806-67

AIAA Guidance, Navigation, and Control Conference and Exhibit
21 - 24 August 2006, Keystone, Colorado

AIAA 2006-6790

Providing Means for Precision Airdrop Delivery from High Altitude

Philip D. Hattis*, Darryn P. Campbell.†, David W. Carter‡, and Marc McConley§
Draper Laboratory, Cambridge, MA, 02139

and

Steve Tavan**
US Army Research, Development and Engineering Command, Natick Soldier Center, Natick, MA 01760

Precision airdrop is essential to insertion of military and humanitarian supplies at remote, globally distributed locations that are involved in conflict or have experienced natural disasters. Enabling precision payload delivery following high altitude release limits risk to carrier aircraft. For the past eight years, the Army and Air Force have combined resources to facilitate major advances in precision, high altitude airdrop. This includes new means for on-board airdrop mission planning for an expanding set of ballistic parachute and guided parafoil airdrop systems that realize accuracy improvement by using detailed system dynamics models, high fidelity atmospheric state models, and means to generate and upload revised mission plans for guided airdrop systems. Development and implementation of an open-architecture Guidance, Navigation, and Control (GN&C) system has also been pursued for use on large parafoil airdrop systems. Implementation features of the personal computer-based Precision Airdrop System (PADS) mission planner are reviewed and the parafoil GN&C design features are discussed. A review is provided of payload delivery performance realized using the PADS for a variety of ballistic and guided airdrop systems and using the GN&C system on the *Dragonfly* 10,000-lb class parafoil. Continued capability development plans for PADS and the GN&C system are also summarized.

Nomenclature

AGAS	Affordable Guided Airdrop System
AGU	Airborne Guidance Unit
CARP	Computed Air Release Point
CD	Compact Disc
CEA	Circular Error Average
CTII	Combat Track II
DZ	Drop Zone
FTP	File Transfer Protocol
FTS	Flight Termination System
GMI	Graphical Map Interface
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
GUI	Graphical User Interface

* Laboratory Technical Staff, Mission Design & Analysis Group, 555 Technology Square/Mail Stop 77, and AIAA Fellow.
† Member of the Technical Staff II, Embedded Software Group, 555 Technology Square/Mail Stop 77.
‡ Principal Member of the Technical Staff, Decision Systems Group, 555 Technology Square/Mail Stop 77.
§ Principal Member of the Technical Staff, Tactics, Guidance, and Control Group Leader, 555 Technology Square/Mail Stop 77.
** Precision Airdrop GN&C Research Lead, NSC Airdrop/Aerial Delivery Directorate, AMSRD-NSC-AD-JP/Kansas Street, and AIAA Member.

JPADS	Joint Precision Airdrop System
OUE	Operational Utility Evaluation
PADS	Precision Airdrop System
PAPS	Precision Airdrop Planning System
PATCAD	Precision Airdrop Technology Conference and Demonstration
PC	Personal Computer
PFPS	Portable Flight Planning System
PGAS	Precision Guided Airdrop System
PI	Point of Impact
PID	Proportional, Integral, Derivative
PIP	PADS Interface package
PSI	Planning Systems, Inc.
TRIADS	Tri-Wall Aerial Delivery System
RS	Ring-Slot
SIPR	Secure Internet Protocol Router
UHF	Ultra High Frequency
YPG	Yuma Proving Ground
4D	Four Dimensional

I. Introduction

The strategic importance of precision airdrop from high altitude has steadily increased over the past decade because of both military applications and humanitarian crises which often result from ground-based hostilities. Airdrop carrier aircraft and their crew are very high value assets that can be put at great risk of hostile ground fire when performing airdrops at low altitude which has been necessary in the past to realize airdrop payload precision delivery. Large scale relief airdrops over the past two decades in theaters such as Bosnia and Rwanda have often delivered payloads many kilometers away from their intended targets, resulting in loss of much of the cargo to surface hazards or to unintended parties on the ground. Furthermore, the on-going decrease in forward basing options by the United States military and the increased risk to surface convoys further motivates enabling reliable precision airdrop capability from the fleet of Air Force cargo aircraft.

The PADS development program began in 1998 to develop a portable, low-cost airdrop mission planner to address the issues noted above [Refs. 1-3]. The initial goal was to perform a prototype demonstration of a portable airdrop mission planner that would enable determination of the Computed Air Release Points (CARPs) on board carrier aircraft for ballistic parachutes released at high altitude. The initial PADS implementation involved two Ethernet-connected laptop Personal Computers (PCs) with a Draper Laboratory-developed simulation-based Precision Airdrop Planning System (PAPS) on one laptop, and a Planning Systems, Inc. (PSI)-developed Four-Dimensional (4D – space and time) wind field data assimilation and prediction generation program called WindPADS on the second PC. The WindPADS system provided means to obtain wind data transmitted by dropsondes through Ultra High Frequency (UHF) antennas on transport aircraft.. The prototype WindPADS implementation was designed to assimilate pre-flight forecast data with the dropsonde wind data to provide the best possible 4D wind field estimate in the vicinity of the Drop Zone (DZ). PAPS was designed to compute a CARP shortly before airdrop system release based on PAPS-simulated airdrop system trajectories that accounted for the WindPADS-derived data, the expected cargo roll-out dynamics, and the expected parachute deceleration trajectory during canopy deployment. By late 2001, the prototype version of PADS was ready for flight demonstration with the capability to support airdrops for G-12 and 26 ft Ring-Slot (RS) ballistic parachutes as well as Sherpa guided parafoils, all capable of payload delivery in the 2,000 lb class. For the ballistic system, PADS provided an intended CARP point on the desired aircraft course to the DZ. For the Sherpa, PADS computed a desired CARP in a realizable release region from which Sherpa could reach the target. A capability was also included for PADS to transmit a revised mission plan wirelessly to Sherpa to be used by its guidance system during descent. A capability to derive expected ballistic airdrop dispersion footprints was also provided by PADS based on Monte Carlo simulation methods.

The prototype PADS implementation was successfully flight demonstrated at the September 2001 Precision Airdrop Technology Conference and Demonstration (PATCAD), applying in-flight mission planning for all three classes of airdrop systems it was then capable of supporting. However, the implementation of PADS at that time not only involved the use of two PCs, but also had Graphical User Interfaces (GUIs) that were still functioning at a diagnostic engineering level, requiring an expert in-flight operator (who was one of the developers).

The flight test success of the prototype PADS implementation motivated subsequent sponsorship to convert it to a more operationally useful form, with expanded capabilities. This meant merger of all the PADS software into a single PC, incorporation of the PC into a small case that included UHF antenna interfaces, development of much more user-friendly GUIs, and extension of its mission planning capabilities to support additional airdrop systems [Ref. 4]. PADS interfaces were generalized to support both C-130 and C-17 carrier aircraft. Planning support was added for the Affordable Guided Airdrop System (AGAS – another 2,000-lb class guided airdrop system at the time) and the Tri-wall Aerial Delivery System (TRIADS – which enables airdrop of many small food packets in humanitarian relief missions). Also, an initial capability was then provided by PADS to acquire updated wind and airdrop target data from the Combat Track II (CTII) system which allowed encrypted data to be sent to PADS through satellites using another UHF receiver. This more-portable and more versatile version of PADS was successfully flight demonstrated at the November 2003 PATCAD for all classes of the parachute and parafoil-based airdrop systems it could then support, with airdrops performed from both the C-130 and C-17 aircraft. In the same time frame, successful Operational Utility Evaluations (OUEs) were performed using PADS for ballistic airdrops from C-17 and C-130 aircraft. The OUEs demonstrated very significant improvement in high altitude airdrops using PADS on both carrier aircraft classes as compared to prior practice. Also, the OUE airdrops were successfully accomplished with on-board PADS mission planning support by military flight crews following one day of training. Limited field use of PADS ensued.

PADS improvements including both capability extension, and improved user interfaces has continued [Refs. 5-6]. This includes addition of support for Screamer hybrid guided airdrop systems, in a variety of weight classes, generalization of the AGAS capability to support a variety of weight classes, support for a 10,000 lb-class parafoil from Para-Flite (known as *Dragonfly*), and support for personnel airdrops using a variety of steerable canopies. Means to wirelessly provide mission files for all the steerable canopies accommodated by PADS has been provided. Many new overlay displays on a FalconView-based Graphical Map Interface (GMI) have been added to assist the PADS user. All these capabilities, as well as support for an updated version of CTII were flight demonstrated at the October 2005 PATCAD. Additional field use is now being made with the evolving PADS design. More capabilities are being added to the PADS software as dictated by an expanding user community, with upgrades periodically provided that can be loaded by Compact Disc (CD) onto the already fielded PADS units.

