# Separation Flight Tests of a Small Unmanned Air Vehicle from a C-130 Transport Aircraft


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## ABSTRACT

*Unmanned Air Vehicles (UAVs) are increasingly being considered for various roles in the civilian and military communities. Various launch methods have been explored and have been mostly ground based. The desire to investigate the feasibility of launching a UAV from a larger surrogate air platform existed, but had not been explored. As part of a concept demonstration program, NAVAIR's Test and Evaluation Flight Test Department was requested to conduct flight tests to determine a flight envelope and launch system configuration for which a small (maximum gross weight of 80 lbs), unpowered UAV glider could be safely launched from the cargo ramp of a C-130 transport aircraft. A secondary goal was to demonstrate that the UAV would remain stable enough for the wings to deploy and be flyable via a pre-programmed profile or remotely located pilot. A roll-on/roll-off pneumatic launch system was devised to eject the UAV into the airstream in a controlled and consistent manner, and a test program was executed to incrementally expand the UAV safe launch envelope by building down to a minimum gross weight. Flight tests were conducted in September 2003. Safe separation from the C-130 aircraft was demonstrated, as well as UAV stability for successful wings deployment and fly-out. The success of these flight tests opens the door for development of similar air launched systems that could be used for a myriad of applications.*


## 1.0 INTRODUCTION

The U.S. Navy's store/compatibility team for C-130 aircraft was tasked to demonstrate launching a small UAV (the XPV/GL Hawkeye) from the cargo ramp of a C-130 aircraft. The XPV/GL UAV was selected as the test vehicle due to its small size and proven flight characteristics. Some limited testing had been conducted with the XPV/GL from the open ramp of a Shorts SC.7 Skyvan, a small civilian cargo aircraft [1], [2]. Testing had also been done with standard airdrop systems that had the UAV attached to an airdrop pallet; the entire pallet/UAV combination was extracted with parachutes and then the UAV detached itself from the pallet and flew away. Results from these previous tests, as well as some limited simulation work, provided information and guidance to the test team as they developed their approach for launching the XPV/GL UAV from the C-130 aircraft.

There were three main challenges for this test program: 1) Do enough predictive analyses so that a safe entry point into flight tests could be determined; 2) Design and build a launch system that ejected the UAV into the freestream such that safe separation from the C-130 would occur as well as provide satisfactory separation characteristics from a UAV fly-away perspective; and 3) Work within a limited budget that didn't allow for


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detailed simulation efforts nor allow for construction and release testing of dozens of UAVs to determine the launch envelope. This paper describes the work conducted in the summer of 2003, and how a complementary balance of pre-test predictive analyses and old-fashioned build-up flight tests were used to accomplish the goals of the demonstration program within a reasonable timeframe and budget.

## 2.0 TEST AIRCRAFT AND EQUIPMENT

### 2.1 LC-130F

The C-130 is a high-wing, all metal construction, medium range, land-based monoplane. The mission of the aircraft is to provide in-flight refuelling or rapid transportation of personnel or cargo for delivery by parachute or landing. The aircraft can land and takeoff on short runways and can be used on unimproved landing strips. Four turboprop engines power the aircraft. The aircraft is equipped with a Gas Turbine Compressor/Air Turbine Motor Auxiliary Power Unit to provide for self-contained starting capabilities. The cargo ramp area opening has a minimum width of 10 ft 3 in., and a minimum height of 9 ft. The distance from the aft edge of the ramp to the end of the tail is 27 ft. The test aircraft was a LC-130F (Figure 1) equipped with skis for landing in snow.


