of maneuvers that were issued to all aircraft involved in a conflict in order to avoid a loss of separation. The team's assumption was that more maneuvers would be required in Scenarios 2 and 3 when the UA was unresponsive; however, as shown in Figure 7, between time ticks 15.60 and 15.80 when the conflict occurs, Scenario 1 actually yielded the highest number of maneuvers. After further analysis, it was determined that this was a result of the software attempting to maximize forward progress for each aircraft, and therefore the simulated controller will maneuver many aircraft minimally, increasing the total number of maneuvers. This makes the interpretation of the maneuver metric difficult.

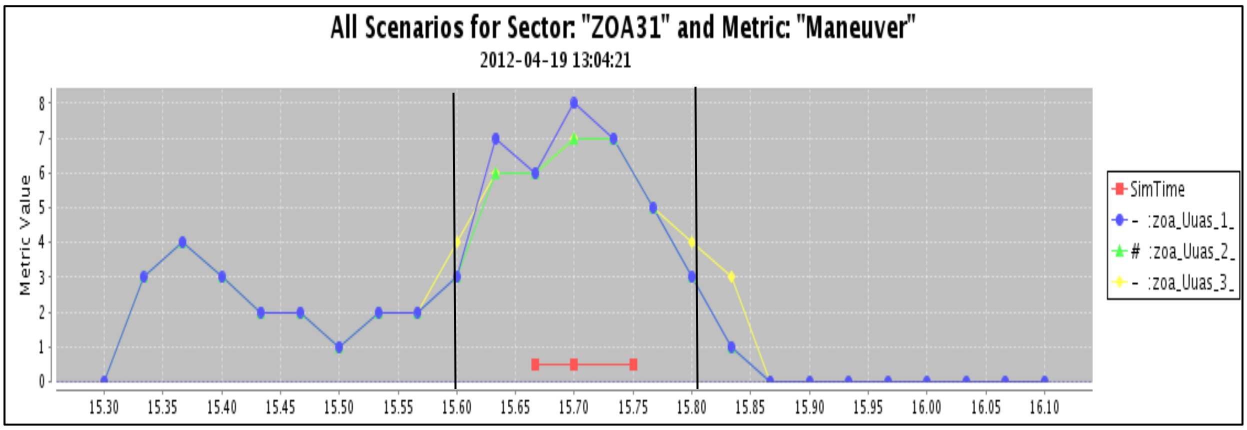


Figure 7 - Maneuver Metric

As shown in Figure 7, the yellow line for Scenario 3 disappears between times 15.60 and 15.80. This is due to the fact that in this scenario, the software is not able to adequately separate all aircraft because of the increased separation requirements for the UA. This loss of separation is characterized by the solid red circles in Figure 8, and qualitatively represents Scenario 3's potential for a significant increase in controller workload as the model is no longer able to maintain minimum separation requirements.

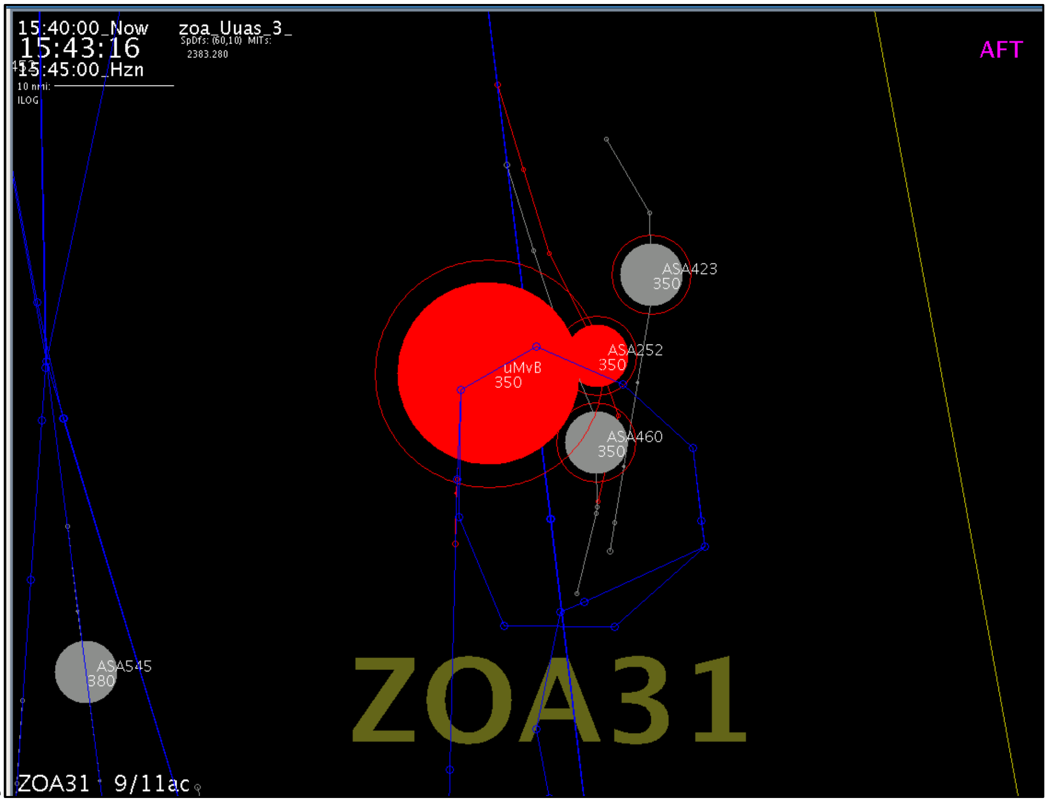


Figure 8 - Scenario 3, UAS Loss of Link, Increased Separation and Loss of Separation