As PADS development proceeded, the Joint Precision Airdrop System (JPADS) program began. JPADS aimed to develop a family of guided airdrop systems from small payload capacity to very large. The Army was interested in developing an open-architecture GN&C system for prototype JPADS airdrop systems that could subsequently be applied by future guided airdrop canopy developers without requiring their own GN&C development staff. This GN&C capability would be built on early open-architecture parafoil GN&C flight software that was demonstrated under the Precision Guided Airdrop System (PGAS) program between 1994 and 1996 [Refs. 7-8]. The GN&C development activities under the JPADS program were coordinated with the of the PADS program, with PADS capability extended to enable mission file generation support capability for guided airdrop systems using the JPADS GN&C software. By the time of the 2005 PATCAD, a JPADS GN&C system for the *Dragonfly* 10,000 lb-class parafoil airdrop system was ready, and was flight demonstrated, with airdrops achieving delivery accuracy on the order of 200 m or better.

Section II below provides an overview of the current PADS implementation objectives, architecture, features, and performance. Section III provides a summary of the JPADS GN&C objectives, architecture, features, and flight-test results to date. Section IV addresses the likely future development directions for the PADS and JPADS GN&C development programs. Section V provides overall conclusions.

II. The Current PADS Implementation

Since 1998, PADS development has proceeded through prototype design on to versions now being used in the field. The objectives for the PAPS have become more ambitious, and the PADS capabilities have increased. The following subsections provide a snapshot of the PADS objectives, the top-level PADS architecture, the current PADS features, and some of the airdrop performance demonstrated using PADS to date.

A. PADS Objectives

PADS facilitates an overall goal of providing in-flight support during transit to a DZ for updated planning of precision airdrops from high altitude. To this end, the following specific capability objectives apply to PADS:

- Enable access and use of preflight weather information from climatology, forecasts, balloons, and manual entries of applicable data.

- Provide means to obtain real-time weather data in transit to the DZ from on-board the carrier aircraft, from near the DZ, or from a remote source.
- Support airdrop planning for ballistic cargo parachutes as well as steerable cargo and manned parafoils. This should include determination of CARPs for a variety of both the ballistic and steerable systems as well as generation of mission file updates for steerable systems. This should also include means to bias the CARP for steerable airdrop systems based on user considerations.
- Include means to generate predicted landing accuracy footprints for nominal ballistic airdrops and failed canopy or failed steering capability airdrops.
- Provide graphical displays of applicable airdrop mission planner data products in forms convenient to the PADS user.
- Generate output files that provide updated mission plan information specific to individual, steerable airdrop systems.
- Include a wireless communication path for PADS input/output applications.
- Generate standard airdrop mission planning forms.

B. The Top-Level PADS Architecture

Figure 1 illustrates the top-level PADS architecture. Initial atmospheric forecast information is obtained from the Air Force Weather Agency via an (File Transfer Protocol) FTP connection over the Internet or Secure Internet Protocol Router (SIPR) net. Other forecast information, such as weather balloon data or pilot reports from aircraft in theater, can be received via satellite using a CTII receiver installed on the aircraft. Through the PADS-CTII interface a remote air or ground station can upload weather data files to PADS. Data regarding winds from Global Positioning System (GPS)-enabled dropsondes can also be acquired en-route to the DZ in real time via a UHF link to PADS through a PADS Interface Package (PIP) connection to an aircraft antenna (with the sonde data processed into a form usable by PADS within the PIP). Note that the sondes may be released from the carrier aircraft or by other vehicles (e.g., unmanned vehicles) in the vicinity of the DZ. In addition, a manually entered one-dimensional wind profile or a simple ballistic wind input can be used, alone or in conjunction with other weather data sources available to PADS.

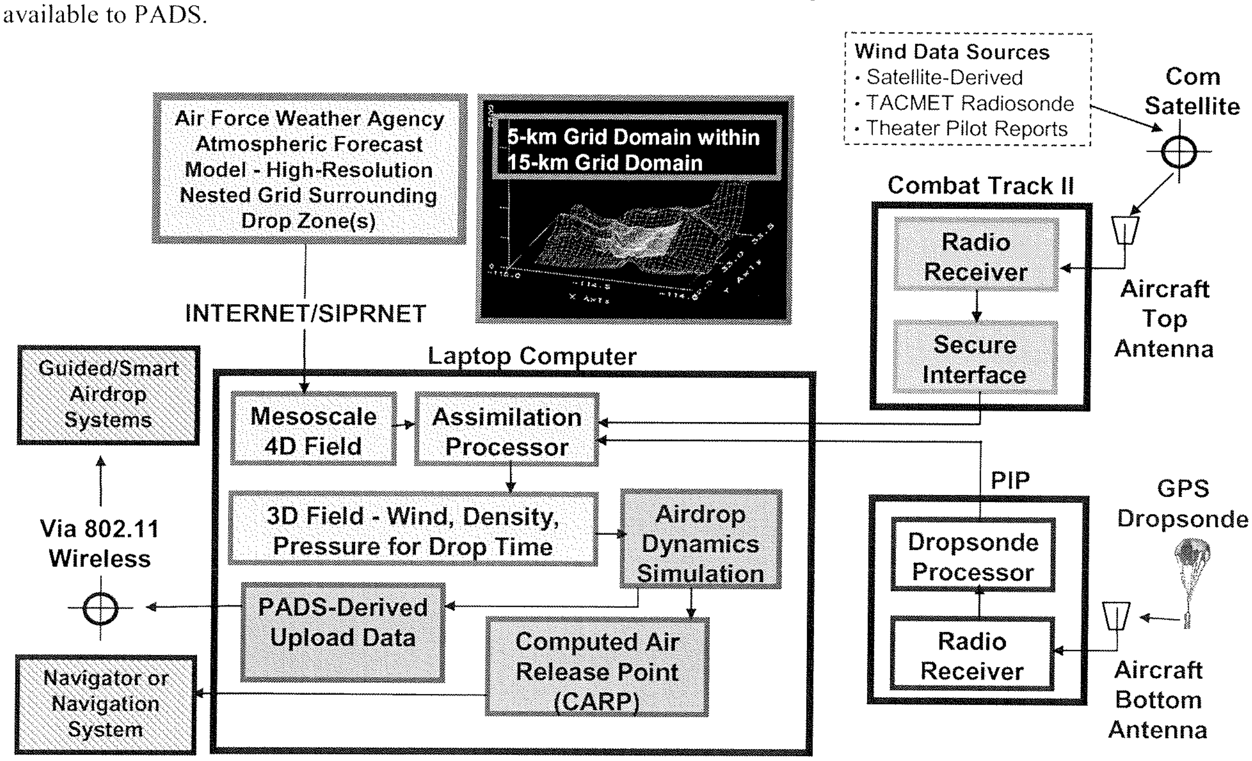

Figure 1. The top-level PADS architecture.

On the PADS laptop, all weather data sources are blended by an assimilation program known as WindPADS that produces a single wind file containing wind speed, density, and pressure profiles for the region of interest. An airdrop dynamics simulation within the PADS mission planner takes the wind file produced, combined with user entered drop information. Using all that data, PAPS determines the ideal CARP for each release pass, derives nominal trajectories for all payloads to be released on each pass, and generates mission update files that can be uploaded to steerable airdrop systems. The mission update files are customized to the specific steerable system, in most cases containing (among other data) simplified wind information. The mission update files can be uploaded using an 802.11 wireless Ethernet connection to any steerable systems being dropped.

C. Current PADS Features

PADS evolved to include many design features to address the objectives identified in Section IIA. The PADS functionality is managed by the user through GUIs, starting with the top-level GUI shown in Figure 2. The buttons in the left column allow selection of the various data entry or data generation processes of PADS, with the tabs on top providing access to varied data and message status pages. The aircraft button currently allows selection of either a C-130 or C-17 carrier aircraft, enabling account for the two different aircraft cargo hold configurations and payload release conditions/dynamics. The Drop Zone button brings up a GUI that allows entry of the DZ location, altitude, and planned approach path, including an option to select the DZ by clicking on a GMI display. The Drop Parameters button brings up a GUI to enter planned release altitude, airspeed, and date/time, each in a variety of user designated reference frames. The expected release date/time is included to enable the weather assimilation program to output a wind and density projection near the DZ applicable at the planned time of release (since the WindPADS program can account for spatial and time variations in expected atmospheric conditions). Note that on the Drop Parameter GUI the user has the option of manually inserting a desired release point rather than accepting a PADS-derived CARP, including an option to select the release point by clicking a location on a GMI display.