**Figure 1: LC-130F Test Aircraft**

### 2.2 Pneumatic Launcher

After continuous design reviews, it was felt that a pneumatic launching system coupled with a roll-on/roll-off cargo pallet would be best suited for ease of use and consistent ejection velocities. The launch assembly developed by NAVAIR & Titan Systems (Figure 2) is capable of holding the UAV safely while the vehicle is awaiting launch. The launcher is designed to provide sufficient velocity and directional control to jettison the XPV/GL into the airflow located aft of the cargo ramp. The launcher mounts to a standard 463L airdrop pallet, which is mounted to the cargo ramp via the standard pallet/tie down system. This places the launcher at the center and rear of the cargo ramp. The launcher is equipped with a locking device that holds the launch ready vehicle in position until the launch sequence is initiated. The launcher has two positions, forward for UAV loading, and aft to the ramp edge for launch. The launch rails are angled downward at approximately 20 deg, but are adjustable from 5 to 20 deg, to launch the UAV down and away from the ramp. The launcher is a pneumatic system that allows the UAV to be launched along rails, pulling a static line that deploys the drogue chute as it enters into the airstream. The static line attaches to the launcher and the nose of the UAV and is designed to initiate drogue chute deployment after the vehicle nose has travelled 12 inches beyond the end of the cargo ramp. The launcher consists of a pneumatic band cylinder capable of providing an ejection velocity of 8-10 ft/s at a pressure of 120 psi. The band cylinder is a pressurized piston-sliding device that requires a Kevlar wound 4500 psi Self Contained Breathing Apparatus (SCBA) cylinder, 3-way flow valve, regulator, mufflers, and hoses. The 4500 psi SCBA cylinder can be filled with dry air or nitrogen. The launch angle, the launch force and static line length are capable of being adjusted to optimize separation characteristics.

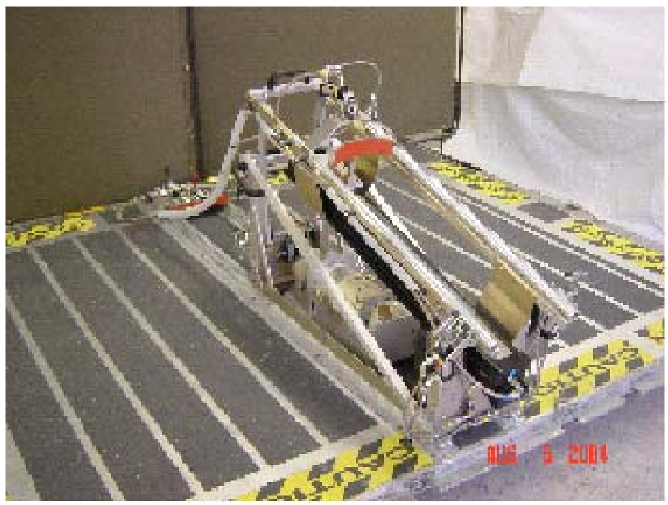

**Figure 2: Pneumatic Launcher**

## 2.3 XPV/GL Hawkeye

The XPV/GL Hawkeye (Figure 3), designed by AeroVironment, is a reconfigurable, unmanned aircraft designed to be pneumatically launched from a host aircraft utilizing the host aircraft's wing or fuselage store hard-points. With wings folded, the XPV/GL is 42 inches long, 11.5 inches wide, and 11 inches tall. For the cargo ramp launching method, the vehicle is ejected into the airstream in a wings folded configuration, tail first, with a static line attached to the nose that initiates deployment of a small drogue chute of 24 inches in diameter. The drogue chute, which is packed in a small canister below the tail and in-between the twin vertical stabilizers, is designed to slow the UAV to a speed at which the wings can safely deploy (approx. 5 seconds after chute deployment). For these tests the UAV was launched and flown in its variable payload configuration. In this configuration the XPV/GL can be flown within a gross aircraft weight (GAW) range of 20 – 80 lbs, depending on the payload. The XPV/GL has a Center of Gravity (CG) position of 17.5 inches aft of the nose in flight with wings deployed.

**Figure 3: XPV/GL UAV**

## 2.4 Separation Test Vehicles

Separation test vehicles (STVs) were built to replicate the mass properties, outer mold-line, and deployment sequence of the drogue chute for launch envelope development testing. The STVs did not have deployable wings and the weight could be changed by adding or removing plates at the vehicles' center of gravity. The STVs were configured with a weight range of 79 lbs to 25 lbs for purposes of build-down testing during the separation tests. Refer to Figure 4.

**Figure 4: Separation Test Vehicle (shown inverted)**

## 3.0 GROUND TESTS

Ground tests consisted of practice and mock launches of the XPV/GL. A pre-launch and launch procedure was developed from the ground events. The ground events also determined the launch assembly loading procedure on-board the aircraft, XPV/GL installation onboard the launch assembly, and pre-launch and launch positions of the launch assembly. The simulated launches evaluated launcher performance, static line length, launcher force, and ejection velocities. These tests were repeated multiple times in support of small design iterations of the launch system. Simulated launches were recorded with regular and high-speed cameras for evaluating ejection velocities. Ejection velocities were confirmed to be 8 – 10 ft/s.