The corresponding graphical depictions of Scenarios 1 and 2 are shown in Figure 9 and Figure 10. The gray lines represent the deviated flight paths that each aircraft had to fly in order to avoid a loss of separation. The white circle represents the unresponsive UA.

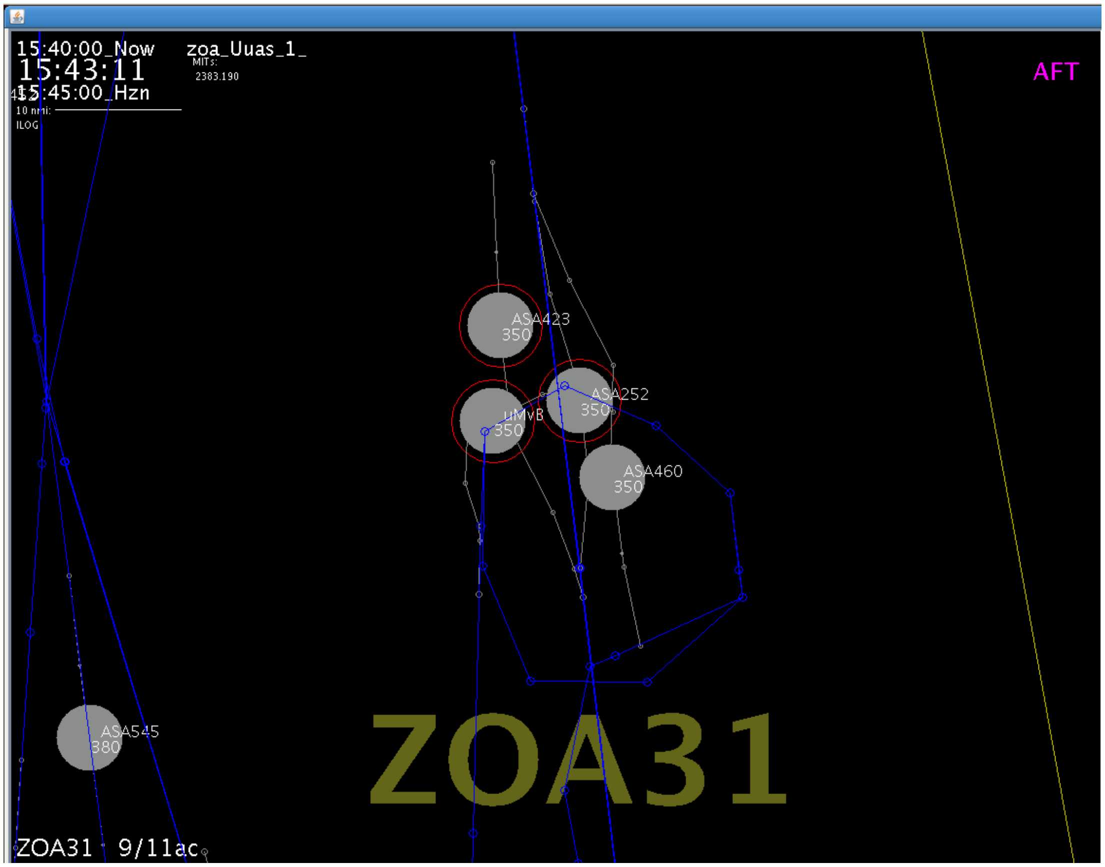


Figure 9 - Scenario 1, UAS Maneuverable

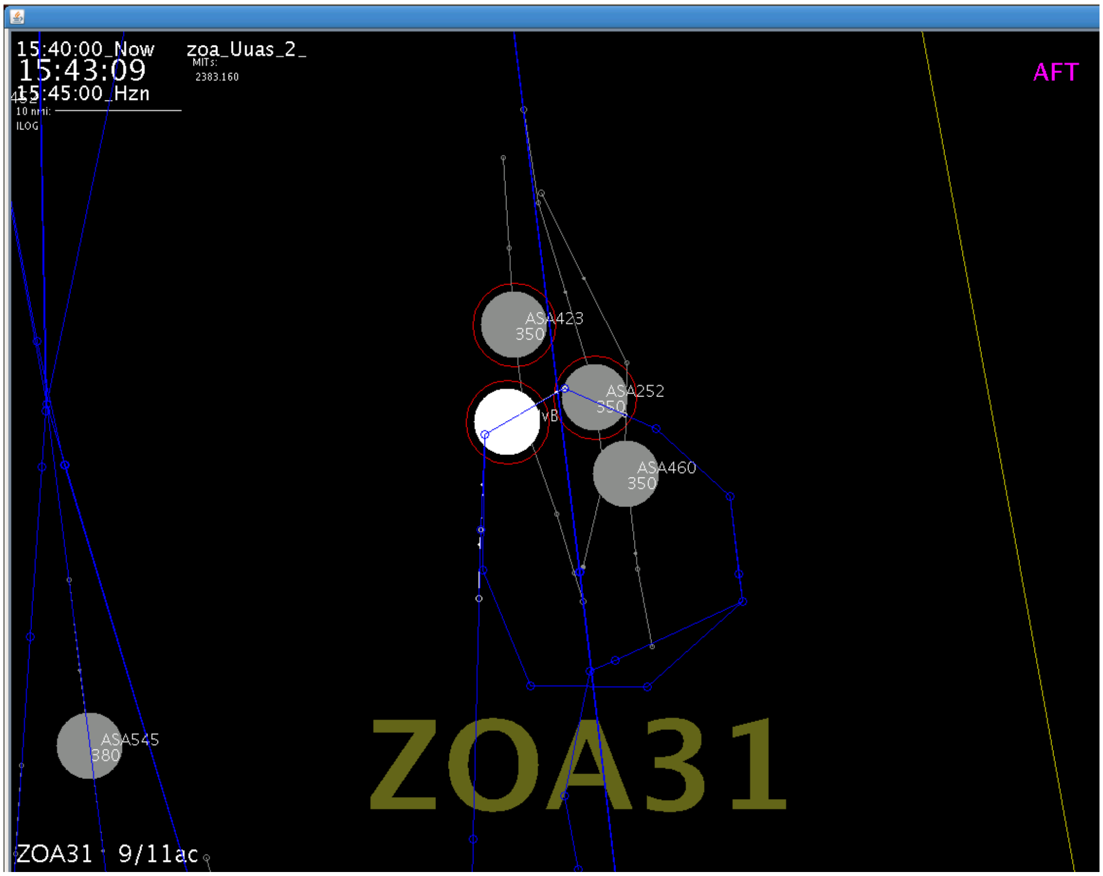


Figure 10 - Scenario 2, UAS Loss of Link, Not Maneuverable

The other metric analyzed, shown in Figure 11, was separation effort ("SeparEffort" as displayed in *airspace*Analyzer). This metric attempts to quantify the amount of time where separation is binding. In other words, minimum separation is all that can be achieved between a particular aircraft pair due to existing traffic conditions that prevent increased separation. Figure 11, between time ticks 15.60 and 15.80, shows an increase in separation effort for Scenario 3, which matches the expectations of the team. This was encouraging; however the SeparEffort metric is less intuitive for an analyst than the count of maneuvers.

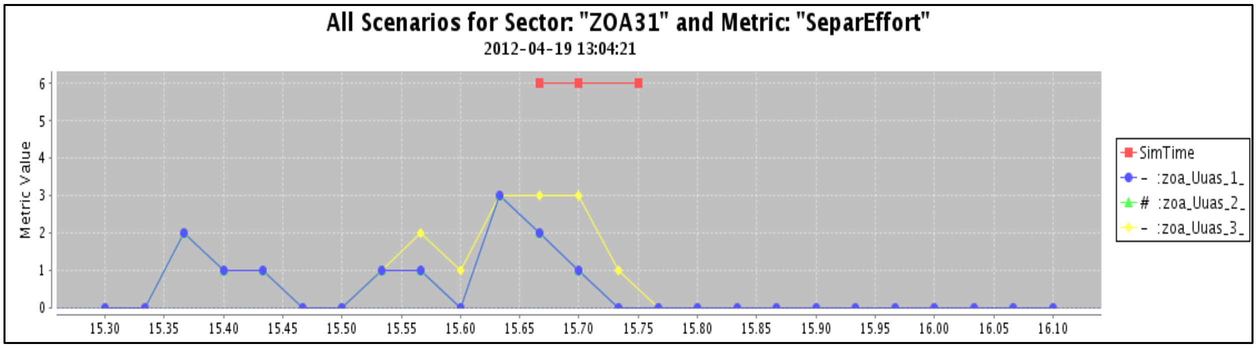


Figure 11 - Separation Effort

After analyzing the results of the simulations, the team determined that the method by which *airspace*Analyzer uses to prevent a loss of separation between aircraft is different from the actions a human air traffic controller would be expected to take. Generally, an air traffic controller would prevent a loss of separation by manipulating as few aircraft as possible while still ensuring safety and maintaining separation. *airspace*Analyzer's logic is based on a linear programming algorithm that attempts to maximize all aircraft's forward movement by diverting them from their original path with the smallest possible magnitude. In a situation where multiple aircraft are predicted to experience a loss of separation, this translates to most, if not all, aircraft being diverted on a smaller path, rather than few aircraft being diverted on a larger path.

These three scenarios were created to demonstrate *airspace*Analyzer's capabilities and usefulness in evaluating the impact loss of link procedures have on controller workload. The initial study suggests some potential limitations in using *airspace*Analyzer as a model to produce surrogate metrics for controller workload. The major limitation is that the software always attempts to maximize forward progress of aircraft, and therefore may maneuver more aircraft than is realistically necessary in order to maintain separation when a potential conflict arises. A less significant limitation is the inability to modify uncertainty in the future trajectories of the UA. It is not uncommon for the contingency procedure of a UA to include multiple possible trajectories that it might choose depending on the current state and location of the UA.