Figure 3 illustrates the GUI that comes up upon selection of the Load & Chute button on the top-level PADS GUI. The right part of the GUI illustrates the applicable carrier aircraft cargo bay and its longitudinal coordinates. Each payload data set entered through this GUI is shown in its applicable cargo bay location. The left data column allows entry of the number of planned release passes, the release path (aft ramp or side door), and the number of loads to be released on a given pass (with multiple loads release on one pass called a stick). For ballistic parachutes there is an option to select which payload in a stick to target for the single CARP derived for a ballistic parachute stick. The right data entry column provides means to designate the cargo hold location, mass, and type of each payload. For steerable payloads, unique Points of Impact (PIs) can be designated for each payload with an option to click on a GMI display to select those PIs. Currently, PADS handles G-12 and 26-foot ring ballistic parachutes, Sherpa, Screamer, AGAS, Dragonfly, and a variety of personnel steerable airdrop systems. Various payload capacity classes (with differing canopies) are accommodated for some of the already included steerable airdrop systems. In addition, PADS now supports planning for the TRIADS that is used to drop Meals Ready to Eat. Also, a new feature is being readied for release to enable PADS to handle generic, multi-stage ballistic parachute airdrop systems.

Upon selection of the Weather button in the GUI shown in Figure 2, the WindPADS software is accessed to enable collection and assimilation of data from any of the available sources noted in Section IIB. Selection of the Compute button generates CARP data and applicable uploadable mission files. The CARP data may be seen by selecting the CARP Solution tab on the GUI shown in Figure 2. Note that under the Compute button is a check box to activate the feature to compute expected airdrop delivery footprints. There are additional GUI pages to enable set up of a Monte Carlo tool that is used for footprint generation. This tool allows specification of nominal and statistical variation data for a number of parameters that affect footprint determination and are applied when the footprint computation is performed.

Figure 4 provides an example of some PADS-derived footprints for a stick ballistic parachute airdrop displayed on a GMI. FalconView is used by PADS for GMI displays that can be presented over images or maps, showing PADS mission planning data with respect to terrain features, political boundaries, threat locations, etc. The green ellipses in Figure 4 represent the nominal airdrop uncertainty footprints for each payload in the stick, with the green box bounding the footprints for the entire stick. The magenta ellipses and box delineate the dispersion footprints for payloads that have canopy deployment failures. Figure 5 provides an example PADS graphical display of feasible release envelopes for steerable airdrop systems and possible dispersion footprints for failed steering for a three-payload stick. Note that with this type of display, PADS enables identification of a Launch Acceptability Region from which all steerable payloads in the stick can be released and still reach each of their separate, desired landing targets. The steering failure footprints help to locate where the payloads may land if they deploy properly, but lose control of the steering at any time during their descent.

As indicated in Figure 1, an important feature of PADS is an 802.11 wireless interface. When PADS generates CARPs for steerable airdrop systems, it also generates updated mission plan files to be used by either the GN&C software on cargo delivery systems or by helmet-mounted navigation-aiding displays that are part of personnel airdrop systems. These mission plan update files are customized to the unique needs of each steerable airdrop system class, generally at least including information that enables account for updated weather information, possibly also including updated DZ target information. The wireless link is used to upload these data files to the cargo delivery systems or personnel helmets shortly before release based on the latest mission plan update information. Status of the steerable airdrop systems can also be sent back to PADS through the 802.11 wireless data link.

Some additional PADS features are for user convenience. These include means to provide a vertical descent profile plot for designated airdrop systems using visualization tools from the Portable Flight Planning System (PFPS). Also included in PADS is means to generate standard Air Force CARP planning forms based on PADS-derived information.

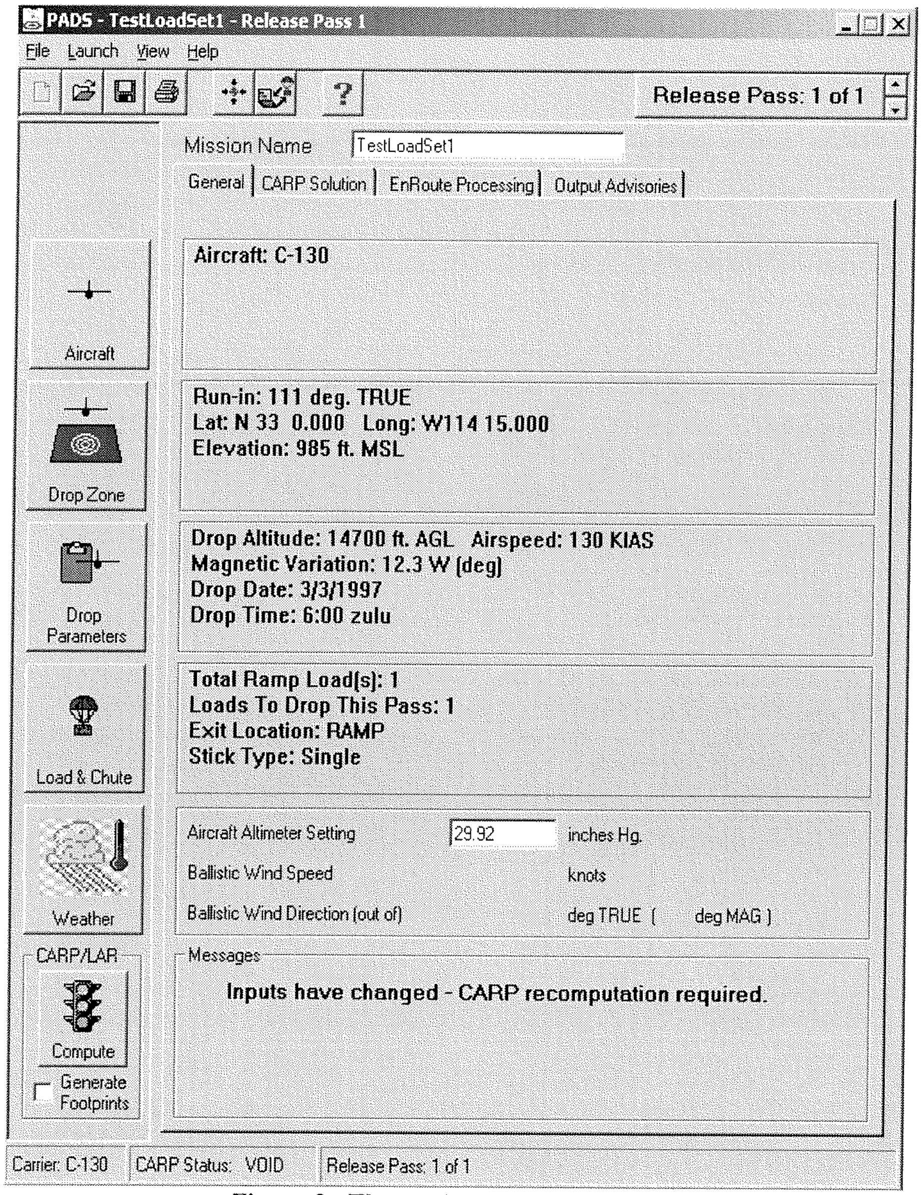

Figure 2. The top-level PADS GUI.