Prior to the flight tests, mass properties (weight, center of gravity, moments of inertia (MOI)) of a 27 lb STV, 76 lb STV and the operational UAV were measured and the variations compared with MIL-HDBK-1763 [3] tolerances for store certification tests.. All three stores were measured with the drogue container attached. An electromagnetic compatibility safety of flight test was also performed.

## 4.0 PREDICTIONS & STRATEGY

Predictions of the UAV's separation characteristics and trajectory during launch were necessary to assess the probability of the vehicle striking the C-130 tail structure. Two recent computational and visualization studies of the flow around the aft region of a C-130 with the ramp open were reviewed, [4] and [5], for applicability to this project. The U.S. Air Force Academy (USAF) was then contacted to request a run of the planned specific flight conditions (150 KIAS, straight and level flight) using their computational fluid dynamics (CFD) solver. The USAF provided vector plots of the flow in the ramp/tail structure area. Using this information and basic fundamentals of aerodynamics to calculate lift and drag on the UAV, the test team created a basic simulation to predict UAV launch trajectories for different UAV gross weights.

### 4.1 C-130 Cargo Ramp Flow Field Studies

Figures 5 and 6 show two plots of the CFD results from the model run by the USAF Academy. These plots are for the x-z geometric plane passing vertically through the center of the aircraft and the UAV launcher.

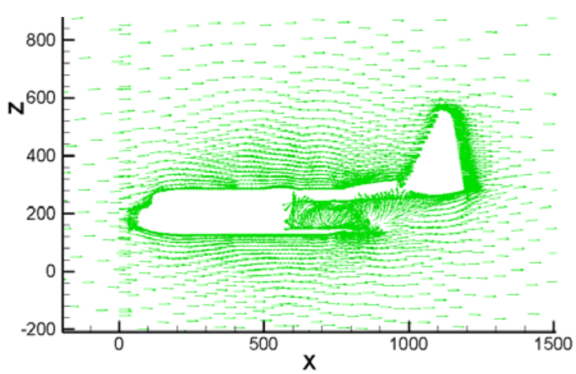


**Figure 5: C-130 Vector Plot**

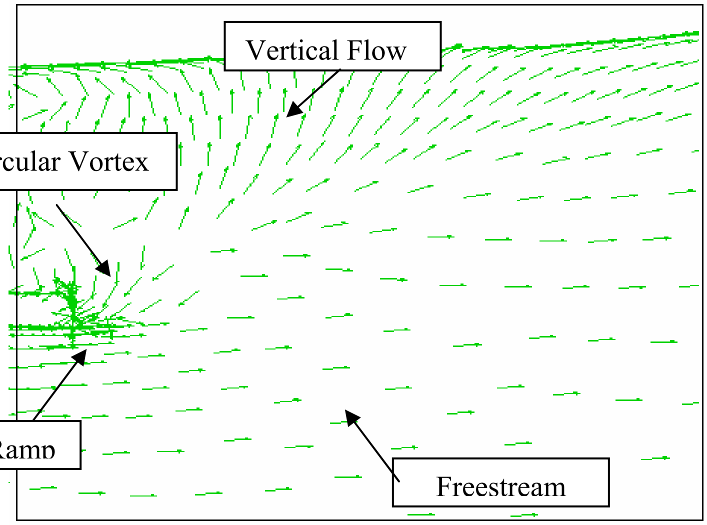


**Figure 6: C-130 Vector Plot (Area of Interest)**

Looking at Figures 5 and 6, it was determined the best test approach was to launch the UAVs at an angle downward and away from the region of vertical flow, thru the circular vortex, and into the free stream. This would place the UAV into the free stream as quickly as possible to maintain maximum separation distance from the C-130 tail structure. Since vertical flow components have the most significant influence on the miss distance of the UAV from the upper tail structure, it was of interest to visualize the changing magnitude of this component as you move incrementally away from the ramp. Figure 7 is a three-dimensional plot of the vertical flow magnitudes (ft/s) in the area of interest shown in Figure 6.