In addition to limitations of the current functionality of *airspace*Analyzer, there are also limitations in workload information that can be captured without involving a human in the simulation. For example, a major component of calculating controller workload is determining the amount of the time that a controller is focused on one particular problem instead of scanning and actively monitoring all traffic within the entire scope. In a HITL experiment, this information can be gathered using eye tracker technology that actively tracks the amount of time the controller spends looking at different areas of the radar scope. This information can prove to be very valuable in determining whether one particular conflict is detracting from the controller's ability to monitor all traffic. This type of information is not available when using *airspace*Analyzer's algorithm to de-conflict traffic.

VII. Summary and Recommendations

The team developed a foundation for evaluating the adequacy of UAS loss of link procedures. Based on discussions with MITRE SMEs, two criterion were identified as being critical to this evaluation: predictability and controller workload. A standardized loss of link procedure would need to be highly predictable while also minimizing the impact on controller workload.

In order to analyze these two criterion, the team developed a model for measuring predictability, and researched a MITRE-developed tool that provides some relevant metrics for measuring controller workload. The two models are independent of one another, but are closely related since a procedure that lacks predictability will often have an adverse effect on controller workload. These two models are the critical components to the team's methodology for evaluating loss of link contingency procedures. The team's suggestions for enhancements to the methodology are in the following sections.

A. Future Work

This project should be further extended to ensure more complete results. Suggestions for improvements and continuations of each of the models are described below:

1. Predictability Model

- Develop a threshold for what the sponsor deems as "acceptable" in terms of the probability of the potential for loss of separation in a loss of link situation.
- Adjust the time to the first maneuver to match the contingency procedure that the sponsor would like to analyze.
- Incorporate a method that will allow the model to evaluate procedures with multiple contingencies.
- Analyze whether different methods of notifying the controller of a loss of link situation (as opposed to RDOF flashing on the scope) will greatly change the identification time.
    - Update the time of detection as more data becomes available.
- Build in predictions for estimating the times of future maneuvers (look at the 2^{nd}, 3^{rd}, n^{th} maneuvers).
- Augment the model to include the probability that aircraft may be in conflict.
- Expand the model to include the probability of the loss of link occurring.

2. *airspace*Analyzer

- More work should be done to further evaluate the functionality and limitations of the software.
- A study that includes thousands of simulations under varying air traffic and sector conditions may yield results that more appropriately reflect workload expectations in a loss of link situation.
- If possible, further modify the parameters of airspaceAnalyzer in order to put more emphasis on minimizing the number of aircraft maneuvers and less emphasis on maximizing forward progress of aircraft.

B. Impact

The team conducted a Critical Design Review with the sponsor's UAS Airspace Integration Team which consists of over 40 analyst and SMEs from across the entire company. This review generated a significant amount of enthusiasm, feedback, and suggestions for extending the work conducted in this project. The sponsor asked that the UL2 Team submit a MITRE Innovation Project (MIP) proposal to request internal MITRE funding for a continuation of the project after the end of the semester. The team submitted this proposal and is awaiting the decision from the MIP board.

In addition, the sponsor suggested that the UL2 Team conduct a 'CAASD Tech Talk' to share the insights gained from the project with a wider audience of CAASD employees. There is also potential for elements of the team's effort to be incorporated in the MITRE research and analysis task directly funded by the Federal Aviation Administration.

Finally, the team's sponsor is collaborating with an informal team of international researchers known as Global Airspace Integration Team (GAIT). The sponsor shared the UL2 team's work with the GAIT team and they have requested a copy of our final report. George Mason University has given the UL2 team permission to distribute this document.

References

[1] GAIT, *Integrating Unmanned Aircraft into Non-Segregated Airspace – Discussion of a Special Purpose Code to Indicate Lost Link,* February 2011.

[2] Kamienski, J.C., E. M. Simons, et al., *Study of Unmanned Aircraft Systems Procedures: Impact on Air Traffic Control,* Proceedings, 29th Digital Avionics Systems Conference, October 2010.

[3] Kamienski, J.C., J. R. Helleberg, et al., *Implications of UAS Operations in Controlled Airspace*, Ninth USA/Europe Air Traffic Management Research and Development Seminar, ATM 2011.

[4] MITRE Corporation, FAA, UAPO, DoD, and NASA, *Contingency Guidelines for Extended Range Unmanned Aircraft System Operations in Class A Airspace,* Private Internal Notes, December 2009.

[5] Niedringhaus, Bill, *Validating airspaceAnalyzer Metrics for ATC Sector Complexity,* Internal Validation Report, November 2009.

[6] United States Department of Defense, *Joint Concept of Operations for Unmanned Aircraft Systems Airspace Integration*, April 2011.