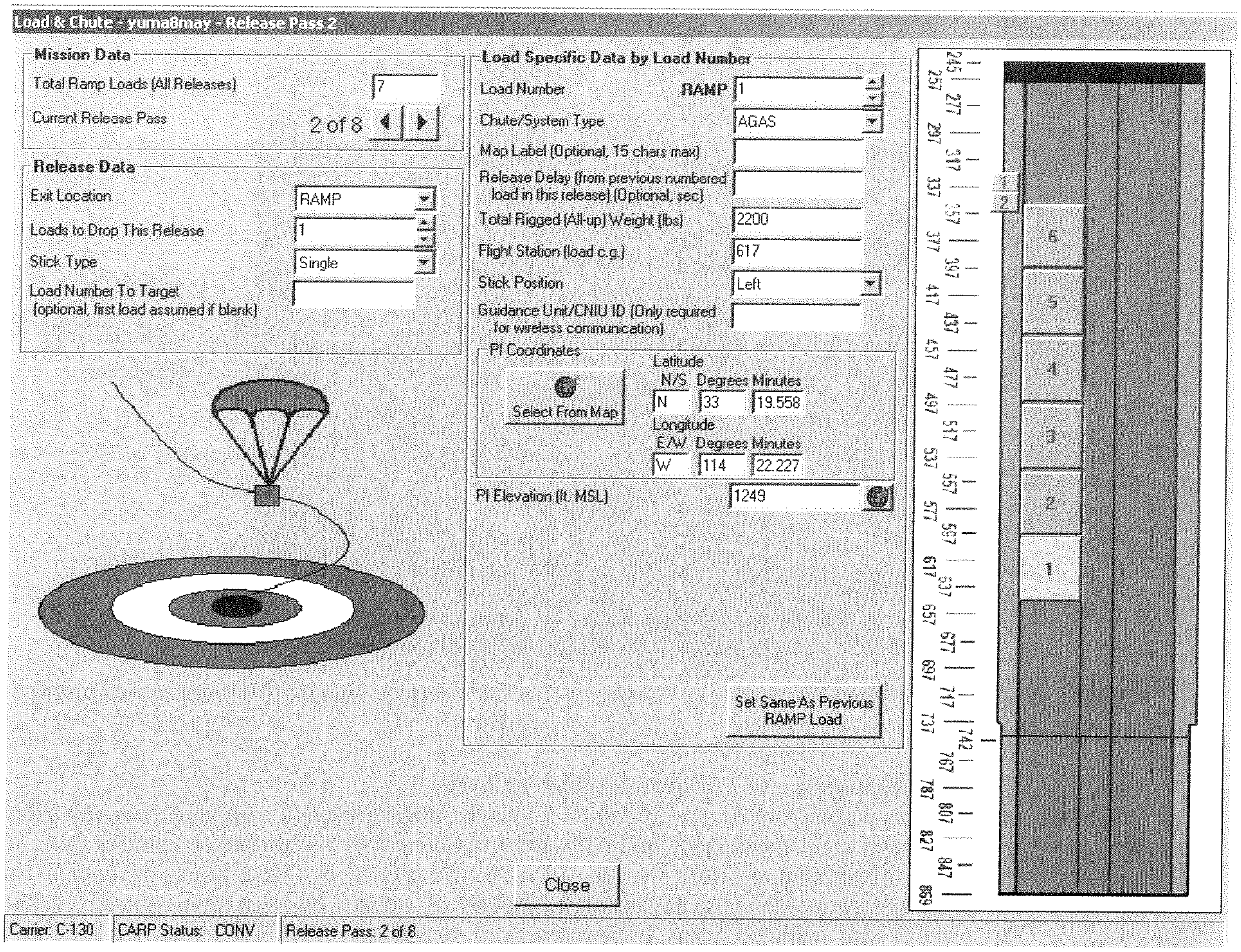

Figure 3. The Load & Chute GUI.

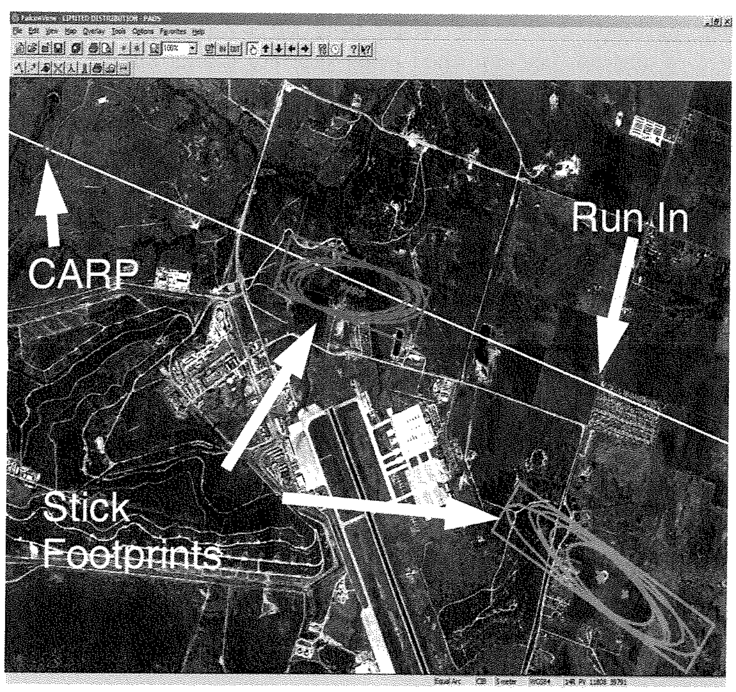

Figure 4. Example Monte-Carlo-Derived ballistic parachute uncertainty footprints.

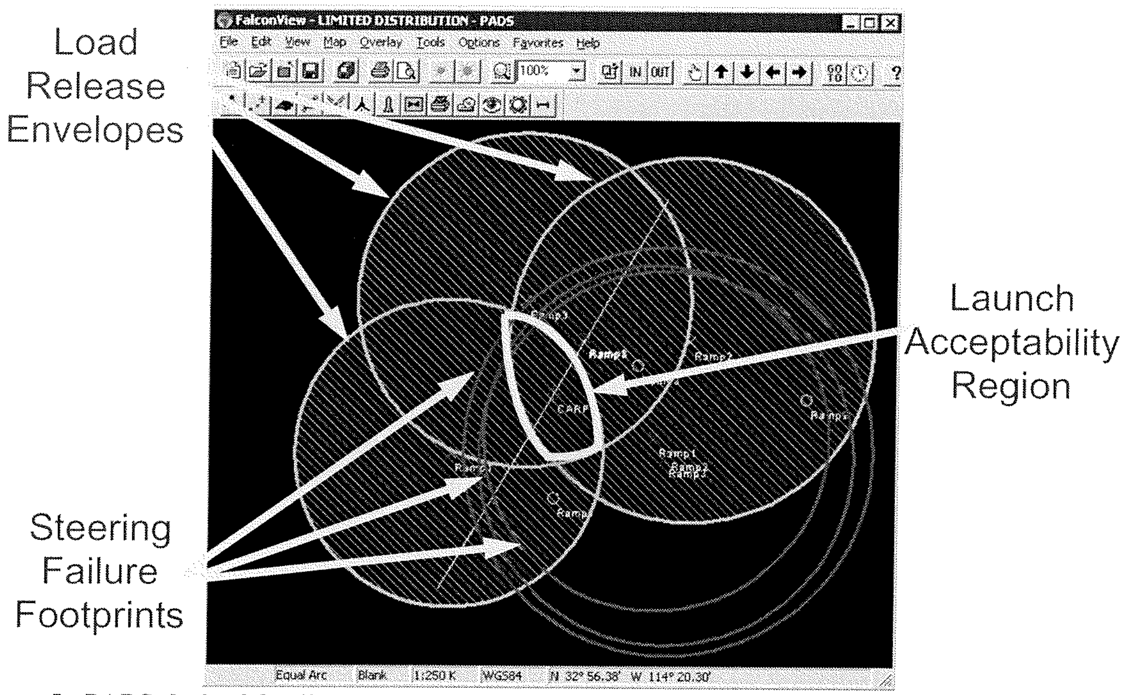

Figure 5. PADS-derived feasible release envelopes and failed steering footprints for steerable airdrop systems.

D. Some Demonstrated Performance Using PADS

PADS underwent an OUE for each of the C-130 and C-17 carrier aircraft classes involving 26 ft RS ballistic parachute deployments. These flight evaluations of PADS were performed by representative operational carrier aircraft crews given one day of training regarding the use of PADS. Each OUE involved dozens of drops of four-payload sticks of 26 ft RS parachutes carrying payloads of a variety of weights between approximately 1,000 to 2,000 pounds. The airdrops also included a mix of releases from 18,000 and 25,000 ft for all payload weight classes. The airdrops were accomplished in a series of carrier aircraft missions performed over a couple of weeks for each aircraft class, enabling the airdrops to occur under a variety of atmospheric wind and density variation conditions. All delivered payloads during the OUEs were GPS-surveyed at the point of impact. A direct comparison was performed of airdrops accomplished using standard carrier aircraft procedures (without help from PADS), and airdrops accomplished using PADS assistance. Furthermore, comparison was also made of the expected payload delivery accuracy performance based on standard release procedures, but assuming that the carrier aircraft mission computer had wind profile information generated by PADS to determine its own CARP rather than a PADS-derived CARP. Figure 6 provides the Circular Error Average (CEA) results from the OUEs. These results provide clear evidence that there is significant improvement in PADS-planned airdrops as compared to drops using standard carrier aircraft procedures without PADS. These improvements are due both to the improved atmospheric modeling in the vicinity of the DZ enabled by the WindPADS part of PADS and the detailed airdrop dynamics modeling accomplished in the PAPS part of PADS.

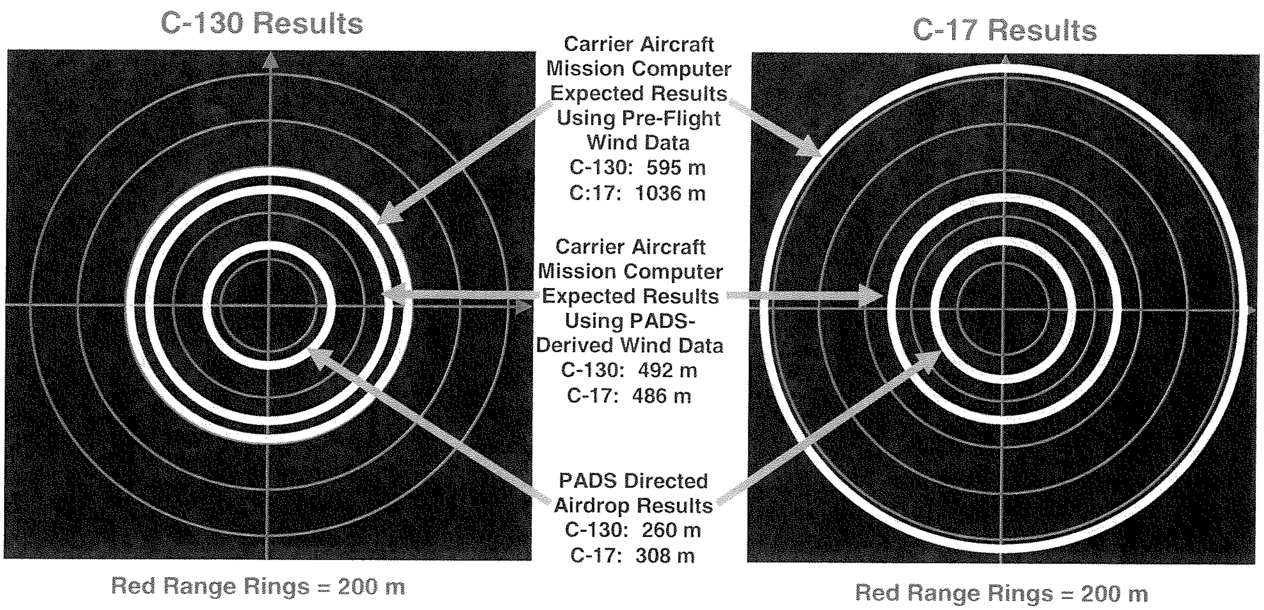

Figure 6. C-130 and C-17 OUE ballistic parachute airdrop CEA results with and without PADS

