Chapter 3 – TRAJECTORY CONTROL OVERVIEW

The trajectory part of precision airdrop is broken into two phases: the on-aircraft part, i.e. the period from load release to load clear of the aircraft; and the recovery period from load clear until impact. The CARP is based on historical average values of time to clear and on average trajectories based on the parachute/ load weight combination. However, there have been significant variations in both these numbers. There have been recent efforts to minimize the variations in both phases. Controlling the trajectory phase would be especially beneficial for low-altitude airdrop, since other errors, such as wind prediction, have a much smaller influence than they do for high-altitude airdrop. Precision airdrop is moving ahead with gliding, GPS-guided, high-performance systems that utilize advanced mission planning capabilities. Examples of such systems are discussed in this chapter.

3.0 ON-AIRCRAFT PERIOD CURRENT AND FUTURE SYSTEMS

The current system in the U.S. for low-velocity platform airdrop is to use an extraction chute, either with or without a tow plate, which releases the inflated drogue parachute to extend the extraction parachute package into the airstream. The extraction system inflates, generates enough drag to overcome the load restraint and pulls the load along the rail/roller system until the loads exits the aircraft. However, systems are being researched to improve airdrop accuracy. These include power extraction, and drogue extraction.

3.0.1 Gravity Airdrop

For an airdrop load to land on the intended impact point of a drop zone, it must exit the aircraft at the proper location in the air. This point in the air, the CARP, is based on the ballistics of the load during the drop, given the initial conditions of the aircraft and load. In a gravity airdrop, which uses no extraction parachutes, when the aircraft reaches the CARP, the green lights in the cargo compartment are turned on, the load is unlocked, and it moves through the cargo compartment and exits the aircraft. The duration of this on-aircraft process is defined as the exit time. The deck angle, or pitch, of the aircraft plays an important role in the exit time, as it influences the gravitational component of the load's acceleration. Often the deck angle changes during airdrop, due to the aircraft center of gravity shifting as the payload moves aft. When the pitch angle is greater than assumed when determining the CARP, the exit time is shortened because the acceleration is greater. This leads to inaccuracies in the impact point. The magnitude of the error is dependent on the aircraft's ground speed. (Note that with many airdrops, the deck angle changes during the airdrop itself, particularly when doing gravity airdrops, as in container delivery. For cases like these, an average deck angle must be assumed when deriving the CARP.)

3.0.2 Power Extraction

As stated previously, the deck angle, or pitch, of the aircraft plays an important role in the exit time, as it influences the gravitational component of the load's acceleration. Powered extraction, defined as extraction assisted by powered rollers, was investigated by M. Seeger, IABG, Germany, as a way to reduce these errors in pitch angle calculation. He concluded that powered roller technology demonstrated that exit time errors could be reduced, but at an unacceptable cost and weight penalty in most cases. However, if an aircraft was equipped with powered rollers for loading pallets, it would be beneficial to use them during airdrop operations, particularly when multiple loads are dropped. [6]

3.0.3 Drogue Extraction

A traditional way of extracting a load from an aircraft has a drogue, or extraction parachute, released into the air stream behind the ramp at green light. The drogue inflates and then pulls the load out of the aircraft.

The inflation time of the drogue can be variable, thereby influencing exit time, and subsequently, the impact point. A technique used to minimize this exit time variation is to deploy the drogue parachute at such a time that it is fully inflated behind the aircraft at green light, at which time, the tow plate is released and the load is extracted. Seeger, et al [7] concluded that drogue extraction technology demonstrated a more favorable improvement in exit time error than powered roller systems for a single load airdrop. They demonstrated improved accuracy improvements associated with drogue parachutes inflated prior to the aircraft reaching the CARP. This means that errors associated with the deployment, inflation and operation of the drogue are greatly minimized, allowing a more accurate and repeatable exit time to be achieved. This technique can only be used when the aircraft has the capability to safely tow the drogue for the required period, accounting for any drogue-release malfunction scenarios.

3.1 RECOVERY PERIOD: CURRENT AND PROPOSED SYSTEMS

The recovery period is particularly affected by the parachute system ballistic trajectory, the effect of winds on this trajectory, and any ability to steer the canopy. The trajectories are estimated and provided to the aircraft manufacturers for input into the mission computer for CARP calculation. (See section 2.0.) However, new models are being developed to reduce ballistic trajectory errors.

Many NATO Nations are investing in precision airdrop technologies/systems and many more will likely begin investments to help meet NATO and national precision airdrop requirements. This section will provide an overview of numerous precision airdrop systems and technologies.

Precision airdrop does not allow for ‘one system fits all’ as the payload weight, altitude range, accuracy, and many other requirements are significantly different. For example, the United States Department of Defense (US DoD) is investing in numerous precision airdrop initiatives within a program known as the Joint Precision Air Drop System (JPADS). The JPADS is a guided precision airdrop system that provides significantly improved accuracy (and reduced dispersion) over currently fielded, unguided (ballistic) airdrop methods.

Within the primary US DoD programs, JPADS is comprised of 4 weight classes (fully rigged weights): JPADS-Extra-Light (JPADS-XL) for 500 to 2,200 pounds, JPADS-Light (JPADS-L) for 2,201 to 10,000 pounds [8], JPADS-Medium (JPADS-M) for 10,001 to 30,000 pounds, and JPADS-Heavy (JPADS-H) for 30,001 to 60,000 pounds. The systems are expected to operate from altitudes up to 25,000 to 35,000 feet MSL, and have accuracies of 100 meters or better. Many other initiatives are also underway in much smaller weight classes for a range of resupply and other applications all the way down to 1- to 2-pound payloads.

This paper focuses on the first two JPADS weight increments, as these are both the most rapidly maturing and the most needed for NATO Nations. However, it also introduces the reader to a few systems outside this weight range and some unique precision airdrop systems and applications. Higher weight range systems are likely only to be fielded by a few NATO Nations.

The use of the term JPADS is used throughout this section and should be considered a generic term for all related technologies. Why the ‘J’? Most NATO Nations consider airdrop a ‘joint’ mission and for most Nations, JPADS capabilities have application to all services. The JPADSs are comprised of the following subsystems.

3.1.1 Parachute

The parachute can be a round parachute, parafoil, or both. The JPADS generally use either a parafoil or a parafoil/round parachute hybrid for deceleration of the load through descent. The ‘controlled’ parachute provides JPADS with directional capability in flight. Often other parachutes are also utilized in the overall

system for final load recovery. Parachute control line(s) run to the airborne guidance unit (AGU) and are used to control the shape of the parachute/parafoil for directional control. One primary difference between each category of deceleration technology, i.e. type of parachute, is the horizontal achievable offset each type of system can deliver. In very generic terms, offset is often measured in terms of the systems lift to drag ratio (L/D) 'in zero winds.' It is clearly much more complicated to compute an achievable offset without accurate knowledge of many parameters affecting the offset. These parameters include the winds the system will encounter (winds can help or hurt offsets), the total vertical distance available for the airdrop, and how much altitude the system needs to be fully open and gliding, along with the amount of altitude the system needs to set up for ground impact. In general, parafoils provide L/Ds in the 3 to 1 range, hybrids (i.e. highly wing-loaded parafoils for controlled flight that transition to ballistic round canopies near ground impact) provide L/Ds in the 2/2.5 to 1 range, while traditional round parachutes controlled via slips provide L/Ds in the 0.4/1.0 to 1 range.

