Flight Testing of a Low-Cost Precision Aerial Delivery System

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The Affordable Guided Airdrop System is essentially an enhancement for a Container Delivery System (CDS) payload that allows the payload to be deployed over a drop zone from high altitude (10,000'+ MSL), while maintaining or even dramatically improving upon the accuracy achievable with low-altitude deployments. The ability of an aircraft to deliver payloads from these high altitudes greatly enhances the survivability of the aircraft when re-supplying units in hostile areas of operation. To achieve accurate payload delivery with the round parachutes used with CDS payloads, we have developed an autonomously guided actuator system that uses knowledge of the wind intensity and direction over the drop zone to guide these low-performance round parachutes to an accurate landing. The effectiveness of this method of aerial re-supply was demonstrated at the Precision Airdrop Technology Conference and Demonstration (PATCAD) 2003 using early prototype Airborne Guidance Units (AGUs). After demonstrating with proof-of-concept prototype AGAS units that riser slips can be used to effectively control the descent of a round parachute system, we set out to design an actuator system that would provide effective control while reducing the weight and complexity of the control unit. We also needed to answer questions about the best method of parachute rigging, what actuation stroke length would provide the best drive performance, expected system response times, what the upper and lower practical payload limits for the system would be, and what factors would have the greatest impact on system accuracy. Instrumented drop tests of the AGAS prototype systems provided data about loads in the parachute risers during actuations, the performance of the parachutes using various actuation stroke lengths, and electrical current-draw requirements of the actuators during operation. The data were analyzed and used to identify the ideal operating characteristics of an AGAS-equipped payload. In a joint effort between Capewell Components and Vertigo Inc., these characteristics were used to refine the design of the guidance system and to develop the design into a mature product. The result of this effort was a lighter, more compact, and more reliable actuator system, and better integration of the subsystems that support AGAS deployments. Five redesigned Airborne Guidance Units (AGUs), two windpacks, and a mission computer were then fabricated. Six separate test missions have been conducted with the new systems, with multiple payloads being deployed on each mission. The payloads were all of similar weight and configuration, were programmed for the same target coordinates, and were deployed on the same pass. This near simultaneous deployment of multiple systems with the same rate of descent and the same target resulted in close formation flying of the systems, and frequent collisions between the systems, but the overall accuracy results were excellent. System development and testing is ongoing, with the

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goal of further improving the AGAS design and integration. Testing has included the use of forecast wind information instead of windpack data for AGAS flight trajectory generation, conflict resolution strategies, and higher altitude deployments of the system. Cumulatively, these test drops have given us enough information about the system to generate statistically meaningful estimates of system reliability and accuracy. This paper summarizes test results with relevant statistics, provides examples of typical flight paths, and discusses strategies for mission planning that will reduce system-to-system contact.

I. Introduction

Two AGAS actuator system concepts suitable for providing control authority for steering round parachutes have been developed by Vertigo, Inc. under two programs, the New World Vista (NWV) program and the Low Cost Actuator Technology program. These actuator systems are positioned in-line between the parachute and the payload, and manipulate parachute riser quadrants (similar to performing riser slips on a personnel parachute) to steer the payload. The four riser quadrants can be manipulated individually or in pairs, providing eight directions of control authority. Achieving accurate results with a guided round parachute system requires an accurate profile of the winds over the drop zone, which must be loaded into the flight-control computer onboard the actuator system. The system steers to the wind profile, and through a combination of steering drive and prevailing winds, reaches the target coordinates.

A. Pneumatic AGAS

The AGAS developed under the New World Vista program used four Pneumatic Muscle Actuators (PMAs)[1], incorporated in-line with the existing parachute risers to control parachute trajectory. Payload steering input was achieved through releasing tension in parachute suspension lines in quadrants as dictated by the guidance software. This slackening of the lines allows air to spill out of the canopy, imparting lateral drive to the system. In addition to the PMAs, the AGAS mechanical components consisted of solenoid valve-based pressure control systems and large compressed-air tanks to perform steering actuations. The control computer was a PC/104-based unit that ran the control software and interfaced with the AGAS pneumatic actuator system[2]. The navigation sensors consisted of a commercial Global Positioning System (GPS) receiver and a heading reference. The navigation system and guidance computer were secured to the existing container delivery system while the PMAs were attached to each of four parachute risers and to the container.