III. The Current Steerable Airdrop GN&C Implementation

An open-architecture version of the JPADS GN&C software has been developed and has completed initial flight testing on the *Dragonfly* 10,000 lb-class parafoil. This GN&C software is now being generalized to enable its subsequent use on a 30,000 lb-class parafoil being developed under the JPADS program. In the following subsections, the objectives for this GN&C development program are addressed, the GN&C software architecture and design features are reviewed, and flight test experience using the GN&C software is summarized.

A. GN&C Implementation Objectives

The primary system objectives are to land precisely at the target coordinates and survive impact. Therefore, in addition to minimizing miss distance, the horizontal and vertical components of ground-relative velocity must also be minimized. In the absence of a preferred orientation at impact, this will normally imply the ability to make the terminal approach and landing into the wind. Alternatively, the system must be able to achieve a different (commanded) terminal heading (e.g., to land within a narrow corridor or on the edge of a cliff).

The need for robustness in the guidance and control of the large parafoil is paramount. Significant dynamic modeling uncertainty and system response lags due to the inertia in the large canopy and control line motors call for careful, robust control law design. Moreover, the onboard wind model is often based on measurements or forecasts that are old or are not based on data directly from the intended DZ, and it is necessary both to estimate winds in real time and guide robustly in the presence of uncorrected wind estimation errors. The system must also be able to reach the target under a wide variety of possible initial conditions (position, altitude, and orientation) after release from the aircraft and full deployment of the canopy.

Finally, the GN&C software must be capable of executing in real time on an inexpensive flight processor.

B. GN&C Design Architecture and Features

The top-level GN&C architecture developed for the JPADS program is shown in Figure 7. Parafoil GN&C sensors and actuators are shown in green and flight software is shown in blue. The user interacts with the flight software by using PADS to create and download a mission file; with this part of the architecture is shown in yellow.

Notice that the mission file includes coordinates of the desired impact point, as well as the planned CARP used to initialize navigation before the GPS receiver obtains a valid satellite-data-derived solution. The mission file also contains a table of predicted north and east components of wind velocity vs. altitude. The layers in this *a priori* wind table need not be uniformly spaced; indeed, the PADS software selects wind table altitudes to obtain a good piecewise-linear representation of wind velocity vs. altitude, in order to minimize interpolation error. The user may also use PADS to specify intermediate waypoints.

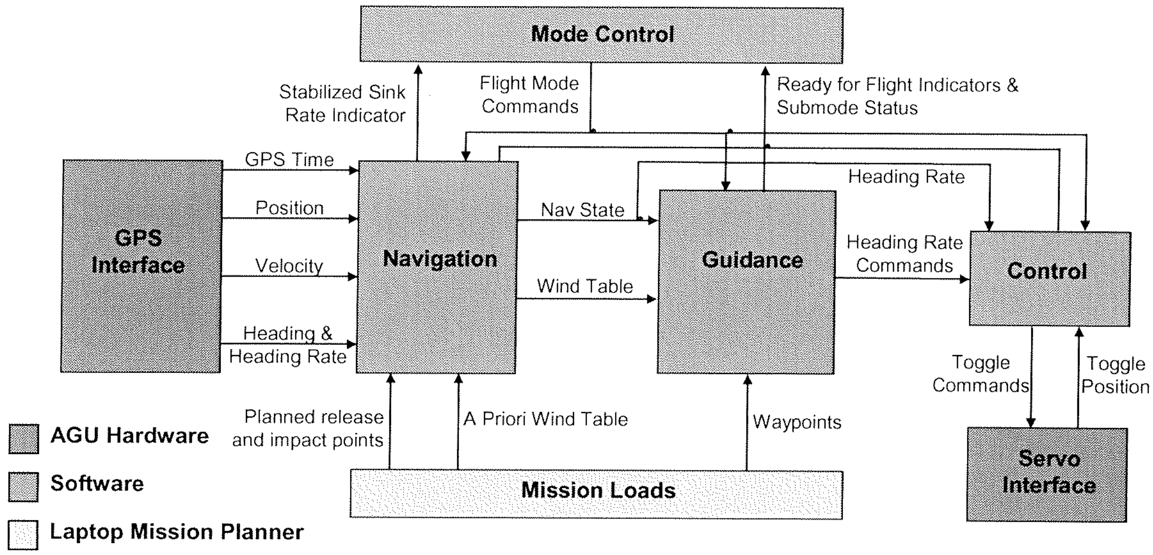

Figure 7. The top-level parafoil GN&C architecture.

JPADS Navigation provides target-relative position, heading, and wind data to Guidance, and heading rate to Control. To accomplish this, the Airborne Guidance Unit (AGU) hardware must provide sensors to measure position, velocity with respect to the ground, heading, and heading rate. The AGU for the *Dragonfly* system used for the initial GN&C flight tests includes the CSI Wireless *Vector* dual-GPS receiver to provide these measurements. With appropriate modifications to Navigation, the required data can also be synthesized using a single-antenna GPS receiver to measure position and velocity with respect to the ground, and yaw-axis rate gyro to measure heading rate. These modifications, which use a Kalman filter to process the sensor data, will be tested on a 30,000 lb-class parafoil which is currently in development for the JPADS program (with a 10,000 pound-class subscale version already undergoing flight test). The ability to navigate using a single-antenna GPS receiver is important, since no cost-effective militarized dual-antenna GPS receiver is presently available.

JPADS Guidance accepts target-relative position, heading, and corrected wind data from Navigation, and sends heading rate commands to Control. Figure 8 depicts the guidance strategy, which is organized by modes corresponding to the different flight phases. Primary GN&C modes are *init, preflight, trimflight, autoflight*, and *flare*. *Init* mode is for system initialization; it begins at power-up, and ends when GPS has been acquired and is healthy, inside the carrier aircraft. (Note that a GPS signal repeater in the carrier aircraft cargo bay may be used to assure GPS reception by the AGU's GPS receiver while still inside the aircraft.) In *preflight* mode the system is attempting to navigate while waiting for exit from the carrier aircraft. This mode ends after exit from the carrier aircraft, when the GPS-derived vertical velocity has stabilized indicating successful deployment of the main canopy. *Trim* mode affords Control a brief opportunity to correct for any initial bias in turning rate. This is followed by *autoflight* mode, which makes up most of the flight, and then *flare* mode just prior to landing.

Autoflight mode consists of three flight phases. Far from the target, Guidance generates *homing* commands; the system turns as needed and flies toward the target. When distance from the target is less than a commandable threshold, Guidance generates *energy management* commands; the purpose is to lose altitude while not straying too far from the target. The JPADS implementation of *energy management* involves flying in a figure-eight pattern oriented transverse to the desired landing direction, which PADS will normally select as into the wind in order to reduce speed at impact. Within this orientation, the large turns needed to fly the pattern are executed in the *upwind* direction – this is called *tacking*. When altitude above the ground is low enough to execute the final approach maneuver, Guidance selects its steering commands using a pre-computed *lookup table* which is stored in inexpensive flash memory. Lookup table turning commands are indexed by altitude, alongtrack and crosstrack position (with respect to the desired landing direction) and heading. This pre-mission-computed table essentially encodes a family of trajectories, one for each choice of initial position and heading. Each of these trajectories either hits the target or, if that is not possible from the given initial state, minimizes a function of position and heading error at impact.

