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DEVELOPMENT OF A HIGH GLIDE, AUTONOMOUS AERIAL DELIVERY SYSTEM – 'PEGASUS 500 (APADS)'

Kenneth W. Sego, Jr.
FXC Corporation
Santa Ana, CA

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Kenneth Wayne Sego, Jr*
FXC Corporation, Guardian Parachute Division, Santa Ana, CA 92704

Over the past several years, the FXC Corporation together with its Guardian Parachute Division has been developing the concept of high glide autonomous aerial delivery to create a viable product for military applications. In this concept, an electromechanical device that uses the Global Positioning System for guidance information controls a ram-air inflated parachute. The guidance device is placed between the payload and parachute confluence point, called an Autonomous Guidance Unit, when activated, it retracts the parachute steering lines and guides the system to desired points in space and ultimately to the desired delivery point. The development of the PEGASUS 500 autonomous precision aerial delivery system has spanned over 5 years and has resulted in a system that is capable of meeting requirements defined for GPADS-L. This article describes the development of a high glide autonomous precision aerial delivery parachute system, its expected and actual performance.

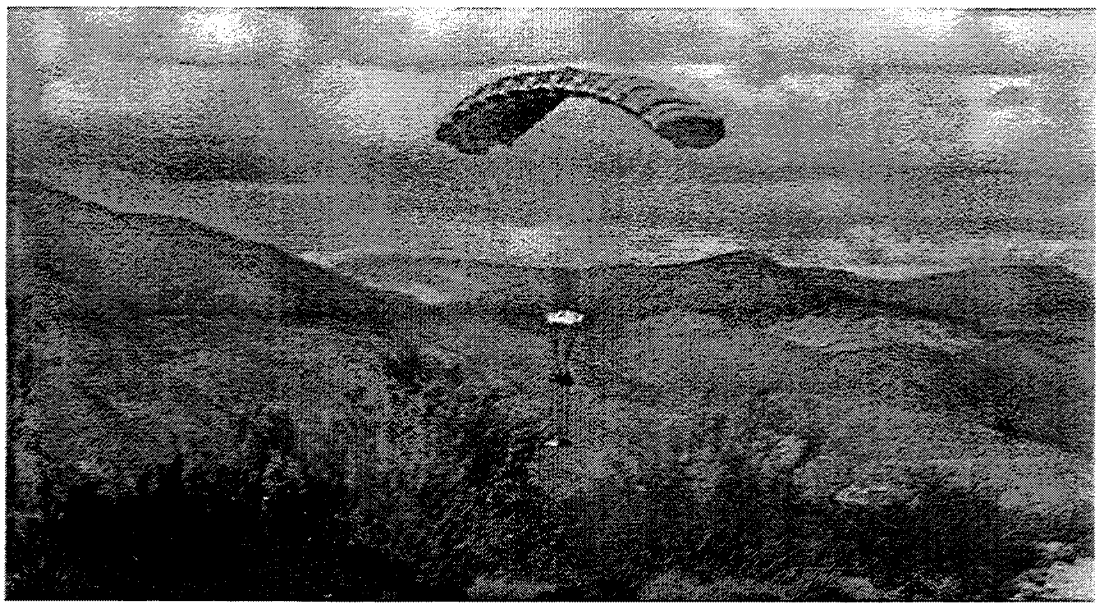

Figure 1. PEGASUS 500 Landing in the Mojave Desert of California

NOMENCLATURE

AGU	Autonomous Guidance Unit
APADS	Advanced Precision Aerial Delivery System
CEP	Circular Error Probable
DZ	Drop Zone (Landing Area)
IP	Impact Point (Landing Point)
GCU	Ground Control Unit
GPADS	Guided Precision Aerial Delivery System
GPS	Global Positioning System
HGP	High Glide Ram-Air Parachute
KEY	Program Memory Key
MPU	Mission Programming Unit

*Engineering Manager, Guardian Parachute Division, Member AIAA

INTRODUCTION

UTONOMOUSLY guided Para foil systems used for erial delivery of military cargo have demonstrated their usefulness during the past few years. Increased military interest has spawned new technologies and more cost effective designs for this application.

The PEGASUS 500 (APADS) is a good example of state-of-the-art robotics working in conjunction with guidance system technologies to create a viable design for use with autonomous aerial delivery. The following is a practical discussion of the design approach as well as a detailed description of the system characteristics used in the PEGASUS 500 APADS.

DEVELOPMENT HISTORY OF THE PEGASUS 500

The PEGASUS has been a continuously evolving design at FXC for several years, during this time the design has developed into a cost effective, functional, and practical autonomously guided precision aerial delivery system. The development and testing of the initial PEGASUS system defined areas, such as the canopy and the flight programming, which could be further enhanced with the incorporation of new technology. The current design, the new PEGASUS 500 APADS, has achieved a cost effective design as well as increased system performance.