Appendix A - Acronyms

ATC – Air Traffic Control

C2 – Command and Control

CAASD – Center for Advanced Aviation Systems Development

EVM – Earn Value Management

FAA – Federal Aviation Administration

FFRDC – Federally Funded Research and Development Center

GAIT – Global Airspace Integration Team

HITL – Human-in-the-Loop

MIP – MITRE Innovation Project

MSL – Mean Sea Level

NAS – National Airspace System

NM – Nautical Miles

RDOF – Radio Failure

RVSM – Reduced Vertical Separation Minima

SEOR – Systems Engineering and Operations Research

SME – Subject Matter Expert

UA – Unmanned Aircraft

UAS – Unmanned Aircraft System

UL2 – Unmanned Aircraft System Loss of Link

Appendix B - Management

A. Deliverables

Below are the project's critical deliverables along with their scheduled dates of delivery.

Table 1 - Deliverables

	Deliverables	**Delivery Date**
Presentations	Problem Definition	February 2, 2012
	Scope Definition	February 9, 2012
	Progress Reports	March 8, 2012 March 29, 2012
	Final Presentation	May 11, 2012
Reports	Project Proposal	February 16, 2012
	Final Report	May 7, 2012

B. Work Breakdown Structure

The team separated the project into the sections shown in Figure 12 below.

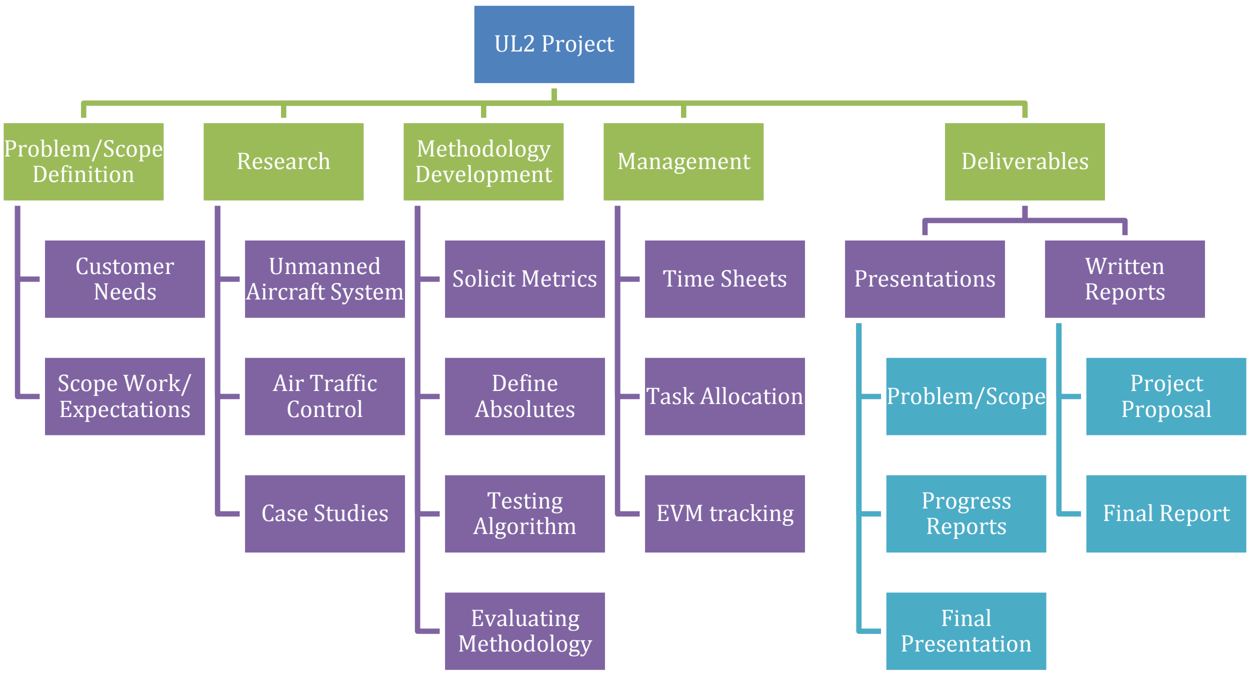


Figure 12 - Work Breakdown Structure

1. Problem/ Scope Definition

In this phase, the team met with the sponsor and determined what outcomes were expected. The project was scoped through discussion with the sponsor and Dr. Laskey.

2. Research

The UL2 team gained a better understanding of the problem by learning more about UAS and the UAS community.

3. Methodology Development

This phase consisted of the bulk of the project's work. The UL2 team worked with the sponsor and UAS SMEs to identify metrics and developed a methodology to evaluate those metrics. The team determined the software that was most suitable for this analysis.

4. Management

The management phase consisted of developing the WBS and allocating resources to itemized tasks. The team scheduled regular meetings with the sponsor.

This phase also consisted of project monitoring to ensure that the project is on track in terms of schedule, cost and results.

5. Deliverables

The deliverables section in the WBS outlines the key milestones throughout the project period including documents delivered to the sponsor and interval presentations to Dr. Laskey. The project concluded with a final document delivery both to the sponsor and Dr. Laskey, and a final presentation to the GMU Systems Engineering faculty and the sponsor.

C. Project Schedule

The team used Microsoft Project to plan this semester-long project. The project schedule was developed to document and track the tasks needed to complete this project. Each individual task served as a step for a major team goal or deliverable. The resources available were the four team members who were assigned to tasks. The tasks and their allocation can be found in Table 2 below, and the corresponding schedule is shown in Figure 13.