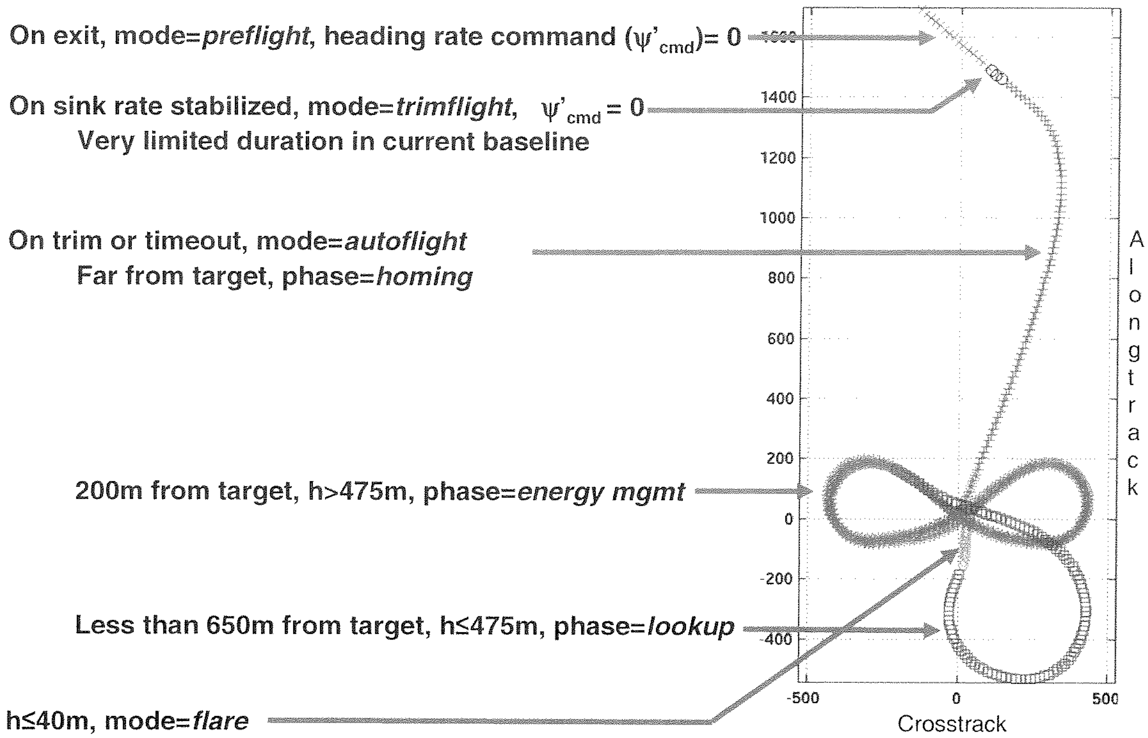

Figure 8. Guidance modes and phases.

Figure 9 shows the JPADS Control architecture. The foundation of the design is a Proportional, Integral, and Derivative (PID) controller whose purpose is to make the navigated heading rate match the commanded heading rate from Guidance. The basic PID design is augmented with configurable low-pass filtering on the heading rate error, and a *heading acceleration estimator* (from a steady state Kalman filter) is used to estimate the heading rate derivative needed by the PID design. The Controller output is clipped so as not to exceed the control toggle position limits. Finally, a configurable dead band with hysteresis is used to reduce servo motor duty cycles.

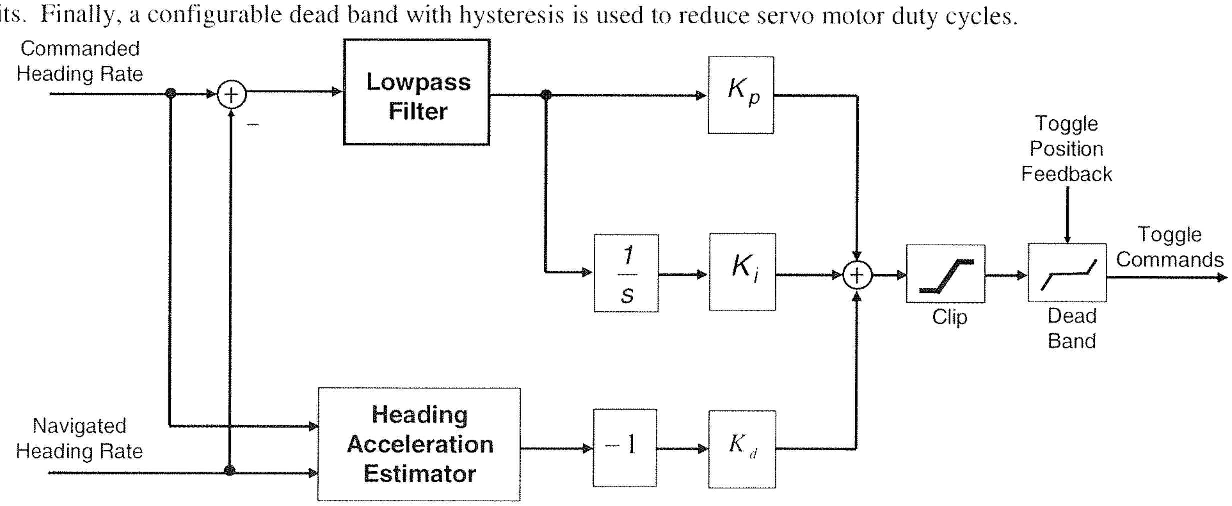

Figure 9. The Control architecture.

C. GN&C Flight Test Experience

Flight testing of the *Dragonfly* 10,000 lb-class parafoil began in March of 2004 at Red Lake in Kingman, Arizona. Focus of the initial tests was on canopy rigging methods, deployment, and identification of aerodynamic characteristics. For the initial flight tests, the parafoil was flown manually, by remote control.

The first autonomous flight using an early version of JPADS GN&C occurred in May, 2004. Testing continued at intervals of approximately six weeks during development of the JPADS GN&C. Since October 2004, all tests have been conducted at the Corral Drop Zone at the Yuma Proving Ground (YPG). Initial testing of the *Dragonfly* implementation culminated in the PATCAD demonstration flights held in October of 2005. Between March, 2004, and October, 2005, there were twelve scheduled test weeks with an average of 4 drops per test week. During this time, the GN&C software was matured as the *Dragonfly* canopy, rigging, and guidance hardware continued to evolve. A major upgrade to the AGU involving new servo motors and gearboxes was accomplished in the spring of 2005.

The following description, extracted from the flight test report prepared by Draper Laboratory after PATCAD 2005, gives an idea of *Dragonfly* performance as realized at PATCAD when preliminary development was complete:

Drop of the system with ... rigged weight of approximately 8,750 lbs occurred at 8:07 AM local time ...almost directly over the target, 1662 feet north-northwest of the planned PI of N 33° 22.708' W 114° 16.566', WGS-84. GPS-sensed altitude at t = 0s, the start of onboard data logging (commencing at lanyard pull), was 9,288 feet. GPS data was valid throughout the entire flight, excepting the normal outage during exit from the aircraft. Autonomous guidance commenced, as expected, at t = 45s, at which point the system executed a left turn and homed toward the target. Transition to energy management mode occurred at t = 92s, and the system successfully executed S-turns upwind of the target. Lookup mode began at t = 253s, as the system began a long maneuver counter-clockwise around the target from NE to SW. Flare occurred at t = 335s, and the system impacted at N 33° 22.588 W 114° 16.580; 212 meters short of the target.

The groundtrack for this flight is shown in Figure 10. The different guidance modes and phases described earlier are shown in this figure, which is constructed from recorded flight data. Note that as indicated in Table 1 (which summarizes *Dragonfly* flight test results from between March, 2004, and October, 2005) the other three *Dragonfly* airdrops during the 2005 PATCAD had substantially smaller miss distances than the one illustrated in Figure 10.