There are numerous concepts and systems exploring much higher L/D systems. Many of these require rigid leading edges or 'wings' that are 'unfolded' during deployment. In general, these systems are more complex and costly for airdrop applications and have shown to use up all available area for cargo in the bay. More traditional parachute systems on the other hand, generally exceed the total weight limit for the cargo bay. High-altitude low opening (HALO) systems can also be considered for precision airdrop applications. These systems are two stage systems. The first stage is generally a small, uncontrolled parachute system that rapidly descends through the majority of the altitude. The second stage is a large parachute that is opened 'close' to the ground for final ground impact. In general, these HALO systems are much less expensive than controlled precision airdrop systems, however, they are not as accurate and will still provide a 'spread' of payloads when more than one payload is dropped at a time. This spread will be greater than the speed of the aircraft multiplied by the time to deploy all the systems (often as much as a kilometer of distance).

3.1.2 Airborne Guidance Unit (AGU)

The AGU houses the GPS receiver and/or other sensors in an avionics suite; guidance, navigation, and control (GN&C) software package; the hardware required to operate the control line(s), and battery power packs for nearly all JPADS. The AGU, using initialization data from the JPADS-MP, acquires its position prior to exit from the aircraft generally through a GPS retransmission kit (RTK). Once the position is reacquired upon exit from the aircraft, the AGU steers in accordance with the planned trajectory or towards waypoints, making corrections in flight as necessary via an actuator/pulley system attached to the control line(s).

3.1.3 Cargo Container/Pallet

For JPADS-XL: A-22 containers or the container delivery system (CDS) or equivalent is used. Many NATO Nations have customized rigging procedures for unique equipment/supplied in a CDS-equivalent weight range.

For JPADS-L: Either a 463L pallet (for payload suspended items), a Type V platform, an enhanced container delivery system (ECDS) platform, and/or equivalents can be used.

Each NATO Nation has differing platform types, requirements for load restraint criteria in the aircraft, and release procedures. For most of the precision airdrop systems described in the following sections, the objective is to be as independent as possible from the cargo shape, platform/container type, center of gravity, and moments of inertia. This goal allows for the maximum amount of flexibility by the user within any weight class.

The ECDS is a multimodal platform sized to the dimensions of a standard USAF 463-L pallet (108 inches by 88 inches). The ECDS enables the airdrop roller systems of the C-130 and C-17 aircraft to support the

10,000 pounds of total rigged weight of one JPADS. The 463-L sizing allows the platform to be transported by a variety of aircraft such as rotary wing using sling attachment points built into the platform. The ECDS is currently being developed by the US Army Product Manager (PM)-Force Sustainment Systems (PM-FSS) and has not yet been fielded.

3.1.4 Mission Planning

Nearly all of the following precision airdrop systems require mission planning prior to being airdropped. The JPADS requires at a minimum, a payload weight and a desired ground impact coordinate (i.e. GPS latitude/longitude). In addition, most systems take advantage of wind information, which also allows the user to determine the area of opportunity in which the aircraft can drop the payload and which the payload can still make it to the intended ground impact target. This view can be reversed by looking at the area of opportunity as the potential ground impact area the payload can land on from a given CARP.

3.1.5 International Precision Airdrop Demonstrations

A variety of international precision airdrop demonstrations have been conducted over recent years as the technology/systems have matured. These smaller demonstrations will not all be discussed in this paper. Other demonstrations have included a wide variety of systems and to date, have been conducted in the U.S. This is often the case due to the need for relatively large test ranges to conduct safe precision airdrop tests of the less mature systems.

The most notable of these are known as the Precision Airdrop Technology Conference and Demonstration (PATCAD). By 2004, two have been facilitated and executed by the U.S. Army Research Development and Engineering Command (RDECOM) Natick Soldier Center (NSC), at the U.S. Army Yuma Proving Ground (YPG) in Yuma, Arizona with numerous sponsors and an ever-increasing audience due to the increased worldwide interest and requirements for precision airdrop. [9]

During the week of 3 through 7 November 2003, the second PATCAD was executed with numerous US DoD and allied Nation attendees and numerous precision airdrop contractors participating. The purpose was to bring together national and industry leaders in the airdrop field to brief, demonstrate, and collaborate on precision airdrop technologies. Among the over two hundred participants in attendance were representatives from nine foreign allied nations (Australia, Canada, France, Germany, Norway, The Netherlands, Singapore, Sweden, United Kingdom). Fourteen different precision airdrop systems were demonstrated at or near the LaPosa Drop Zone at YPG. The systems demonstrated ranged in maturity from new prototypes having their first autonomous drops to relatively mature systems that are already in use by some nations. In general, PATCADs are not a competition but rather an opportunity for NATO and other Nations to view a range of precision airdrop systems of various technology readiness levels (TRLs) all during the same week.

More PATCAD information is available at the following website:

http://yuma-notes1.army.mil/patcad2003.nsf

Those interested in obtaining a site username and password may contact Richard Benney at:

Richard.Benney@Natick.army.mil

3.1.6 Joint Precision Airdrop System Mission Planner (JPADS-MP)

Each of the following systems has some type of laptop-based mission planning system and each requires different input parameters and data prior to being deployed. One mission planning system under development and in use by Special Operations Forces within the U.S. DoD is the JPADS-MP; it is the

most sophisticated mission planner for precision airdrop systems being developed at this time. The JPADS-MP is being developed by a large team for the USAF Air Mobility Command, Scott AFB, Illinois, including: Program Management and Execution by the U.S. Army Natick Soldier Center, Planning Systems Inc., Reston, Virginia (lead contractor for hardware, weather, and integration), Charles Stark Draper Laboratory, Cambridge, Massachusetts (mission planning), Forecast Systems Laboratory, Boulder, Colorado (weather assimilation software), and many other supporting services.

The JPADS-MP enables aircrews to plan and initiate load release at an accurate CARP (or area) through the application of accurate models of the JPADS components and enhanced wind profile/weather knowledge. As the US DoD is investing in a family of JPADS decelerator systems, the requirement has been established to have a single JPADS-MP capable of programming any/all JPADS parachute systems both on the ground and/or while in-route to the CARP.