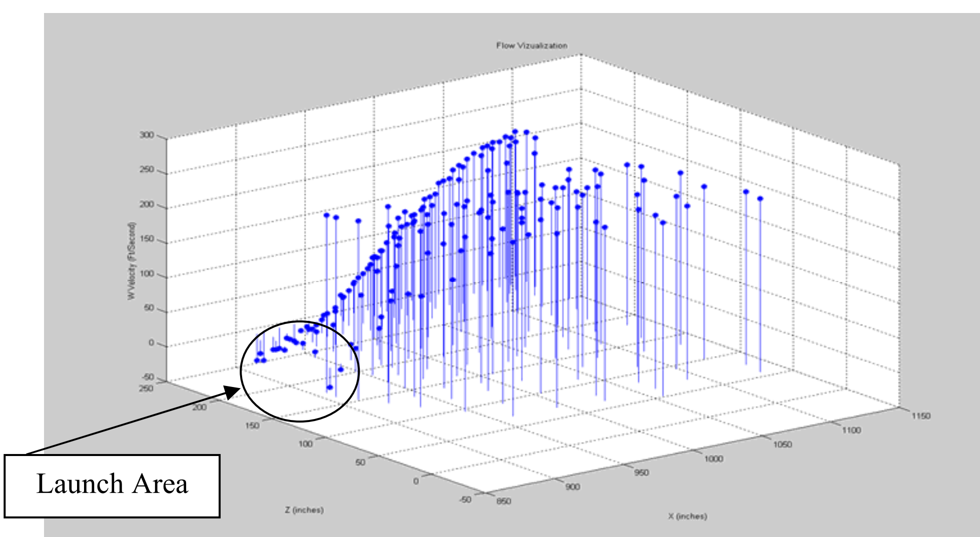


**Figure 7: Vertical Flow Magnitudes aft of Cargo Ramp (centerline X-Z plane)**

Figure 7 shows the rising magnitude of the vertical flow in the region of Z = 150 to Z = 250, and X = 900 to X = 1100 inches. The free stream velocity = 250 ft/s (150 knots) is shown for comparison. The region that is circled is the area at which the launcher was located, Z=150 to 180 inches, X=860.

## 4.2 Basic Simulation of UAV Launch Trajectories

In addition to the above CFD studies, a simulation was completed of the UAV being ejected at various weights that calculated a resultant aerodynamic force acting upon the vehicle at the C.G. with no chute deployed. The simulation used the up winds and head winds from the CFD analysis provided by USAF Academy portrayed in Figures 5 & 6. The head winds and up winds only add velocity components at the C.G. of the UAV (i.e. no pitching moment is accounted for or predicted). Table 1 presents a *generic* flow field used in determining a sample 76lb UAV trajectory. Figure 8 shows the sample 76lb UAV trajectories for a downward launch angle of 20 degrees at approximately 8 ft/s for each of the flow fields. Note, Figure 8 (x,y) point (0,0) represents the end of the ramp, (0,10) represents the bottom of the tail structure above the ramp, and (25,10) is the end of the aircraft tail structure. A complete description of the simulation, including the governing equations may be found in reference [6].

**Table 1: Flow Fields**

| FLOW FIELD | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| HEADWIND fps | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
| UPWIND fps | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |