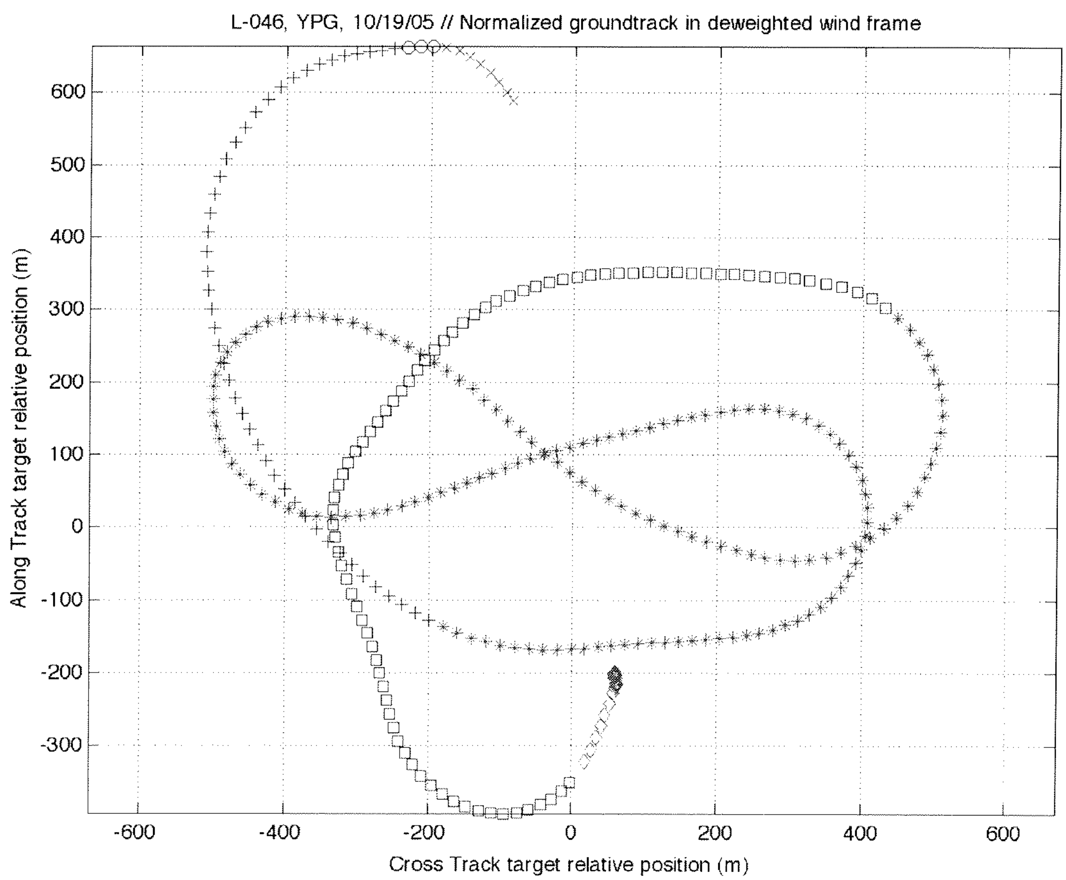

Figure 10. Ground track of October 2005 Dragonfly test flight L-046

Table 1. Summary of *Dragonfly* Flight Test Results

Date	Carrier Aircraft	Drop Speed (KIAS)	Release Altitude (ft MSL)	Gross Weight (lb)	Miss Distance (m)	Comments
3/1/04	C-123K	110	8707	8,000	n/a	Good flight characterization data
3/2/04	C-123K	110	9461	8,000	n/a	Good flight characterization data
3/3/04	C-123K	110	8566	8,000	n/a	Malfunction of Main Canopy During Opening, No flight characterization data
3/4/04	C-123K	110	8841	8,000	n/a	Good flight characterization data
3/5/04	C-123K	110	8841	8,000	n/a	Good flight characterization data, hard landing but no damage
4/19/04	C-123K	110	11780	8,000	n/a	No flight characterization data
4/20/04	C-123K	110	12027	8,000	n/a	Unreliable flight characterization data due to D-brake cutter failure
4/21/04	C-123K	110	11971	8,000	n/a	Good flight characterization data
4/23/04	C-123K	110	12K	8,000	n/a	Malfunction of Main Canopy During Opening, No flight characterization data
5/17/04	C-123K	110	12K	8,000	n/a	Good Opening but middle right D-brake cutter failed to fire, still controllable, uneventful landing, no useful data
5/18/04	C-123K	110	12K	8,000	n/a	D-brake cutter failed to fire; GN&C flew away, R/C take over to land on DZ. Soft Landing
5/19/04	C-123K	110	12K	8,000	n/a	Malfunction on main parafoil deployment due to overloading of the D-brake risers
5/20/04	C-123K	110	12K	8,000	~400	Excellent deployment and auto flight. Very good landing
5/21/04	C-123K	110	12K	8,000	~1000	Excellent deployment and auto flight. Very good landing
8/9/04	C-123K	110	12K	8,000	366	Main Canopy D-bag and Flight Termination System (FTS)* bridle interfere during opening, result in 1 broken suspension line and minor canopy damage. Flight software problems detected and subsequently fixed. Good Landing
8/10/04	C-123K	110	12236	8,000	488	Landing soft and controlled; GN&C data recording failed.
8/11/04	C-123K	110	12368	8,000	480	Slow inflation, landing soft and controlled. Guidance table never used due to avionics failure
8/12/04	C-123K	110	12314	8,000	183	Guidance table mode disabled; very soft landing
8/13/04	C-123K	110	12 K	8,000	n/a	Slider hang-up prevented autonomous flight
10/26/04	C-130A	130	~10K	8,000	> 3 km	Motor cables disconnected preventing system control. Activated FTS*. Evidence of systemic software problems post flight
10/28/04	C-130A	130	~10K	10,000	~ 670	30" retraction did not take place; ground crew took over landing. Left gearbox failed at 250 sec. Evidence of systemic software problems
12/6/04	C-130A	130	~10k	10,000	n/a	Bad drogue deployment. Main Deployed at ~25 psf; total malfunction, no control. GN&C continued to function.
12/6/04	C-130A	130	~10k	10,000	n/a	Canopy failed to open due to packing error, long free fall, then canopy blew. No control. GN&C continued to function.
12/8/04	C-130A	130	~10k	8,000	~1400m	Extended drogue descent, good main opening, auto system steered away from planned PI at landing. Bad GPS heading rate.
12/8/04	C-130A	130	~10k	8,000	142	1021 AVN has (old design) 16 MB flash; all others this week have 8 MB. Extended drogue descent, good canopy opening, good EMC and final approach, flare
12/10/04	C-130A	130	~10k	8,000	n/a	Extended drogue, good canopy opening. Lost GPS during drogue transfer, switched to radio control, uneventful landing on DZ
12/10/04	C-130A	130	~10k	10,000	170	Extended drogue, good canopy opening, auto, high offset, navigation to target, good final and flare
2/2/05	C130H2 (AF)	130	13,314	8,000	255	First flight from USAF a/c. New motor controllers had incorrect gain settings, invalidating auto flight results.
2/2/05	C130H2 (AF)	130	14,167	8,000	n/a	Tension knots prevented proper canopy opening
3/7/05	C130H3	130	14,230	10,000	914	Motors did not deliver stroke requested by GN&C
3/7/05	C130H3	130	14,000	10,000	n/a	Main never opened due to cutter failure
3/8/05	C130H3	130	16,500	10,000	914	Right side of parafoil destroyed during deployment
3/8/05	C130H3	130	16,450	10,000	n/a	Drogue transfer failure - system descended at ~ 120 fps
3/10/05	C130H3	130	14,500	10,000	6056	Overheated actuator motor controller due to higher than anticipated control line loads, motor controller reduced power to protect itself resulting in loss of control
4/18/05	C-130H3	130	16,500	10,000	n/a	Main never opened due to bridal failure, complete loss of AGU 007 and canopy
4/20/05	C-130H3	140 (GS)	14,300	10,000	375	Sweet, AGU-W2 finally proves itself worthy! Oscillation issues, 68.5:1 Gear Ratio
4/20/05	C-130H3	150 (GS)	14,300	10,000	429	Oscillation issues, 68.5:1 gear ratio
4/20/05	C-130H3	136 (GS)	14,400	10,000	309	Oscillation issues, 54:1 gear ratio - not as much control stroke as I-036&37, but adequate to land on DZ
6/20/05	C-130A	n/a	15000	10,000	n/a	Major canopy damage. All flights from here after have S28-400 motors in AGU.
6/20/05	C-130A	186 (GS)	15300	10,000	333	Full Auto Flight, 68.5:1, good flare
6/21/05	C-130A	n/a	15000	10,000	n/a	Intermittent 12V AGU power resulted in no control - traced to damaged/defective circuit breaker
6/21/05	C-130A	185 (GS)	15300	10,000	230	Adjusted control gains in flight, performed RC maneuver to observe system response, 54:1, good flare
6/23/05	C-130A	186 (GS)	15140	10,000	286	Adjusted control gains in flight, 68.5:1, good flare
6/23/05	C-130A	174 (GS)	15050	10,000	23	Adjusted control gains in flight, 68.5:1, good flare
9/16/05	C-130A	130-140	14770	10,250	582	Single 48' drogue, larger slider, auto switching of control gains based on altitude. Put out at huge offset, barely enough time to get back close to DZ, enlarged slider
10/19/05	USAF C-130	130-140	10270	8750	211	Full Auto Flight, 68.5:1, good flare
10/19/05	USAF C-130	130-140	10208	8700	99	Broken A line, canopy 009, full Auto Flight, 54:1, good flare
10/20/05	USAF C-130	130-140	10340	8700	85	Full Auto Flight, 68.5:1, good flare
10/20/05	USAF C-130	130-140	10386	9300	152	Full Auto Flight, 54:1, good flare

* Note that the FTS is a small round drag chute that can be deployed by radio command to force the parafoil to continuously turn, thereby avoiding an uncontrolled gliding flight of the airdrop system to a ground impact location off the flight test range

IV. On-Going/Planned PADS and JPADS GN&C Capability Extensions

Both the PADS and JPADS development programs are on-going and currently very active. A variety of significant PADS capability and software architecture improvements are in work or planned. As for the JPADS GN&C software, a number of features to accommodate new avionics and to improve its robustness are being investigated even while the software is being generalized for the 30,000 lb-class airdrop system application. Some of the major PADS upgrades and JPADS GN&C improvements currently in work or under consideration are summarized in the following subsections.