Vertigo, Inc. developed the PMAs and an actuator control system to affect the control inputs for this system. The PMAs are braided fiber tubes with urethane inner sleeves that can be pressurized. Upon pressurization, the PMAs contract in length and expand in diameter. When depressurized, the PMAs are completely flexible allowing for efficient packing of the actuators with the parachute. Extensive testing of the “pneumatic AGAS” showed that a round parachute could be guided to a designated target effectively, yielding an impact accuracy with a Circular Error Probable (CEP) significantly less than 100 meters (the performance goal). Pneumatic AGAS development culminated with the successful demonstration of the system at the first Precision Airdrop Technology Conference and Demonstration (PATCAD) held at U.S. Army Yuma Proving Ground in September 2001. Although the pneumatic AGAS program achieved the accuracy goal, the pneumatic actuator system required a readily available source of high-pressure compressed gas to operate, thus making the pneumatic AGAS unattractive for use as a military system.

B. Electromechanical Prototypes

The U.S. Army Natick Soldier Center recognized that there was a need to reduce the cost and complexity of actuator systems for payloads in the range of 2,000 to 20,000 pounds. Therefore, under the Small Business Innovative Research (SBIR) program, Phase I and Phase II contracts were subsequently awarded to Vertigo, Inc. to explore Low Cost Actuator Technology (LCAT). Although production pneumatic AGAS units would have been far less expensive than other precision aerial delivery systems then in development, the goal of this research was to investigate innovative use of commercial, off-the-shelf electromechanical components to further reduce cost. Under Phase I of the LCAT SBIR program, alternatives to the PMA system were examined that could be used for both guided round cargo parachutes and guided parafoil systems. These studies centered on actuation methods that would provide adequate performance with the lowest cost and weight, and without requiring significant modification of existing system harnesses and rigging methods for heavy airdrop.

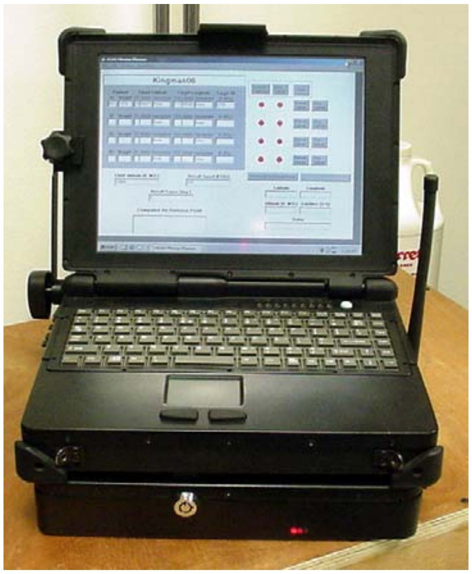
Under Phase II a simplified actuator system, using electromechanical controls, was developed to replace the pneumatic actuator system. Also, the PC/104 hardware was replaced with a less expensive and simpler microcontroller based processor, and new control software was developed to guide the system. This electromechanical AGAS system has been proven capable of fully autonomous guidance of payloads up to 2,000 lbs., with a target impact accuracy of well under 100 meters CEP. The electromechanical AGAS consists of four main subsystems: the frame and housing, the actuators, a motor controller, and the flight-control unit. Each of these subsystems was designed to be inexpensive without sacrificing system-level accuracy and reliability. In addition to the subsystems that make up the AGAS unit, two supporting systems were developed: a windpack and a mission computer. The windpack consists of a GPS receiver, wireless serial data transceiver, and power supply. It is deployed under a small parachute and is used to gather the data required to generate wind profiles over the drop zone. The mission computer and software were developed to receive and record wind information from the windpack, generate wind profiles, upload these profiles to the AGAS units, and generate a calculated air release point (CARP) for the payloads.