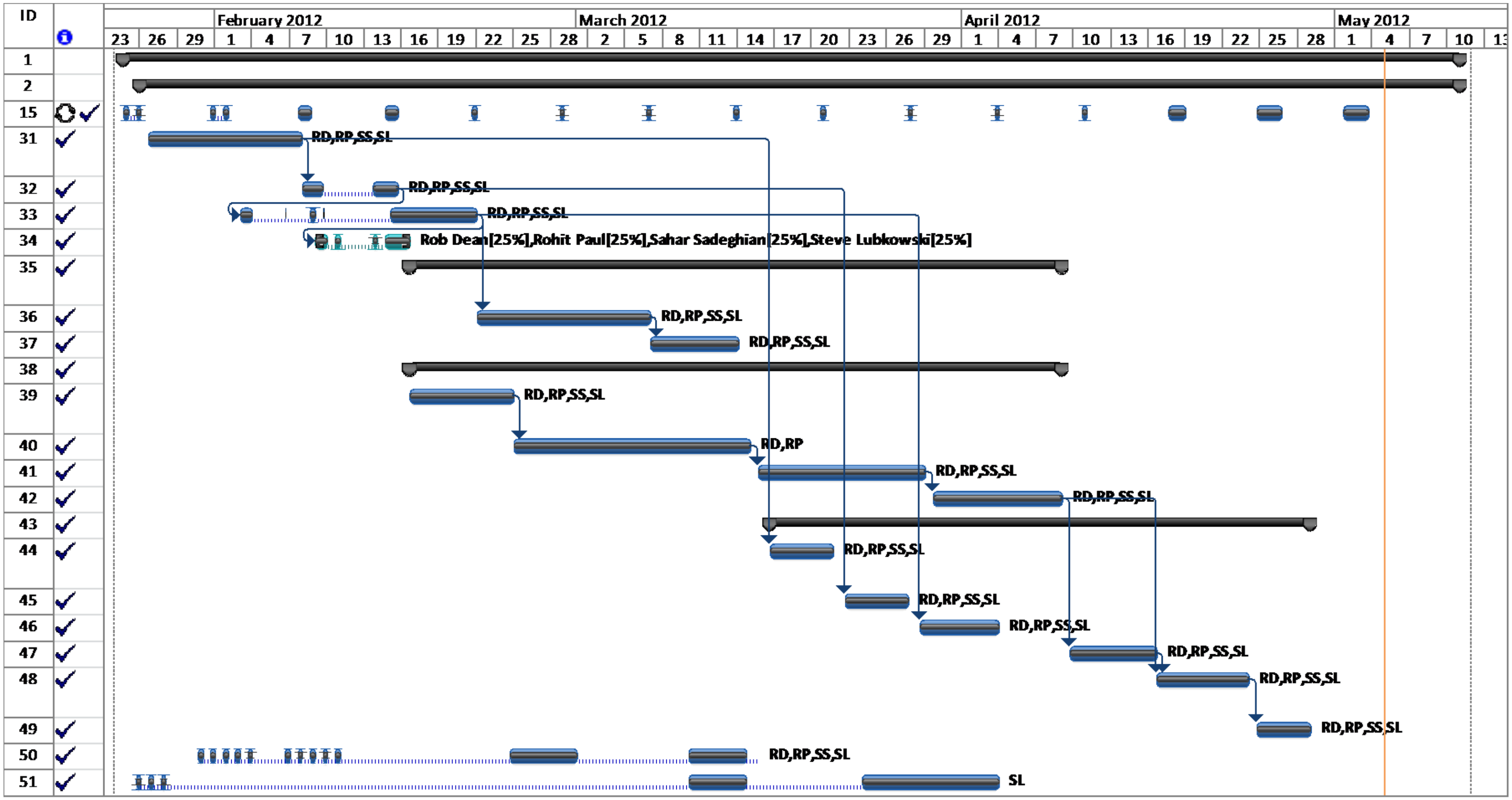


Figure 13 - Project Schedule

Table 2 - WBS Tasks

WBS	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1	**UAS Lost C2 Link**	**234 hrs**	**Tue 1/24/12**	**Fri 5/11/12**		
1.1	**SEOR Class Milestone**	**228 hrs**	**Thu 1/26/12**	**Fri 5/11/12**		
1.2	**Group Meetings**	**215 hrs**	**Tue 1/24/12**	**Thu 5/3/12**		
1.3	Define Problem Statement	26 hrs	Thu 1/26/12	Tue 2/7/12	3	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.4	Define Project Scope	10 hrs	Tue 2/7/12	Wed 2/15/12	31	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.5	Identify Approach	20 hrs	Fri 2/3/12	Tue 2/21/12	32	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.6	Project Proposal	20 hrs	Thu 2/9/12	Thu 2/16/12	33	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.7	**Define Methodology Process**	**115 hrs**	**Thu 2/16/12**	**Sun 4/8/12**		
1.7.1	Solicit Metrics	30 hrs	Tue 2/21/12	Tue 3/6/12	33	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.7.2	Define Absolutes	15 hrs	Tue	Tue	36	Rob Dean[25%],Rohit