The JPADS-MP models the parameters of aircraft position, altitude, airspeed, heading, ground speed, course, onboard load position (station), roll-out/exit time, decelerator opening time, load trajectory to stabilization, descent rate due to weight and decelerator drag, and the descent trajectory to the desired point(s) of impact due to the atmospheric three dimensional (3D) wind and density field encountered by the descending load under canopy. Additionally, JPADS-MP provides programming and targeting information to many (eventually all) AGUs to include: drop and target altitudes, steering waypoints (if applicable), and weather/wind magnitude/directions as a function of altitude, opening altitudes, and GPS 'hot start' information. Planning is done using the aircraft's power, antenna, 1553 data bus when available, and GPS. In addition, the US DoD has linked the Combat Track II (CTII) secure satellite communications transceiver (when installed) to run on the JPADS-MP laptop allowing for small 'emails' to be sent to the JPADS-MP (i.e., updated weather information and/or new impact points for any/all of the payloads to be airdropped).

The JPADS airdrops are executed using a JPADS-MP-derived CARP based on updated, in-situ, and atmospheric information. Weather information can be downloaded via a secure or nonsecure U.S. Air Force Weather Agency (AFWA) website known as the Joint Air Force Army Weather Information Network (JAAWIN). Downloaded weather can include a 3D cube of data centered over the preliminarily intended impact point, generally a volume of 100 by 100 kilometers (328,083 by 328,083 feet) by 40,000 to 50,000 feet in altitude, and in multiple 1-hour time intervals around the intended drop time. This allows the aircrew maximum flexibility to compute a CARP and reprogram JPADS in flight if the mission drop time and or drop locations change while airborne.

The basic JPADS-MP hardware components include a portable, rugged, low- or high-pressure tolerant laptop computer, a JPADS-MP interface processor (PIP), dropsondes, a GPS RTK, and cabling for C-130, C-17, and other aircraft. When used with JPADS systems, the JPADS-MP also comes with wireless common navigation interface units (CNIUs), which are under development. The CNIUs are attached to the AGUs for wireless programming and can either be removed prior to exit from the aircraft or stay with the AGU through flight. The PIP includes an ultra-high frequency (UHF) radio receiver and a dropsonde interface processor. The JPADS-MP hardware is man-portable and installed aboard the selected precision airdrop aircraft in a roll-on/roll-off configuration in less than one hour. The high-pressure tolerant laptop computer and system components enable operation in unpressurized flight up to 35,000 feet MSL pressure altitude.

The JPADS-MP assimilates high-resolution four-dimensional (4D) forecast weather fields, high-resolution topographic data from the National Imagery and Mapping Agency (NIMA), and wind data measured in near-real-time with dropsondes to produce a 3D wind, pressure, and density field for a given DZ at the planned drop time. The JPADS-MP is fully integrated with the FalconView map overlay program and provides crews the ability to determine a safety landing area footprint of where ballistic and/or precision airdrop systems could land if they malfunction. The ability to compute such a footprint is particularly useful for test as well as safety considerations. The current JPADS-MP fly-away kit is shown in figure 1,

including its carrying case and an A-sonde (lower right corner). The system is certified to fly on C-130 and C-17 aircraft.

Figure 1: JPADS-MP Fly-Away Kit.
(From Right to Left: Dropsonde, JPADS-MP Hardware, Laptop, and Carrying Case)

Enhancements include the ability to use JPADS-MP to program a number of parachute systems by either plugging the JPADS-MP into each AGU respectively or wirelessly programming each AGU individually or in combination while the JPAD-MP is installed in the aircraft cockpit. The systems this is being implemented into and will be demonstrated with at PATCAD-2005 include the AGAS, SCREAMERS, Sherpas, and DRAGONFLY systems at a minimum.

The JPADS-MP is being developed for potential use with all high-altitude airdrop systems within the DoD. It recently passed two Operational Utility Evaluations (OUEs). One was for use on the C-17 aircraft and one for the C-130 aircraft. Both were executed by the USAF Air Mobility Command Test and Evaluation Squadron, Scott AFB, Illinois, and both used high-altitude, high-speed, CDS systems using a 26-foot ring slot (ballistic) parachute system (figure 2).

Figure 2: JPADS-MP Deployed 26-Foot Ring Slot CDS Drop.

The JPADS-MP (for this limited number of airdrops) demonstrated a 70 percent improvement in accuracy over current C-17 MP (i.e., C-17 mission computer) methods and a 56 percent improvement over current

C-130s MP methods. Many JPADS-MP enhancements are ongoing at the time of this report and as noted, many other MP systems exist of varying levels of maturity for programming (in most cases) a specific JPADS. [10, 11, 12, and 13]

3.2 WIND SENSING SYSTEMS

3.2.1 Rawinsonde

This system uses a GPS unit with a transmitter. It is carried under a balloon, which is released near the drop zone prior to an airdrop. The position data received are analyzed to produce a wind profile. This profile can be used by the drop controller to offset the CARP.

3.2.2 Light Detection and Ranging (LIDAR)

The Air Force Research Laboratory, Sensors Directorate at Wright-Patterson AFB, Ohio, has developed a high-energy 2-micron carbon dioxide Doppler LIDAR transceiver with a 10.6-micrometer eye-safe laser to measure winds at altitude. It was designed to: 1) provide real-time, 3D maps of wind fields between the aircraft and ground, and 2) significantly improve airdrop accuracy from high altitudes. It produces accurate measurements, with a typical error less than one meter per second. The advantages of LIDAR are: provides full, 3D wind field measurement; provides real-time data feed; remains on aircraft; and covertness. The disadvantages are: cost; useful range limited by atmospheric obscurants; and required minor modification to aircraft. [14]

The C-130 aircraft have had LIDAR transceivers mounted on them in a side-looking configuration or on a fuel pod. The system interfaces with the C-130 avionics system and several system displays and user interfaces. A scanner sweeps the transceiver output beam in an elliptical path, sensing winds. The LIDAR optical subsystems are isolated from the harsh vibration and shock environment present on C-130 aircraft. The isolation system dampens the shock loads present during flight and rapidly realigns the sensor to the aircraft boresight. The ballistic winds signal processor collects all data pertaining to the problem of estimating LOS Doppler velocities with calculations of a velocity for each bin of a set or range bins. Data collection includes laser radar data as well as aircraft state of motion data. The LOS range bin data are then converted into 3D wind fields along the sight line path to the ground. The complete wind field is calculated in approximately seven seconds. [15]

3.2.3 GPS Dropsonde

Because variations in time and location of data collection can influence wind estimation, especially at lower altitudes, testers should consider the use of GPS dropsondes to measure winds in the area as close to test time as possible. The dropsonde (or, more fully, the dropwindsonde) is a compact instrument (i.e., a long, thin tube) that is dropped by an aircraft. Winds are derived using a GPS receiver in the dropsonde that tracks the relative Doppler frequency from the RF carrier of the GPS satellite signals. These Doppler frequencies are digitized and sent back to the aircraft data system. The dropsonde can be deployed from another aircraft, even from a jet fighter, before the cargo plane arrives. The dropsonde can also be dropped from the same aircraft but the aircraft must circle around to airdrop the load, adding to the risk of detection. [14]

3.3 PRECISION AERIAL DELIVERY – CURRENT AND FUTURE SYSTEMS

Numerous companies and organizations have been designing systems to control parafoil canopies for the purpose of precision cargo airdrop. Some systems are autonomous while others are manually controlled from a ground or airborne station.