This Phase II SBIR effort culminated with successful demonstration of the electromechanical AGAS at the second PATCAD held at Yuma Proving Ground in November 2003. There the electromechanical AGAS proved to be the most accurate system demonstrated overall[3]. Four electromechanical AGAS units are shown above landing in a group during developmental testing at Red Lake dry lakebed in Arizona. The electromechanical AGAS is shown descending during the demonstration conducted at the November 2003 PATCAD in the figure to the right.

II. AGAS Concept and Implementation

The primary requirement of the AGAS guidance unit was that it be compatible with the CDS payloads without requiring modifications to the parachute or payload system. Since the US military already has substantial inventories of the G-12 parachutes and A-22 containers that comprise a CDS payload in stock, and a large number of personnel that are trained to rig and deploy CDS payloads, a guidance system that requires little modification to the payload or additional training to rig to a payload, becomes very inexpensive to field and operate. This economy is the driving force behind the development of the AGAS.

The actuator system works by generating “riser slips” that deform the parachute and create a vent in one edge of the parachute canopy that imparts horizontal drive to the system. By separating the G-12 parachute’s risers into four equal groups and manipulating these groups individually or in adjacent pairs, the parachute can be “slipped” in eight directions. The actuator system is placed in-line between the parachute and the payload, with the AGAS unit strapped to the top of the payload and the four parachute risers attached to the AGAS actuation risers (a CDS payload rigged with an AGAS unit is shown in the figure at the right). During payload descent, the actuator system pays out and reels in the actuation risers to generate riser slips that guide the system. Instrumented tests of payloads equipped with AGAS units have shown that the effective glide ratio that is achieved is approximately 0.6 [4].



Since AGAS equipped CDS payloads have low glide performance, knowledge of the winds over the drop zone – from the payload's deployment altitude to the ground – is required to achieve an accurate landing. This wind information can be garnered from two sources: near real-time wind data can be collected from a wind-sonde deployed over the drop zone, or a wind forecast file for the drop zone can be downloaded from the Joint Air Force and Army Weather Information Network (JAAWIN) web site. The wind data are loaded into the AGAS mission computer (shown in the figure on the left), which then merges the wind data with the desired target coordinates, release altitude, and payload weights, and generates a unique flight trajectory for each payload. The mission computer also generates a Computed Air Release Point (CARP) based on the drop aircraft's deployment speed, run-in heading, and the payload trajectories. After the trajectories are generated, they are uploaded from the mission computer to the AGAS flight computers using a wireless serial data link. During the payload's descent, the AGAS flight computer monitors its current position and altitude, compares these to the planned flight trajectory, and commands riser slips that will drive the payload closer to the flight trajectory.

AGAS is also compatible with the PADS flight planning system, which is able to fuse wind data from multiple sources and generate a reference trajectory for AGAS[5&6]. When PADS is used, the reference trajectory is loaded directly from PADS to the AGAS flight computer; the AGAS mission computer is not needed.

III. Testing

Over the past year, AGAS-equipped CDS payloads were deployed 39 times. While some of these drops were developmental in nature and the end goal was not accuracy, the system has been dropped enough times for us to gauge the accuracy of these "smart" CDS payloads. When the system is dropped in its nominal configuration, i.e., using data gathered from a windsonde dropped over the target immediately before the system deployments to generate the flight trajectory, the system has achieved an accuracy of 43 meters Circular Error Probable (CEP). When the system is deployed using forecast wind generated flight trajectories this accuracy degrades to 211 meters CEP.