			3/6/12	3/13/12		Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.7.3	**Simulation**	**115 hrs**	**Thu 2/16/12**	**Sun 4/8/12**		
1.7.3.1	Define Simulation	20 hrs	Thu 2/16/12	Fri 2/24/12		Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.7.3.2	Build Simulation	40 hrs	Fri 2/24/12	Wed 3/14/12	39	Rob Dean, Rohit Paul[80%]
1.7.3.3	Test Simulation	30 hrs	Thu 3/15/12	Wed 3/28/12	40	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.7.3.4	Validate Results	25 hrs	Thu 3/29/12	Sun 4/8/12	41	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.8	**Write Report**	**92 hrs**	**Fri 3/16/12**	**Sat 4/28/12**		
1.8.1	Problem Statement	10 hrs	Fri 3/16/12	Wed 3/21/12	31	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.8.2	Project Scope	10 hrs	Thu 3/22/12	Tue 3/27/12	32	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.8.3	Project Process	15 hrs	Wed 3/28/12	Tue 4/3/12	33	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.8.4	Analysis	15 hrs	Mon	Mon	42	Rob Dean[25%],Rohit

			4/9/12	4/16/12		Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.8.5	Outcomes and Conclusions	15 hrs	Mon 4/16/12	Mon 4/23/12	47,42	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.8.6	Recommendations	10 hrs	Tue 4/24/12	Sat 4/28/12	48	Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.9	Research Hours	100 hrs	Mon 1/30/12	Thu 3/15/12		Rob Dean[25%],Rohit Paul[25%],Sahar Sadeghian[25%],Steve Lubkowski[25%]
1.10	Web Site Design	35 hrs	Wed 1/25/12	Tue 4/3/12		Steve Lubkowski

D. Earned Value Management (EVM)

Once the UL2 team assigned resources to the tasks mentioned above, a budget was determined for each task. The overall budget estimate for the project came to $28,000. This estimate includes the labor from the team members at $40 per hour as well as a slack of approximately $3,000. The UL2 team started discussions with the sponsor the week before the project officially started so the EVM chart in Figure 14 starts on January 19, 2012. This EVM chart was maintained throughout the project period and inspected weekly to ensure that the team was within cost and schedule parameters.

At the end of the project period, the UL2 team completed the project on time, under the estimated cost.