A. Planned and Possible Future PADS Upgrades

With some PADS units already delivered and being applied to initial field use, lists of candidate user improvements and capability extensions for PADS are being maintained. User feedback provides the basis for a list of candidate user improvements that are prioritized and then implemented as PADS sustaining software support from the government permits. Self-installing PADS updates will be released to the user community on CDs approximately twice a year with the latest user improvements. PADS capability extensions are pursued whenever a sponsor steps forward with resources to support development of the desired new features. The following are some PADS capability extensions currently being considered for funding:

- Wireless initiation of an internally sequenced, automatic gate cutter system to provide appropriately timed and predictable load separation/de-confliction (already in work).
- Automatic import into PADS of the PFPS DZ database for PADS user application (already in work).
- Addition of mission planning support for the ATAIR Onyx and other guided airdrop systems.
- Graphical display of generated wind field data.
- Utilization of lidar-derived wind profile data collected using equipment on-board carrier aircraft for CARP determination and for steerable airdrop system mission file updates.
- Integration of PADS into the Joint Mission Planning System (a long-term capability goal).

B. Planned and Possible Future GN&C Improvements

The JPADS GN&C software development by Draper is a work in progress. Extensive testing has already been accomplished on the 10,000 pound-class *Dragonfly* parafoil and subscale versions of a 30,000 pound-class parafoil. Generalization of the GN&C software design for varied airdrop system size classes and testing of the software on existing 2,000 pound-class and new 30,000 pound-class parafoils will begin in the fall of 2006. Even as the GN&C software is made generically capable of handling a wide range of steerable airdrop systems, the following additional improvements are being addressed:

- Accommodation of new militarized, lower cost avionics. This will include a single-antenna militarized GPS receiver for position and linear velocity determination and some inertial sensors for airdrop system orientation and angular rate measurement. The upgrade will also include improved processing and flash memory capabilities (based on the evolution of low cost processor and memory chips since the original AGU baseline design). The added flash memory will enable extension of the guidance lookup table to make specific account for airdrop system response lag effects.
- Control system features to constrain actuator duty cycles for 30,000 pound-class airdrop systems (which is needed due to expected current draw and heating limitations on the control line actuation motors when applied to very heavy payload airdrop systems).
- Software design robustness to a wider variety of initial conditions. This is necessary since some significant, non-linear airdrop system dynamics properties make the GN&C response sensitive to initial conditions.
- Application of an on-board, real-time wind sensor to improve the guidance performance.
- Use of a precision height-to-ground sensor to improve landing flare timing and the resulting payload delivery accuracy.

V. Conclusions

Both a PC-based airdrop mission planning capability for ballistic parachutes and steerable airdrop system, and GN&C software for the steerable systems has been developed to facilitate precision airdrop payload delivery following high altitude release.

The PADS airdrop mission planner provides capabilities on-board carrier aircraft for CARP determination for ballistic parachutes and steerable airdrop systems as well as means to generate and wirelessly transmit mission file updates to steerable airdrop systems. In support of the CARP generation, PADS provides means to generate models of spatial and time-dependent atmospheric conditions near the DZ based on assimilation of pre-flight forecast data with any of a variety of updated data sources that can be obtained in transit to the DZ. These PADS capabilities have now been successfully demonstrated for a variety of ballistic parachute cargo airdrop systems as well as cargo and personnel steerable airdrop systems. OUEs from C-130 and C-17 aircraft have proven the ballistic airdrop mission planning capability to provide very significant improvement in payload delivery precision from high altitude when compared to prior baseline airdrop methods from C-130 and C-17 airdrops. PADS is now in initial field use, and is also undergoing capability extension, with updates of new capabilities to be released about twice per year.

An open-architecture GN&C system for use on steerable airdrop systems has been demonstrated on the *Dragonfly* 10,000 pound-class parafoil. The GN&C software currently enables delivery accuracy for *Dragonfly* averaging better than 200 meters. This GN&C system is now being generalized for use on a wide range of steerable airdrop systems, with demonstration on 2,000 pound-class systems and 30,000 pound-class systems to be accomplished in fall 2006. Flight demonstrations to date have relied on a two-antenna GPS receiver that provided position, velocity, and heading information for navigation. Guidance operates with a variety of modes and phases during flight that includes a table look-up final approach. Control is PID-based, but also includes dead zone and hysteresis features to limit control actuator duty cycles. Prior to planned fall 2006 flight testing, the GN&C software will be updated to accommodate a new set of avionics that uses a single-antenna GPS receiver and some inertial sensors to enable reduced avionics cost and militarization of the avionics hardware. The navigation software will be updated to accommodate the new avionics while generating at least as good a navigation state accuracy as with the already demonstrated configuration. Work also continues to make the guidance and control algorithms more robust, to improve the expected airdrop system delivery accuracy, and to further reduce control actuation duty cycles.

Acknowledgments

The PADS system has been the product of a successful collaborative development effort by the Draper Laboratory and PSI. The *Dragonfly* system on which the GN&C algorithms have been flight tested was developed by Para-Flite (for the canopy and rigging), Wamore (for the AGU), and RoboTek (for the current AGU avionics).

The authors gratefully acknowledge the funding support of Joint Forces Command JPADS Advanced Concept Technology Demonstration, the Office of the Secretary of Defense, the US Army 30K Army Technology Objective, as well as the US Air Force Air Mobility and Transportation Commands. We would also like to thank the large team of professional system testers at the US Army Yuma Proving Ground as well as Jim Blumenthal and his team at Kingman, Arizona who helped bring the JPADS – Mission Planner system to the point of initial field use.

The material in this paper is based upon work supported by the US Army Natick Soldier Center under contract Nos. W9124R-04-C-0154, -0144, -0118, and W9124R-06-C-0110. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Natick Soldier Center.

References

[1]Hattis, P., Fill, T., Rubenstein, D., Wright, R., and Benney, R., "An Advanced On-Board Airdrop Planner to Facilitate Precision Payload Delivery," presented at the AIAA Guidance, Navigation, and Control Conference, CP 2000-4307, Denver, Colorado, August 14-17, 2000.

[2]Hattis, P., Fill, T., Rubenstein, D., Wright, R., Benney, R., and LeMoine, D., "Status of an On-Board PC-Based Airdrop Planner Demonstration," presented at the AIAA Aerodynamic Decelerator Systems Conference, CP 2001-2066, Boston Massachusetts, May 22-24, 2001.

[3]Hattis, P., Angermueller, K., Fill, T., Wright, R., Benney, R., and LeMoine, D., "An In-Flight Precision Airdrop Planning System," presented at the 23rd Army Science Conference, Orlando, Florida, December 2-5, 2002.

[4]Hattis, P., Angermueller, K., Fill, T., Wright, R., Benney, R., LeMoine, D., and King, D., "In-Flight Precision Airdrop Planner Follow-On Development Program," presented at the AIAA Aerodynamic Decelerator Systems Conference, CP 2003-2141, Monterey, California, May 19-22, 2003.

[5]Campbell, D, Fill, T., Hattis, P., and Tavan, S.., "An On-Board Mission Planning System to Facilitate Precision Airdrop," presented at the Infotech@Aerospace Conference, CP-2005-7071, Arlington, Virginia, September 26-29, 2005.

[6]Wright, R., Benney, R., and McHugh, J., "On-Board Atmospheric Modeling System to Support Precision Airdrop," presented at the Infotech@Aerospace Conference, CP-2005-7070, Arlington, Virginia, September 26-29, 2005.

[7]Philip D. Hattis and Richard Benney, "Demonstration of Precision Guided Ram-Air Parafoil Airdrop Using GPS/INS Navigation," presented at the Institute of Navigation's Fifty-Second Annual Meeting, Cambridge, Massachusetts, June 18-20, 1996.

[8]Hattis, P., Appleby, B., Fill, T., and Benney, R., "Precision Guided Airdrop System Flight Test Results," CP 97-1468 presented at the 14th AIAA Aerodynamic Decelerator Systems Conference, CP 97-1468, San Francisco, California, June 3-5, 1997.

[9]Carter, D, George, S., Hattis, P., Singh, L., and Tavan, S., "Autonomous Guidance, Navigation, and Control of Large Parafoils," presented at the AIAA Aerodynamic Decelerator Systems Conference, CP 2005-1643, Munich, Germany, May 23-26, 2005.

[10]George, S., Carter, D., Hattis, P., Singh, L., Berland, J.C., Dunker, S. Markle, B., Lewis, J., Tavan, S., and Barber, J., "The Dragonfly 4,500 kg Class Guided Airdrop System," presented at the Infotech@Aerospace Conference, CP-2005-7095,Arlington, Virginia, September 26-29, 2005.