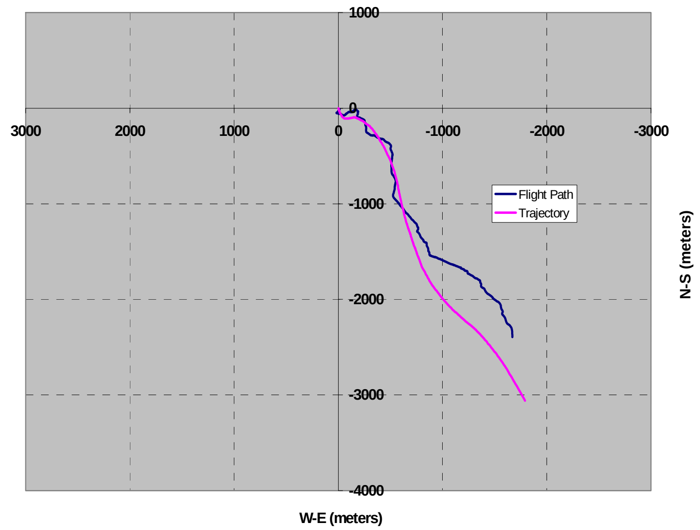
Each AGAS flight computer records flight data during descent that can be retrieved after the systems are recovered. The information is sampled and recorded once per second. This mission data are useful in determining how well the systems are performing and are useful for determining the cause of any system inaccuracy, especially when the units are deployed with forecast wind trajectories. Each sentence in the data file contains the following information:

- System ID#
- Universal Time Code
- Current system latitude and longitude
- Current system altitude
- System orientation
- Magnetic variation for the current position
- Target latitude and longitude for the current system altitude

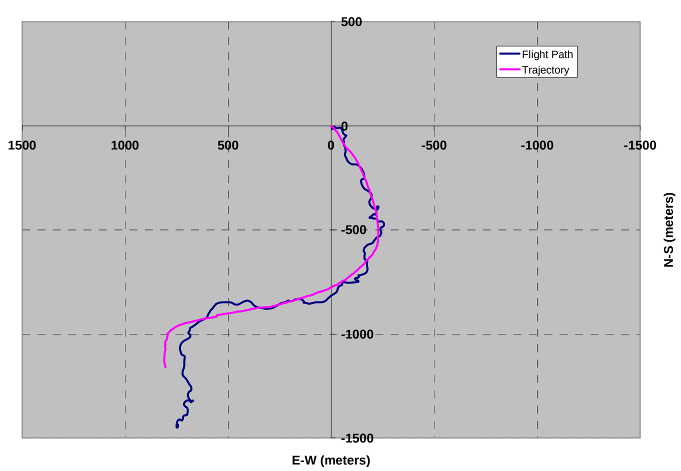
The graphs shown in the following sections are generated from the system flight data recorded by the AGAS flight computer.

A. Windsonde Generated Flight Trajectory Deployments

Accurate knowledge of the wind direction and intensity in graduated altitude segments above the drop zone are necessary for the most accurate delivery of AGAS enhanced CDS payloads. The most accurate method of generating these trajectories is to deploy a windsonde over the drop zone prior to the drop. The windsonde consists of a GPS receiver and a serial data transceiver that broadcasts the windsonde's position and altitude once per second to the AGAS mission computer, which is carried onboard the drop aircraft. When the windsonde has reached the ground, the mission computer operator generates the trajectories for the payloads and transmits them to the systems using a wireless data link.