The PEGASUS 500 APADS has been under-going development at FXC for over five years. During this time, several approaches have been taken to create a product that would meet the rigorous need of the military. A briefly summarized below is a description of the previous PEGASUS system.

Initial PEGASUS Design Approach

Initially, the PEGASUS was designed with modular electrical components that were electrically and physically robust for military applications. The design was rugged, but was costly for both development and expected production. Figure 1 shows an internal view of the original PEGASUS guidance unit. Each section of the unit was housed in it's own metal container and mounted to a support plate. The Central Processing Unit, Compass, GPS, Barometric Pressure Sensor, and Gyro are attached together using military specification cables and connectors.

The flight programming of the original version of the PEGASUS was accomplished solely through the use of a laptop computer. However, the programmed unit had the capability to fly waypoints and provided a quasi-flair landing capability.

One of the most significant advantages of the original version of the PEGASUS system was low battery power consumption, which would later be significantly enhanced and incorporated into the new PEGASUS 500 design. The original PEGASUS incorporated the use of two small (2"x 3" x 6") 12-volt gel cell batteries, which would control the system for extended flights from relatively high altitudes.

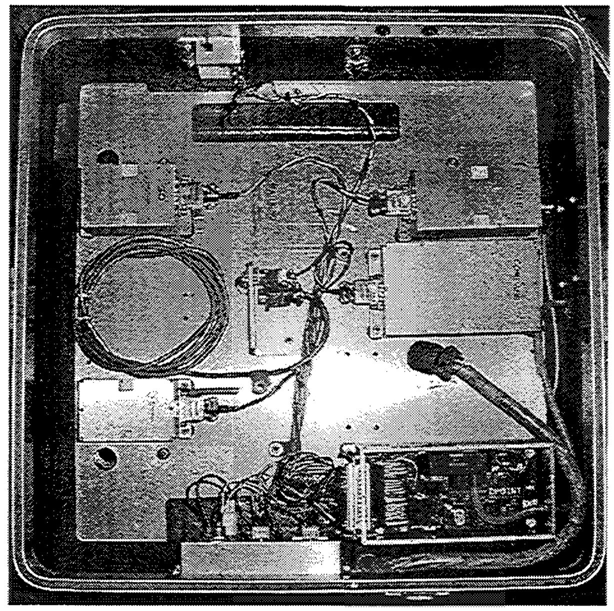

Figure 1. Early PEGASUS Guidance System

The ram-air parachute used in the initial PEGASUS system was a design of an older generation and did not have a sufficient glide ratio, less than 2.5:1, to meet the Guided Precision Aerial Delivery-Light (GPADS-L) performance requirements. The original parachute, with its less efficient airfoil design and inherent drag, did not have the ability to overcome nominal wind conditions. These factors limited the offset capability of the system as well as decreased its accuracy.

The system performed relatively well, but it was not very practical for real-world military applications. Therefore, continued development was focused on better parachute performance, more practical and user-friendly programming, and a more cost effective design.

Final System Approach

The current PEGASUS 500 system design approach is discussed below, which includes the system design criteria, description of the system components, a functional description of the system, and actual measured test results from Yuma Proving Grounds (YPG), Yuma Arizona.

SYSTEM DESIGN CRITERIA

The PEGASUS 500 APADS design included the following criteria; overall cost effective design, ease of use, robust design, low system weight, low battery power consumption, high glide parachute, and consistent landing accuracy.

The primary design criteria of low cost would be maintained from the Static Line through the Parachute and Guidance unit to the payload harness. The purpose of maintaining low cost was one of practicality. The expected customers would be more inclined to use the system if the cost was reasonable considering the significantly improved accuracy and the cost compared to other methods of aerial delivery.

Another design criteria priority would be ease of use and minimal training. Discussed in more detail later in this article, the method of programming the guidance unit, AGU, must be very simple to reduce the burden of high skill level personnel and extensive training.

The latest version of the PEGASUS must have a robust design to be intended for real-world applications. The most likely damaging effects expected are handling prior to use, impact from landing, and storage environments.

Low system weight was also a design objective, to permit increased payload capacity and reduce rigging and handling related issues.

Battery power consumption was also an important issue to address in the new PEGASUS design. The power consumption for extended flights and high servo cycles would be limited to the capacity of a single 12-volt gel cell battery.

The other components of the PEGASUS would not have significant value without a high glide ratio parachute. Then parachute would be designed to have a glide ratio of 4:1 minimum to provide extended standoff range. The parachute would also be required to deploy reliably from a variety of aircraft, including the C-130 and C-17 at normal airdrop speeds.

The system would be required to provide a consistent landing accuracy to within 150 meters Circular Error Probable (CEP). This requirement enables the end user to have confidence in the capability of the system, in that it would deliver the cargo to the point were it is most useful.

The trend that can be seen in reviewing the design criteria discussed above is that low cost and practicality were of prime concern while developing the latest version of the PEGASUS 500 APADS.