3.3.1 Mist Mobility Integrated System Technology, Inc. (MMIST) Sherpa

The Sherpa is a commercial-off-the-shelf (COTS) cargo delivery system manufactured by MMIST of Nepean, Ontario, Canada. The system consists of a programmable timer-released drogue parachute that deploys a ram-air canopy, a parachute control unit, and a remote control. The system is capable of delivering between 400 and 2,200 pounds of payload with 3 to 4 different parafoil sizes and small modifications to the AGU cage. The Sherpa mission can be planned before flight by entering the coordinates of the intended impact point, current available wind data, and payload characteristics. The Sherpa MP software uses the data to generate a mission file and calculate a CARP within the release area. Upon release from the aircraft, the Sherpa system drogue parachute, a small round stabilization parachute, is static-line deployed. The drogue is attached to a release latch that can be programmed to release at a preset time after deployment. Upon releasing the drogue, it pulls out the main parafoil, which inflates while concurrently deflating the drogue. This is a desired feature of all JPADS systems to ensure that all components of the system are retained by the system throughout flight for both simplified recovery and to minimize residuals (residuals are any items that leave the aircraft and do not stay with the system all the way to ground impact) in the airspace. The Sherpa system then flies autonomously towards preprogrammed waypoints (if used) or the intended impact point.

The Sherpa system also comes with a ground control. Ground control is difficult to do during low-visibility and at far distances, but has advantages for testing and some military applications. In addition, the Sherpa ground control unit has a beacon mode in which a ground user can reprogram the intended impact point by wirelessly sending the ground GPS location via the ground controller, which has a built-in GPS receiver.

The Sherpa system has been purchased by a number of NATO Nations and has been used operationally by the United States Marine Corps (USMC), as of 8 August 2004, in Iraq.

Four Sherpa systems are shown (figures 3 and 4) just after deployment from a US C-17 aircraft during PATCAD-2003.

Figure 3: Four Sherpa Systems Exiting a C-17 Aircraft.

Figure 4: The Sherpa system is shown in-flight just prior to landing during an operational mission in Iraq by the USMC.

MMIST has also developed the Snowbird system for smaller payloads of 50 to 500 pounds. Although the Snowbird AGU is smaller and lighter than the Sherpa AGU, the system has most of the Sherpa features with the exception of an internal modem. Figure 5 presents the Snowbird system in flight. [16]

Figure 5: Snowbird in Flight.

3.3.2 Strong Enterprises SCREAMER

The SCREAMER concept was developed by Strong Enterprises, Orlando, Florida, and first produced in early 1999. The SCREAMER system is a hybrid JPADS that uses a ram-air drogue (RAD) canopy for controlled flight throughout the vertical descent and also uses traditional, round, uncontrolled canopies for the final phase of flight. Two versions, each using the same AGU, are described in the following paragraphs. The first is a 500- to 2,200-pound capacity system and the second is a 5,001- to 10,000-pound capacity system. [17]

The SCREAMER AGU is provided by Robotek Engineering, Inc. of Garland, Texas. The 500 to 2,200-pound SCREAMER system utilizes a 220-foot^2 ram-air parachute as the drogue with wing loading up to 10 pounds per foot^2 and flies at high rates of speed capable of penetrating most upper level wind conditions. The SCREAMER RAD is controlled either remotely via a ground control station or (for military applications) autonomously during the initial phase of flight by a 45-pound AGU. It is guided to a point above the intended landing location. Knowledge of current winds is used to calculate the offset for this point. When the system reaches this point, a ballistic round cargo recovery parachute (example: a standard G-12 cargo parachute) is deployed for the final stage of flight through ground impact. Figure 6 shows the 2,000-pound-capacity SCREAMER system. [18]

Figure 6: 2,000-pound CDS Payload SCREAMER System Transition from Guided Flight to Recovery Chute Landing.

The 10,000-pound SCREAMER system began testing in September 2003. It utilizes a 650-foot^2 RAD and two standard G-11 (100-foot diameter flat circular parachutes) for the final phase of ballistic flight. The system has demonstrated 10,000-pound capacity autonomous flight from nearly 18,000 feet MSL. The system, with a breakout of components, is shown in figure 7.

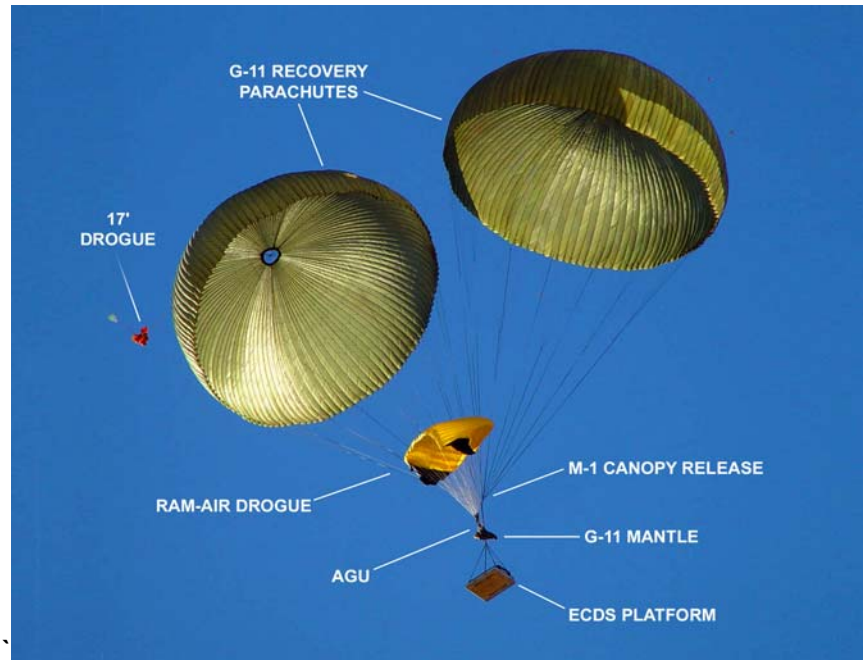

Figure 7: 10,000-pound SCREAMER System in the Final Stages of Flight.