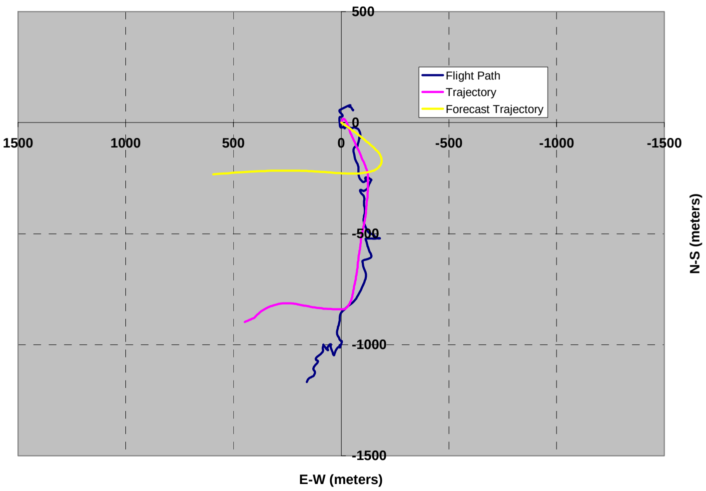
The majority of the AGAS CDS payload deployments performed to date have been performed using windsonde generated flight trajectories. Weather conditions have varied widely throughout these deployments, but the system has still managed to achieve a high level of accuracy. The first series of deployments with an AGAS equipped CDS payload in its nominal configuration took place during the last week of June 2004. These deployments were from 10,000' AGL using a C-123 aircraft. Identically weighted CDS payloads equipped with AGAS guidance units, programmed with the same target coordinates and windpack generated trajectories, were deployed near-simultaneously on a single pass. A plan view of the flight paths of a typical deployment from this test series is shown in the graph at the right. In this graph the pink line represents the "ideal" trajectory generated by the windpack. If the system was deployed on this line at the correct altitude and there were no changes in the wind direction or intensity from when the windpack was deployed to when the system was deployed, the system would follow this path and land exactly on the target. The blue line shows the actual flight path of the unit. The AGAS unit steers toward the trajectory and eventually achieves proximity to the planned flight trajectory. The system then makes minor position corrections to maintain this proximity for the remainder of the descent.



Another series of deployments performed in July 2004 using the nominal AGAS configuration shows how well the AGAS units can maintain proximity to the flight trajectory when the wind trajectory generated by the windpack and the actual winds over the drop zone are close to identical (graph shown on the left). In the case of this deployment, the unit achieves proximity to the planned flight trajectory early on in the descent and then makes many small corrections to maintain this proximity and ultimately lands very close to the target. Unfortunately, we did not gather forecast wind data for these two drop test series and do not have any data for comparison of the forecast winds versus the actual winds.

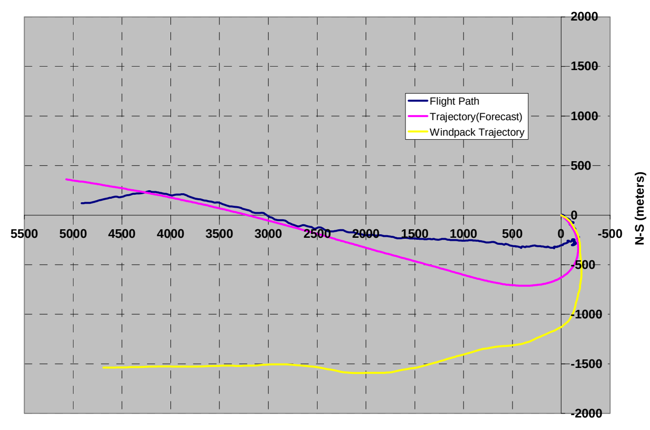
During this test series and the previous series, the payloads were all ballasted to the same weight and had the same rate of descent. This resulted in many collisions between the payloads during descent since the systems would descend in a tight group to the target. In one instance during the July deployments, one of the parachutes deflated after flying into the wake of another parachute, dropped past the lower payload and re-inflated inside the other parachute. This close proximity flying did not affect the overall system accuracy but did cause some damage to the parachutes and indicated that some form of payload de-confliction would be required when deploying multiple AGAS units simultaneously.