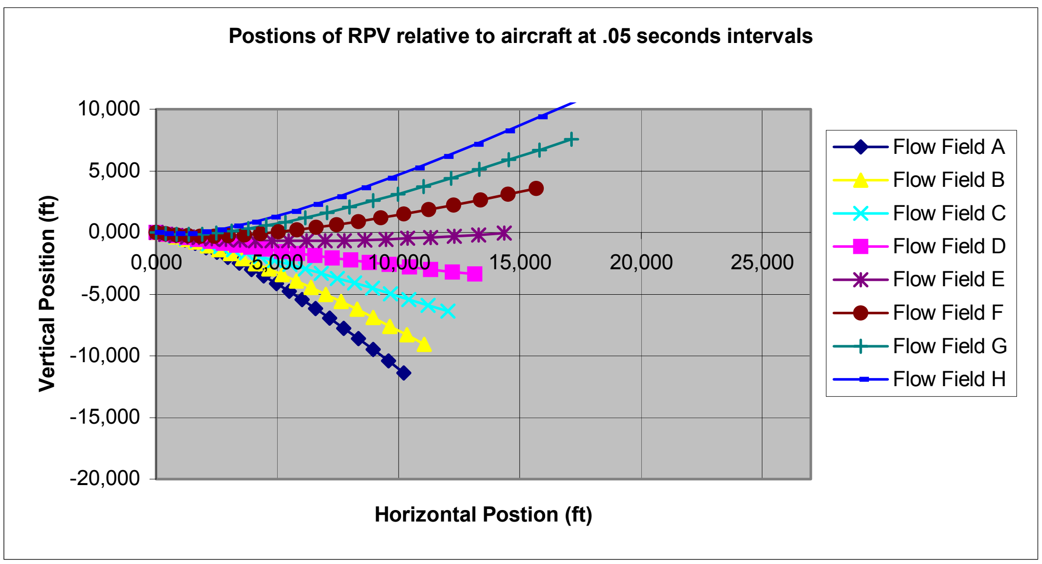


**Figure 8: 76lb STV Simulation**

### 4.3 Flight Test Strategy

Results of these analyses were used to determine the final configuration of the launcher and its range of adjustments with respect to launch angle and static line length; i.e. to maintain maximum separation from the C-130 tail structure and vertical flow components in that region, the launcher was configured to eject the UAV at a downward angle (nominally 20 degrees) and the drogue chute deployment was delayed until the nose of the UAV was 12 inches aft of the cargo ramp. While this was the planned configuration for the first test point, the launch angle and the drogue deployment time were capable of being adjusted to optimize separation characteristics, based on results of preceding separation flight test points.

The launch trajectory simulations also indicated the level of sensitivity to UAV gross weight. The simulation predicted maximum miss distances for the heaviest weights and minimum miss distances for the lightest, and allowed the formulation of a test matrix that quickly moved from heavy GAW UAVs to the lightest, with more gradual steps between weights at the lighter GAW test points. The strategy was to start heavy and then refine the build-down if necessary based on test results.

## 5.0 FLIGHT TESTS

### 5.1 Separation Criteria

As part of the test planning process and prior to executing the flight tests, it was necessary to determine safe separation criteria for continuation with subsequent test points. Straying slightly from the guidance in reference [3], it was determined that criteria for progressing from one test point to the next would be to demonstrate acceptable separation characteristics, defined as stable vehicle motion that moved consistently away from the C-130 cargo ramp with minimal upward translation towards the horizontal tail. If the miss distance between the UAV and the aircraft tail surface was perceived to be less than approximately 5 ft, testing would not continue without more in-depth analyses of the separation data.

### 5.2 Methodology

Flight tests commenced with the STVs in a build-down fashion from lowest risk to highest risk, starting with the heavy weight configuration (approximately 79 lb) and moving toward the minimum weight configuration (approximately 25 lbs). The test team had the latitude to repeat test points to evaluate small configuration changes in the launcher or to confirm separation characteristics prior to proceeding with the next point. Configuration changes that were authorized were: 1) Launcher angle within its pre-designed adjustment limits (5, 10, 15, and 20 degrees down); 2) Static-line length; and 3) Launcher pressure setting. The decision to change one of these parameters was based on the separation characteristics of the STV during previous releases. For example, if the vehicle pitched up too far prior to drogue chute control, the launch angle could be made more shallow; or if upon drogue deployment the vehicle rose toward the C-130 tail more quickly than desired, the static line could be lengthened to delay the chute's effect.

The first test point was a 79 lb STV launch at the pre-determined launcher settings of 20 degree launch rail angle, pressure setting 120 psi, and total static line length of 68 inches, which allowed the nose of the STV to travel 12 inches beyond the end of the ramp before the drogue chute was deployed. The test matrix in Table 2 shows the remaining STV test points. Note that test point number four was conducted twice to confirm good separation characteristics prior to launching the lowest GAW STV. All releases were conducted with the C-130 flying at 2000 feet above ground level (AGL), 145 knots indicated airspeed (KIAS), straight and level, balanced flight.

**Table 2: Test Matrix**

| Test Point | STV Weight (lbs) | Launcher Angle (degrees) | Pressure Setting (psi) | Static Line Length (in) |
|---|---|---|---|---|
| 1 | 79 | 20 | 120 | 68 |
| 2 | 66 | 20 | 120 | 68 |
| 3 | 50 | 20 | 120 | 68 |
| 4* | 38 | 20 | 120 | 68 |
| 5 | 25 | 20 | 120 | 68 |

* Test point conducted twice

## 5.3 Separation Results

For each test point, the STV separated cleanly from the LC-130. The STV moved positively down and away from the aircraft with minimal pitch and yaw oscillations, and random roll motion. As the chute deployed, the vehicles rose only slightly toward the underside of the LC-130 tail structure, but the deployment of the chute did not significantly influence the trajectory of the STV.