3.3.3 DRAGONLY 10,000-pound Capacity Parafoil System

The DRAGONFLY system is being developed by the U.S. Army Natick Soldier Center JPADS ACTD Team and is a collaborative effort between Para-Flite, Inc., Pennsauken, New Jersey, developer of the decelerator system; Warrick & Associates, Inc., Prescott, Arizona, developer of the AGU; Robotek Engineering, provider of the avionics suite; and Draper Laboratory, leader of the GN&C software development. The program began in fiscal year 2003 and fully integrated system flight tests commenced in the first quarter of fiscal year 2004. [19]

The primary decelerator for the DRAGONFLY system is a 3,470-foot^2 high-performance parafoil. The canopy is a true advancement in the state of the art of large parafoil system design and construction. Para-Flite has implemented advanced manufacturing techniques, such as the use of laser cutting of the rib sections, to achieve system cost goals without sacrificing performance goals. The high aspect ratio (3.2:1) semielliptical planform uses an advanced airfoil section and a multigrommeted slider to control the deployment of the canopy. The elimination of a multistage pyrotechnic deployment system permits drastic reductions in canopy design complexity, further reducing the production cost. Packing and rigging time of the system is also greatly reduced. The canopy, with a wingspan slightly in excess of 100 feet, can be easily repacked by two persons in less than 3 hours.

Effective application of advanced wing design features such as taper, twist, and variable anhedral has resulted in a parafoil with substantially better flight performance than previously demonstrated by other large parafoil designs. Wind-corrected glide ratios in excess of 3.5:1, at flight speeds better than 40 knots, have been recorded at the objective payload weight. Further, the canopy is exceptionally responsive to control input. Only one-sixth of the outboard trailing edge of the canopy is deflected on each wingtip to affect directional control and braking (flare) for landing. As such, control line loads and total stroke are much lower than comparable systems. This has permitted substantial reduction in the power requirements and total weight of the AGU used to control the parachute.

The AGU connects to the parafoil risers and is suspended between the parafoil and the payload. The AGU weigh approximately 175 pounds. Though lightweight, the design has proven itself extremely rugged and

robust through flight test. As with the parafoil design, great attention has been paid to minimization of unit cost. The AGU and its avionics suite rely heavily on the effective integration of COTS components. Primary system electromechanical subcomponents include: a pair of 1.5-horsepower brushed servomotors, motor controller, 54:1 gear reducers, 900-megahertz RF modem, microprocessor, dual GPS, and three 12-Volts direct current sealed lead acid batteries. Two batteries provide 24-Volts direct current to the actuators, while the third battery provides power to the avionics.

As noted, an important goal of this program is to keep recurring system costs at a minimum. Hence, the avionics selected are the ultimate in simplicity. The sole navigation sensor is the *Vector* dual-GPS receiver by CSI Wireless of Scottsdale, Arizona. Using two tightly coupled GPS receivers and antennas, the system provides not only system position and velocity, but also heading and heading rate. This approach avoids including a magnetic compass for the heading reference, which has difficulties due to local changes in the magnetic field and field perturbations from the various metal masses in the AGU. The flight processor selected is the RCM3400 microcontroller by Rabbit Semiconductor of Davis, California. The RCM3400 is augmented by 8 MB of flash memory to hold guidance data tables and record GN&C parameters during flight for later analysis. A 902 to 928 megahertz spread-spectrum modem by Freewave Technologies, Boulder, Colorado, is also used to receive remote control commands from the ground and to downlink mission data for postflight analysis. This modem can be used for downloading mission files prior to airdrop system release, though 802.11g wireless network components will be integrated as a replacement for operational use.

A key element of the JPADS ACTD is the development of GN&C software to autonomously fly the DRAGONFLY 10,000-pound-capable parafoil. This software must guide the parafoil from deployment altitudes up to 25,000 feet MSL to landings within a 100-meter circular error probable (CEP) of the target. Other key goals include robustness to a variety of failure modes, algorithms that are sufficiently generic to facilitate adaptation to both smaller and larger decelerators, efficient enough to perform well on a very modest microprocessor, and capable of meeting system performance requirements with a navigation sensor suite limited by recurring system costs. Also important are US Government ownership of the resulting code, the ability to handle user-supplied waypoints, plus efficient and cost-effective integration with the previously developed Air Force and Army Precision Airdrop System (PADS) mission planner.

Flight testing commenced in March 2004 at Red Lake in Kingman, Arizona. Initial flights were remote controlled, executing planned maneuvers to establish the flight characteristics of the Dragonfly system; these occurred in March and April. Draper Laboratory used the results of these flights to conduct system identification and establish GN&C parameters as described elsewhere in this paper. First flight of the autonomous flight software occurred in May 2004. Testing has continued since then at approximately six-week intervals, with flights starting in October occurring at the Corral DZ at YPG. During this time, the GN&C software was matured in parallel with evolution of the canopy, rigging, and airborne hardware, including a major upgrade to the AGU involving new actuation motors, necessitating revised flight software motor interfacing. The move to YPG was a milestone as this was the first time the system flew from a C-130 airplane, deploying at 130 knots indicated air speed (KIAS), considerably faster than the C-123 used in Kingman. Flights from military aircraft commenced in February 2005. As the flight test program proceeded, system weights were gradually increased up to the DRAGONFLY maximum of 10,000 pounds, as were drop altitudes, heading toward a goal of flights from 18,000 feet MSL by spring 2005. Initial autonomous flights were deployed directly over the targeted impact point, and then gradually more offset from the target was introduced. The GN&C software was initialized in early tests assuming no winds, then forecast winds were used, and eventually flight tests will include updates of the GN&C mission file while enroute to the DZ with current winds estimates based on an assimilation of forecast and dropsonde wind and density data. [20] An image of the system in flight is shown in figure 8.

Figure 8: 10,000-pound DRAGONFLY in Flight.

3.3.4 Capewell and Vertigo AGAS

The Affordable Guided Airdrop System (AGAS) by Capewell Components, Inc. of South Windsor, Connecticut and Vertigo, Inc. of Lake Elsinore, California, is an example of a controllable, round JPADS. The AGAS is a U.S. government/contractor development effort that started in 1999. It uses two actuators within its AGU that are positioned in-line between the parachute and the payload, and which manipulate opposite parachute risers to steer the system (i.e. slip the parachute system). The four riser quadrants can be manipulated individually or in pairs, providing eight directions of control. The system requires an accurate profile of winds that it will encounter over the DZ. Before the drop, these profiles are loaded into the flight-control computer onboard the AGU in the form of a planned trajectory that the system 'follows' during descent. The AGAS is able to adjust it's location via slips all the way to ground impact point. Figure 9 shows two AGAS in flight. [21, 22, and 23]

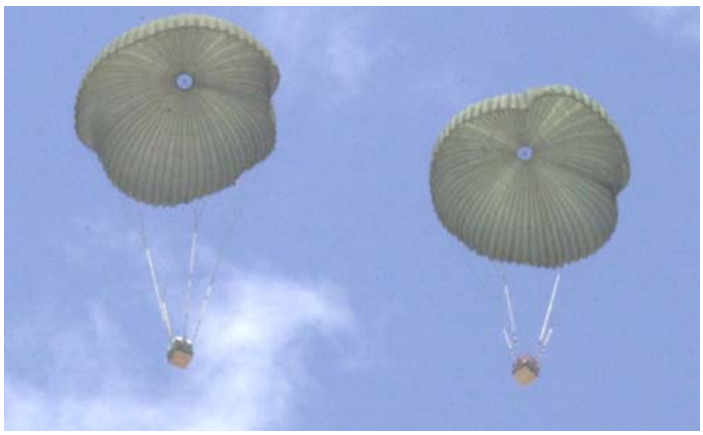

Figure 9: Two AGAS Systems in Flight and During a Double and Single Riser Slip.