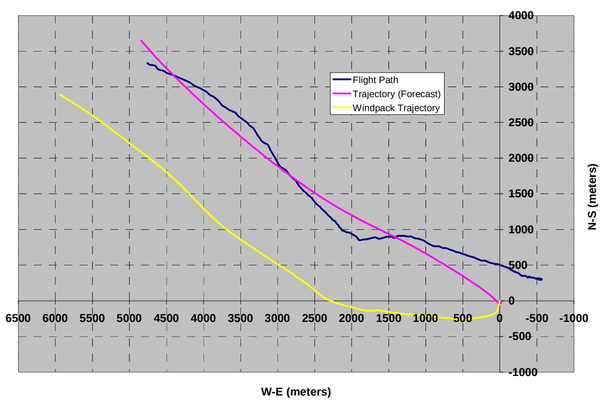
In February 2005, additional AGAS CDS deployments were performed using a similar configuration to that deployed in June and July of 2004, but we also collected forecast wind information during these drops. Multiple payloads were deployed simultaneously from 10,000 feet AGL using the same C-123 aircraft and windpack generated flight trajectories. During these deployments, a storm front had just moved through the area and the wind conditions were changing constantly throughout the deployment series, especially in the lower 1,000 feet of elevation. The forecast wind information that was collected for these drops was used to generate forecast trajectories for comparison to the windpack trajectories. Clearly these data show that there can be large discrepancies between the two trajectories and that using the windpack to generate the planned flight trajectory offers a substantially better chance of an accurate system landing. An example of this information is shown in the graph to the right. In this graph, the actual system flight path is shown in blue, the windpack-generated flight trajectory that it was driving to is shown in pink, and the yellow line represents the flight trajectory the system would have been driving to if the forecast winds were used as the wind data source.



B. Forecast Wind Generated Flight Trajectory Deployments

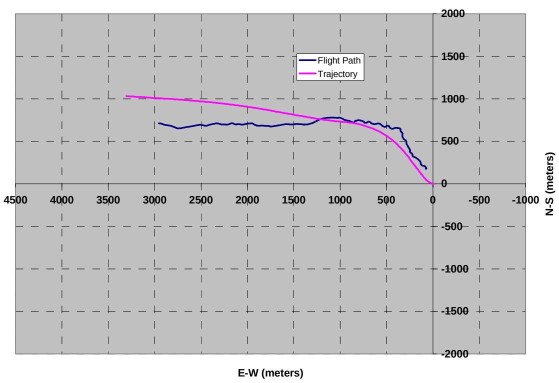
With the added capability of using forecast wind to generate the planned flight trajectories, the AGAS units become more flexible and useful in a variety of situations that preclude the use of a windpack. The first deployment of the units using forecast wind generated flight trajectories took place in December 2004 at Yuma Proving Ground. Prior to each system deployment, a forecast wind data file was downloaded from the Joint Air Force and Army Weather Information Network (JAAWIN) and loaded into the AGAS mission computer. The flight trajectories were generated and loaded into the system hours before the mission execution time. Windpacks were deployed on each mission, and their data recorded by a ground station, so that we could reference the actual winds at the drop zone against the forecast wind data. These drops





were also the first deployments of the electromechanical AGAS from 17,500 feet MSL.

On the first day of the deployment series, systems were deployed in a single pass and all of the systems achieved reasonably accurate landings. A review of the flight data from a typical system from that deployment series shows that the forecast wind generated flight trajectories for the systems were fairly close to those predicted by the windpack, especially down close to ground level where wind accuracy becomes even more critical. The system was able to achieve proximity to the flight trajectory early on in the descent. However, about mid-way through the descent, when the winds were supposed to continue with a northerly wind component, the windpack shows that the winds below this altitude, in actuality, were from the south. The AGAS unit had sufficient drive performance to overcome these discrepancies and achieve an accurate landing.