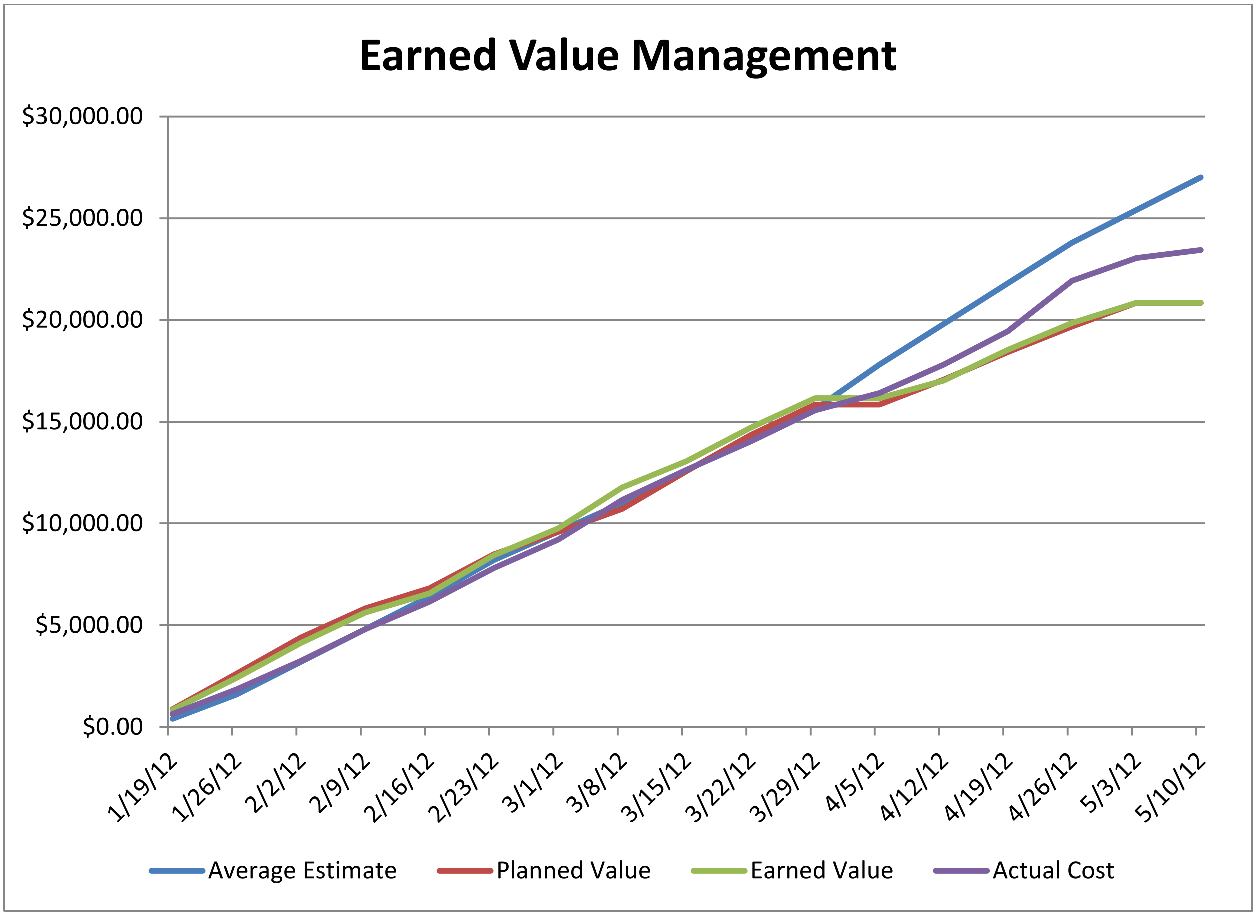


Figure 14 - Earned Value Management (EVM)

Appendix C - Predictability Model Data

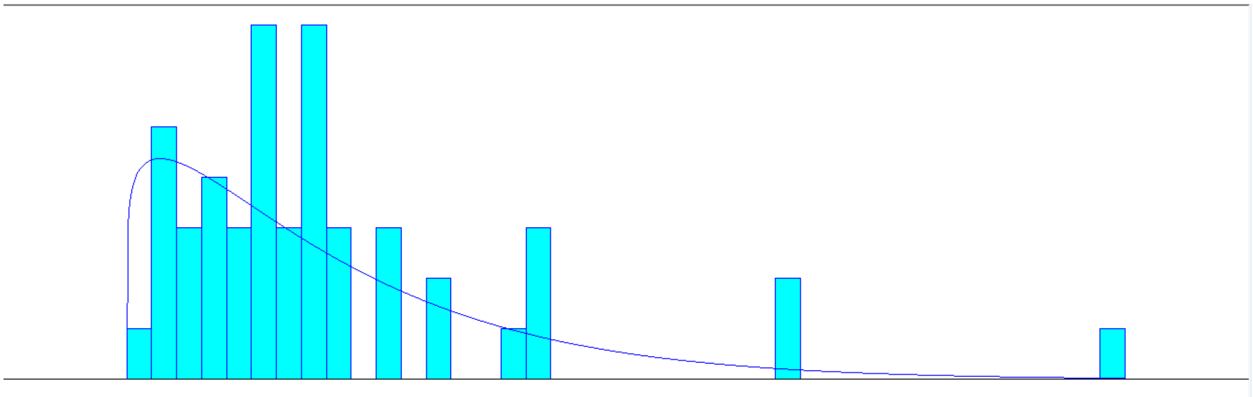


Figure 15 - Distribution Fit

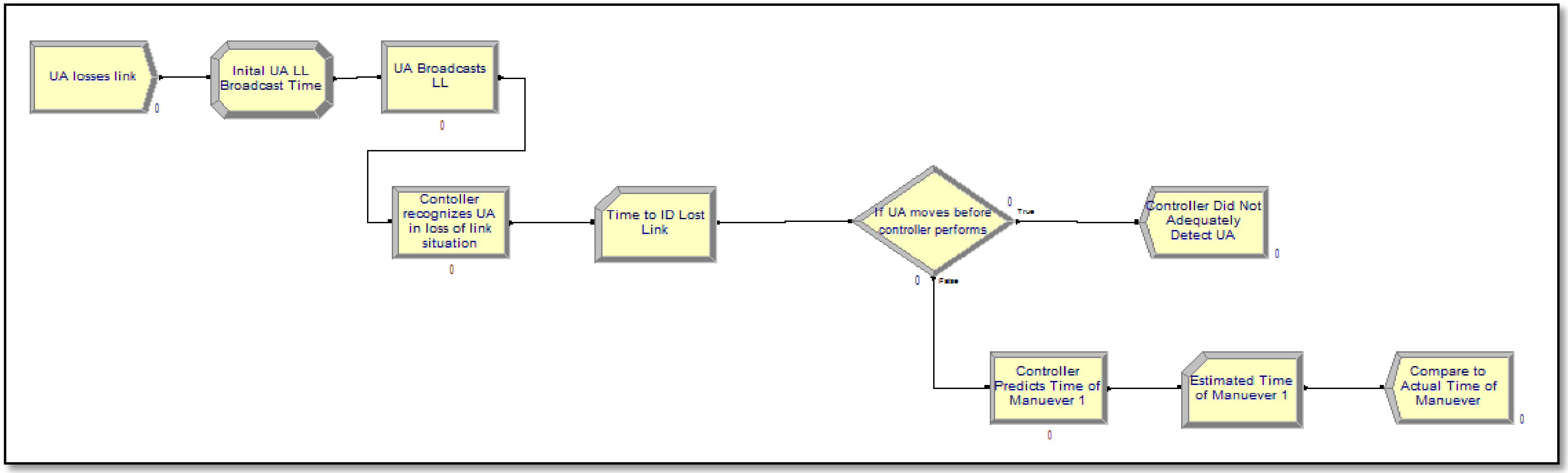


Figure 16 - Arena Model