3.3.5 Atair ONYX

Atair Aerospace of Brooklyn, New York, developed the ONYX system under a US Army SBIR Phase I contract for 75-pound payloads and have been scaling up the ONYX weight capability with a goal of

reaching 2,200 pounds. The 75-pound ONYX guided parachute system divides guidance and soft landing between two parachutes – a ram air for guidance and ballistic round parachute that is opened above the impact point for ground impact. The ONYX system has recently incorporated a 'flocking' algorithm that allows in-flight communication between systems for 'flocking' flights. An image of the 75-pound ONYX at the PATCAD is shown in figure 10.

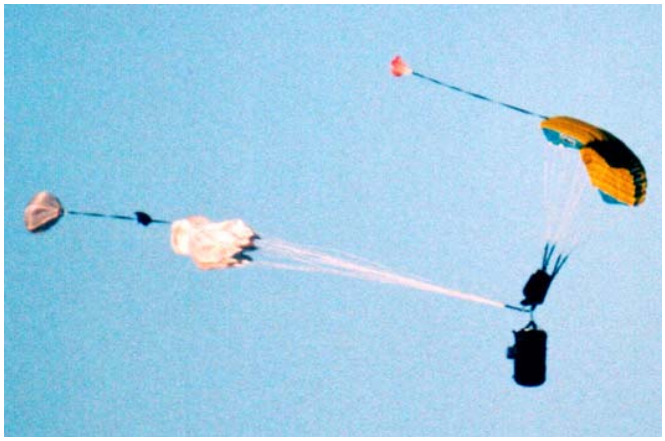

Figure 10: Onyx System – Recovery Chute Opening.

3.3.6 SPADES

The Small Parafoil Autonomous Delivery System (SPADES) (figure 11) is being developed by Dutch Space of Leiden, The Netherlands, in partnership with the National Aerospace Laboratory (NLR) of Amsterdam, The Netherlands, and supported by the parachute supplier Aérazur of Issy-Les-Moulineaux Cedex, France. The SPADES is a cargo delivery system for 100 to 200 kilograms (220 to 440 pounds). The system consists of a 35-meter^2 (377-foot^2) parafoil parachute, a control box with on-board computer, and the payload container. It can be dropped at an altitude of 30,000 feet at a stand-off distance of up to 50 kilometers (31 miles). It is autonomously guided using GPS. The accuracy is 100 meters (328 feet) when dropped from an altitude of 30,000 feet. The SPADES equipped with a 46-meter^2 (533-foot^2) parachute delivers payloads in the range 120 to 250 kilograms (265 to 551 pounds) with the same accuracy. Development of SPADES systems for higher payloads is in progress. [24]

Figure 11: SPADES Airdrop.

3.3.7 Free Fall Navigation Systems

A number of companies are developing personnel airdrop navigation aid systems. There are primarily for use during high-altitude high opening (HAHO) missions. The HAHO is an airdrop that occurs at a high altitude and the recovery parachute system is deployed upon load exit. These freefall navigation systems are expected to guide Special Operations Forces to desired impact points in adverse weather conditions, and to maximize the release point stand off distance. This minimizes the risk of detecting the infiltrating unit as well as the threat to the delivering aircraft.

3.3.7.1 USMC/Coastal System Station/NSC Free Fall Navigation System

This system has gone though three prototype phases all with direct input from the USMC. The current configuration is: fully integrated civil GPS with antenna, AGU, and display drivers within an aerodynamic pod attached to the jumper's helmet (manufactured by Gentex Helmet Systems, Simpson, Pennsylvania). The display is wired and attached to the jumper's goggles. The system program is designed to process user inputted data, three impact points, winds, and canopy characteristics. Based on current altitude and speed, the arrival altitude or distance short of the selected impact point will be displayed. This configuration has proved be a reliable, low-cost capability that will soon be fielded in limited numbers to the USMC. The current configuration and the graphical user interface in both the night time and day time screens are presented in figure 12.

Figure 12: USMC/Coastal System and Day and Night Screens.

3.3.7.2 NanΩhmics Inc.

NanΩhmics, Inc., Austin, Texas, has performed well under a Phase 1 SBIR, and has been invited back to propose on a Phase 2 system. NanΩhmics will be an integrator of components that will be multimission capable. Their proposal will focus on the overall mission capability of the Special Operations Warrior, and provide a tool that performs well beyond the initial infiltration phase of the operation. The concept will be a rugged personal data assistant (PDA) or hand-held computer system, with secure GPS processor and wireless communication to the HUD. The operator could place the system inside the rucksack, with the GPS antenna connected by a cable and placed on top of the pack. The system will be in a sleep mode until programming is required or needed to perform the infiltration. Once on the ground, the operator will be able to utilize the system for many of the requirements currently expected of Special Operations Forces.

Since all components are expected to be COTS, the NanΩhmics systems will be very conducive to spiral technology. As new PDAs and displays are developed they will quickly be added to enhance the system with plug and play technology. Figure 13 presents one possible set of components under evaluation.

Figure 13: NanΩhmics Free Fall Navigation System.

3.3.7.3 EADS ParaFinder

The ParaFinder, made by European Aeronautic Defence and Space Company (EADS) of Schiphol Rijk, The Netherlands, was demonstrated at PATCAD 2003 and is intended to provide an improved horizontal and vertical standoff capability, i.e. the offset from the impact point at which the load can be dropped, for the high-altitude military freefall paratrooper to reach a primary target or up to three alternate targets in any environmental condition. The jumper wears a GPS helmet-mounted antenna with a central processing unit (CPU) on the paratroopers' body/pocket, which communicates to a HUD, also called a helmet-mounted display (HMD), mounted within the user's helmet. The HUD displays the paratrooper's current heading and the desired track, which is based on the mission plan (i.e. winds/ release point etc), current altitude, and position. The HUD also displays recommended steering cues indicating which control line to pull to steer to the intended 3D point in the sky along a ballistic wind line generated from winds inputted by the mission planner. The system also features a HALO mode that guides the jumper to the impact point on the ground. The system is also used as a tool to navigate to the group assembly point after the jumper has landed. It is designed for use in situations where the paratrooper may have difficulty acquiring a visual sighting of the target while on the ground and to help maximize offset. The restricted visibility may be due to inclement weather, thick ground cover, or night drops. Figure 14 presents the EADS ParaFinder airdrop and display. A typical HUD display (sample) is shown in figure 15. It is anticipated that the paratrooper will always rely on experience and remove (flip up) the HUD for the final preparation and landing phase of flight.