With the STV launch envelope of 79 lbs to 25 lbs GAW determined to be safe and acceptable for UAV performance, two operational XPV/GL UAV test launches were conducted; one with GAW of 44 lbs and one with GAW of 25 lbs. Separation characteristics of the UAVs were identical .to the STVs'; after launch, each proceeded to successfully demonstrate wings deployment and autonomous flight. Figure 9 shows an in-flight view of an STV launch.


**Figure 9. STV In-Flight Launch**

## 6.0 SEPARATATION TEST CONCLUSIONS

Separation characteristics of the XPV/GL UAV in the weight range of 79 to 25 lbs from the cargo ramp of C-130 aircraft in straight and level flight at 145 KIAS, excluding C-130J models (not tested), with the launcher configured for a 20 deg downward launch angle and 8 – 10 ft/s ejection velocity, were satisfactory [7].

The concept of launching small, lightweight air vehicles from the cargo compartment of a large transport aircraft was demonstrated. The capability was proven with a traditional flight test approach, starting with lower risk test points and incrementally advancing to the higher risk endpoints. Today, with modern predictive tools such as CFD, this approach can be implemented with less test points and can start at what used to be considered high risk conditions. Caution must be exercised, however, to closely compare predictions to actual results at every step so that dangerous trends that may not match the analyses are identified. Similarly, if predictions turn out to be overly conservative, the test matrix can be modified to more quickly get to the desired endpoint. For this test program, the flight test results matched the predictions very well, and the GAW envelope was cleared with only six releases.

The success of these flight tests opens the door for development of similar air launched systems that could be used for a myriad of applications. Overall, the flight test program validated a complementary balance of pre-test analyses and build-up flight tests to accomplish demonstration goals, quickly, efficiently, and successfully.

## 7.0 FOLLOW-UP TESTING

The purpose of this testing was to expand the launch envelope to higher altitudes, conduct a military utility assessment of the UAV, and assess the overall reliability of the system. The testing was conducted from a DC-130A and used the same methodology as the previous LC-130F testing. 10 flight ready UAVs with GAW ranging from 65 lbs to 45 lbs were launched at an altitude range of 8000 feet MSL to 16000 feet MSL. Airspeed remained the same at 145 KIAS in straight and level balanced flight. The altitude increase allowed longer UAV flight times and a qualitative analysis of higher altitude releases.

### 7.1 Test Aircraft

The DC-130A aircraft was equipped with four large pylons for carrying sub-scale aerial targets and was not equipped with skis on the main gear. The DC-130A cargo ramp is similar in dimensions to the LC-130F cargo ramp. Figure 10 shows the DC-130A test aircraft.


**Figure 10: DC-130A Test Aircraft**

### 7.2 Results

For each test point, the UAV separated cleanly from the DC-130A. The UAVs moved positively down and away from the aircraft with minimal pitch and yaw oscillations, and random roll motion. Separation characteristics of the 10 vehicles were consistent, demonstrating travel positively down and away from the DC-130A. In comparison, separation characteristics observed during LC-130F testing demonstrated some upward motion at lighter weights (≤ 50 lbs). The LC-130F skis may have contributed to additional turbulence and upward flow around the cargo ramp area as compared to the DC-130A.

Two test points experienced UAV failures. During one high altitude (16000 ft MSL) launch, a 65 lb UAV separated cleanly from the aircraft with a functional drogue chute, released the drogue, and then experienced structure failure of a forward wing during vehicle pull-out from an extreme nose down attitude. It appears that the UAV may have exceeded safe wing opening speed and subsequent over-stress during the pre-programmed pull-out. An additional failure was experienced during a low altitude (9000 ft MSL) launch of a 65 lb UAV when the drogue did not deploy and subsequently the wings failed to open; however, the UAV did separate cleanly from the DC-130A without the drogue.

### 7.3 Conclusions

This follow-up testing points out two areas of concern with respect to successful air launching of the XPV/GL: 1) C-130 aircraft external configuration may have a noticeable affect on small UAV separation characteristics from the cargo ramp; and 2) High altitude launches may require a larger drogue chute to slow the UAV for safe wing opening.

Overall, separation characteristics of the UAV in the weight range of 65 lbs to 45 lbs from the cargo ramp of the DC-130A aircraft in straight and level flight at 145 KIAS, with the launcher configured as specified in Table 2 were satisfactory. The launcher design was proven to be adequate and reliable for launching the XPV/GL UAV. It is recommended that further analysis and testing be conducted for high altitude launches.

## 8.0 REFERENCES

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