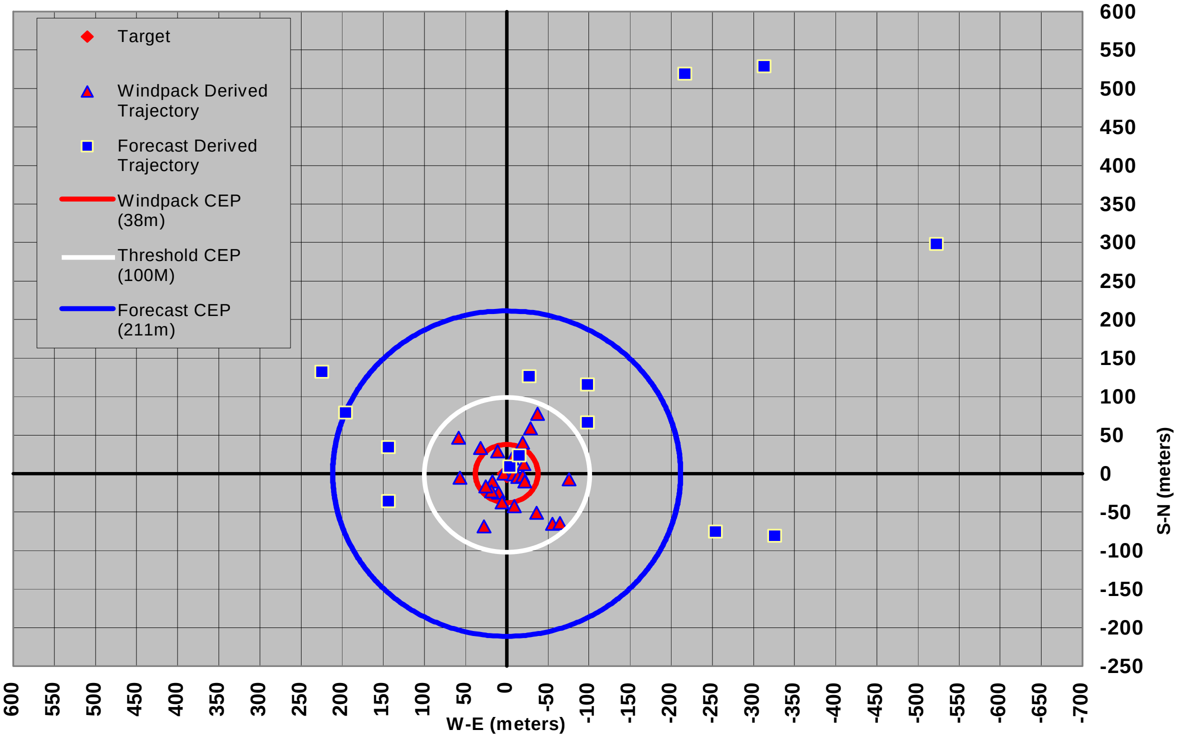


The day after these deployments, another load of AGAS systems were deployed using forecast winds. The weather conditions over the drop zone had deteriorated since the previous day and the wind intensity picked up. The forecast predicted a steady wind out of the northwest from drop altitude to the ground, but the graph of the windpack generated flight trajectory shows that the winds had shifted so that they were actually out of the west. The AGAS unit in this graph was able to maintain close proximity to the flight trajectory during its initial descent, but the performance of the unit was not sufficient to completely overcome the difference in the winds and it landed northeast of the target. We also experienced our most accurate system landing to date during the final day of deployments, with the unit landing about three meters from the target (shown in the figure below).

A drop test series conducted in March 2005 at Ft. Bragg, NC saw the first deployments of cargo parachute systems at the base from over 3,000 feet MSL in anyone’s memory. Four AGAS equipped CDS payloads were ballasted to different weights in order to provide some vertical separation between the payloads during descent, since they were all programmed to land at the same coordinates. The four AGAS CDS payloads were programmed with forecast wind generated flight trajectories, and all four achieved a reasonably accurate landing on the drop zone; landing in a group on the DZ. No windpack was deployed for these flights so there is no comparison information.

IV. Conclusions

System accuracy and knowledge of the winds over a given drop zone are closely linked in the AGAS. In certain weather conditions, the AGAS units can use forecast wind generated planned flight trajectories without much degradation in overall system accuracy, but when weather conditions are rapidly changing, the quality of the forecast winds is reduced and this has a direct affect on the accuracy of the AGAS systems. Although the integration of the PADS computer with its more sophisticated trajectory generating algorithms will improve the quality of the forecast wind trajectories, there is a significant advantage to deploying a windpack over the drop zone to generate the most accurate wind information possible for the generation of the planned flight trajectory. This is clearly illustrated in the chart below. The pink triangles represent system deployments performed using windpacks to generate the flight trajectories and the blue squares represent system deployments performed using forecast winds to generate the flight trajectories.



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