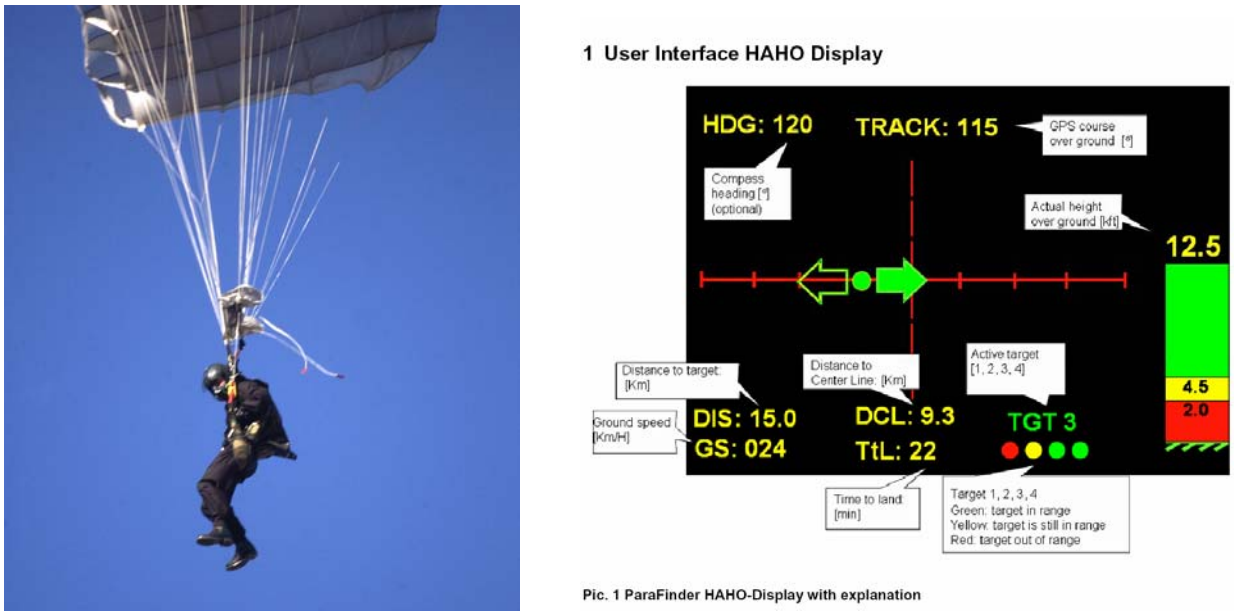

Figure 14: EADS ParaFinder Airdrop and Display.

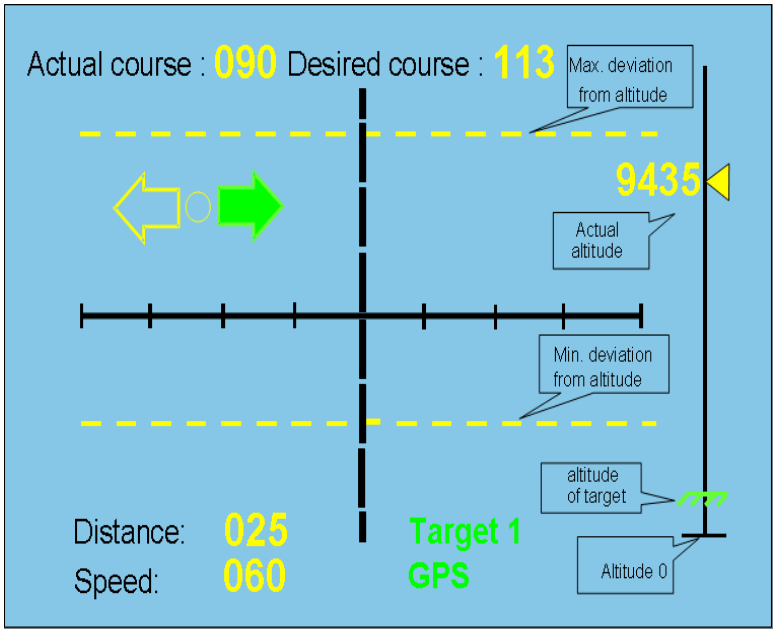

Figure 15: Typical HUD Display.

Navigational aids (NAVAIDs), as these types of systems are known, also require a download of the anticipated weather the paratrooper will encounter during flight to ensure accurate steering 'suggestions' are provided.

European Aeronautic Defence and Space Company is also developing a guided parafoil system known as the ParaLander. It is in the parafoil class of systems and controlled throughout flight. An image of the ParaLander is shown in figure 16. [25]

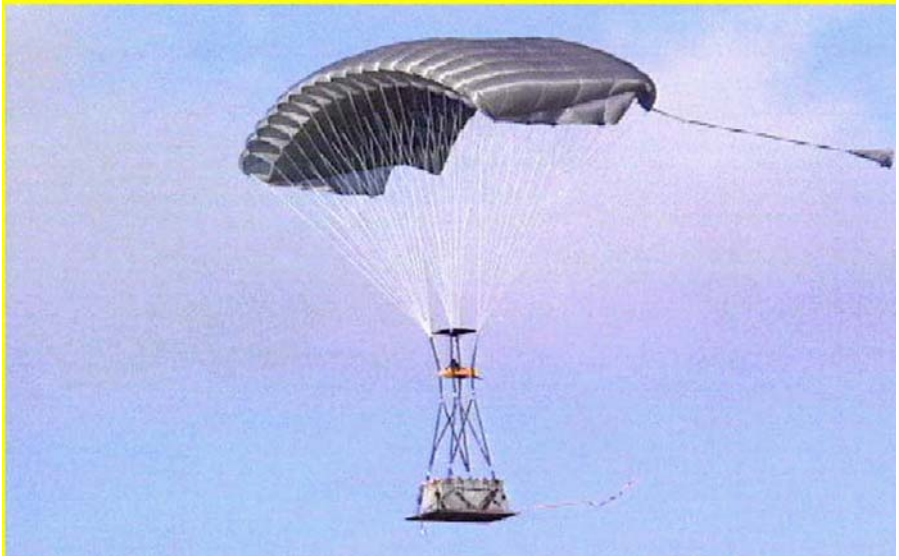

Figure 16: EADS ParaLander.

3.3.8 Stara Generic Delivery System (GDS)

The GDS, also known as the gnat, created by Stara Technologies, Inc., of Mesa, Arizona, utilizes miniature guided parafoils from previous programs. The units carried payloads systems of approximately 3 to 5 pounds. The GDS uses miniature versions of typical AGU components to control itself throughout flight. GDS sized precision airdrop systems have been demonstrated out of a range of unmanned aerial vehicles (UAVs) and have numerous applications from very small resupply to accurate 'unmanned' placement of sensors. Stara is working on a wider weight range of systems for deployment from a wide range of aircraft and UAVs.

Figure 17: GDS Airdrop.

3.3.9 4,200-foot^2 Parafoil System

National Aeronautics and Space Administration (NASA) Johnson Space Center, Houston, Texas, and the U.S. Army Natick Soldier Center, Natick, Massachusetts, have teamed on a variety of precision airdrop programs. NASA was developing the X-38 Assured Crew Return Vehicle until the program was cancelled

in 2003. The 4200-foot^2 parafoil system was supported by numerous contractors including Pioneer Aerospace of South Windsor, Connecticut. The test objectives included the demonstration of an autonomous flight to deliver 10,000-pounds of useable payload. NASA and the U.S. Army Natick Soldier Center have demonstrated many autonomous large parafoil airdrop tests at higher weights as well. [26, 27]

Figure 18: 10,000-pound Payload Delivered by a 4200-foot^2 Parafoil.

3.3.10 Strong Enterprises Airborne All Terrain Vehicle and Trailer

Strong Enterprises developed a manned airborne all-terrain vehicle (AATV), designed to achieve sustained flight, and a manned airborne trailer (ATR), capable of transporting up to four people. Strong Enterprises modified the AATV by incorporating a ROTAX 53-horsepower motor and propeller. The AATV was dropped from 10,000 feet AGL and descended at 70 miles per hour under drogue until 6,000 feet AGL, where the main parachute was activated. After a visual check of the fully deployed main parachute, the pilot raised the retractable motor/propeller system into position and started the motor. When the motor was wide open, sustained level flight was achieved. The power to the prop motor was shut off for final descent and the AATV engine was started. Upon landing, the pilot released the main parachute, shifted into gear and drove away within 5 seconds of touchdown. The total descent from 10,000 feet lasted over 15 minutes. The powered AATV is pictured in figure 19.

Figure 19: Flight of Powered AATV.

Designed for precision aerial delivery missions of up to four personnel, or, a combination of personnel and equipment, into a specific target area, the ATR (figure 20) may is also used as a training vehicle. After normal drogue-fall the 1,200-foot^2 canopy opened and flew smoothly. After flying to the target site and landing, the AATV and ATR pilots jettisoned the parachutes, the AATV was driven to the ATR and the ATR was hitched to the AATV and became a completely mobile, tactical transport unit.

Figure 20: ATR in Flight.

3.3.11 MMIST Snowgoose

The line between precision airdrop systems and unmanned 'powered' aerial vehicles is less clear with the development of the Snowgoose by MMIST, with sponsorship from U.S. Special Operations Command (SOCOM). The MMIST Snowgoose is a UAV that uses a 115-horsepower Rotax-914 engine and a 500-foot^2 canopy (725-foot^2 canopy for air launch) for powered flight. The system can be airdropped from a cargo plane or ground launched off the back of a High Mobility Multiwheeled Vehicle (HMMWV) (figure 21). The Snowgoose features six cargo bays that can carry various combinations of modular fuel bins and custom payloads with a total cargo weight of 600 pounds. Each cargo bay can be individually opened at specified points during flight for payload release. The maximum sustainable flight altitude is approximately 18,000 feet MSL. The Snowgoose can be programmed preflight to provide fully autonomous waypoint-to-waypoint flight control, payload release, and autonomous landing. Ground control can override an autonomous flight via an RF modem or also via a satellite modem (manufactured by Iridium Satellite of Bethesda, Maryland). Applications of the system include precision cargo delivery, communications and remote sensing, and leaflet disbursement. Custom payloads for the Snowgoose include a meteorological sensor suite; dropsonde dispenser payload; comm-relay package; optical payload; sensor monitoring, control, and logging module; and wireless Ethernet.

The Snowgoose demonstrated its ability to collect wind data, dispense leaflets, and drop cargo. During one flight, the system had a broken control line and had to land to be repaired. Shortly after, the system was relaunched and climbed to altitude and dispensed three dropsondes, which transmitted weather data to a JPADS-MP ground station, to a nearby airborne aircraft, and back to the Snowgoose itself. The JPADS-MP was able to use these wind data to assist in the mission planning of other drops later in the day.

Two leaflet drops were executed. About 30 pounds of leaflets were dropped each time from an altitude of 1,000 feet AGL. The target areas were both 1 kilometer^2 (0.386 mile^2). The first leaflet was on target (figure 22). The second leaflet drop was about 600 meters (1,970 feet) off target.

The Snowgoose has demonstrated dropping of resupply cargo bundles from its cargo bays. After completing the two missions, the Snowgoose flew back to the C-17 landing strip where its landings were radio controlled. However, the Snowgoose also can execute autonomous landings.

Figure 21: Snowgoose Ground Launch from HMMWV.

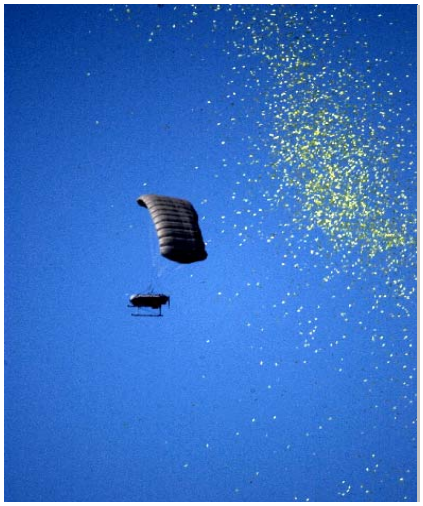

Figure 22: Leaflet Cloud dropped by Snowgoose.

3.4 AIRDROP TESTING CONSIDERATIONS

Airdrop test techniques can be found in AGARD Flight Test Techniques Series Volume 6, *Developmental Airdrop Testing Techniques and Devices* [28]. These basic techniques can be used for precision airdrop testing up to load exit.

In testing, accurate recording of all test conditions is extremely important. This includes knowledge of wind conditions at the drop area at the time of the test. Data collection should be done in the area as close to the drop time as possible. Again, because variations in time and location of data collection can influence wind estimation, especially at lower altitudes, testers should consider the use of GPS dropsondes to

measure winds. The dropsonde should be weighted to produce the same rate of descent as the payload when using winds for CARP calculations.

Differences in piloting technique can cause variations in test results. Use of autopilot, autothrottle, and autoinitiation of load release and attitude hold also helps to minimize variation during an airdrop test. Testing using the same initial conditions in calm air, using new drogue parachutes for each cargo airdrop test, would all help minimize variation and provide more repeatable results.