PEGASUS 500 SYSTEM DESCRIPTION

The following discussion covers the description of the system components and also provides a functional description.

Description of System Components

The Mission Programming Unit (MPU) is a hand-held device that allows the user to communicate mission landing-coordinate information using thumb-wheel switches.

Figure 2. Mission Programming Unit (MPU)

A memory KEY device is used for transferring data from the Mission Programming Unit (MPU) to the AGU. One KEY can be used to program multiple Autonomous Guidance Units.

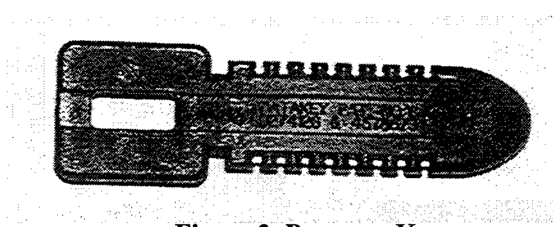

Figure 3. Program Key

Laptop PC Programming remains an option for programming the system if more complex flights are required. Sophisticated map or space position data used to program multiple waypoints may be accomplished using the laptop method.

The Autonomous Guidance Unit (AGU) is the heart of the PEGASUS 500 APADS system. The AGU uses a small gel-cell battery for servo and guidance system power. The dual servomotors are unique in their low power consumption while maintaining high torque. This servomotor and battery combination has the capability to fly a high altitude mission with power to spare.

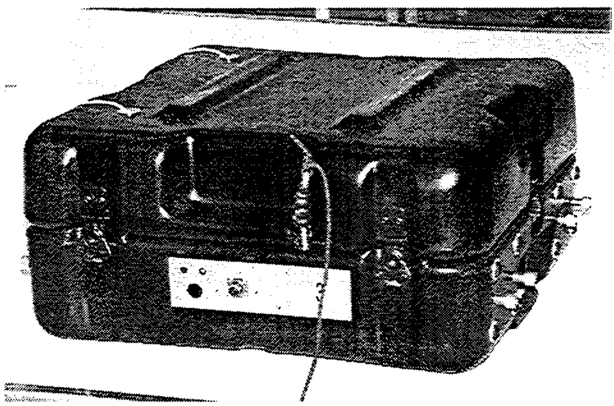

Figure 4. Autonomous Guidance Unit

The Ground Control Unit (GCU) is a user-friendly device, which allows for manual control of the system from the ground. The GCU transceiver operates at 900 MHz using spread spectrum technology and is powered by a single 9-volt battery. While the GCU is "Off" the AGU operates in fully autonomous mode. When the GCU is turned "On", it has control of the system.

Figure 5. Ground Control Unit

The Parachute was designed to provide high offset distances for longer standoff missions. This was accomplished primarily with a thin airfoil shape, high aspect ratio, and low drag suspension lines. Some of the Parachute specifications are listed below. Figure 6 shows a frontal view of the PEGASUS 500 Parachute.

- 575 FT^2 Ram-Air
- Eleven Cell Design
- 2.9: 1 Aspect Ratio
- 40 Foot Span
- 14 Foot Chord
- Spectra™ Suspension Lines
- 25 to 30 (mph) Forward Speed
- 8 to 12 (ft/sec) Descent Rate
- 400 to 600 (lb) Payload Capacity
- Good Stability Throughout Entire Flight Envelope

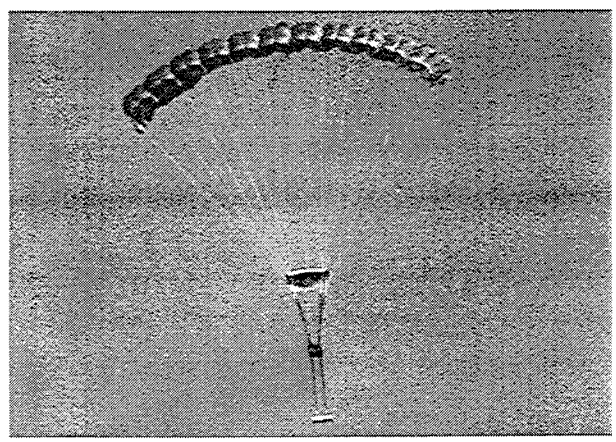

Figure 6. High Glide Parachute

A stabilization drogue is used in the PEGASUS system to align the payload, ensuring a reliable deployment. The Stabilization Drogue also regulates the inflation of the main canopy by controlling the Slider descent during deployment.

Other deployment and rigging sub-components include the parachute Deployment Bag, Bridles, and Payload Attachment Harness.

The Deployment Bag plays an important role in the reliable deployment of the parachute by controlling the payout of the suspension lines, and subsequently the deployment of the canopy itself. Like the Stabilization Drogue, the Deployment Bag function is to control and regulate the Main Canopy deployment. Further, it provides secure a mounting location for the Stabilization Drogue in addition to providing area for the stowage of the Static Line.

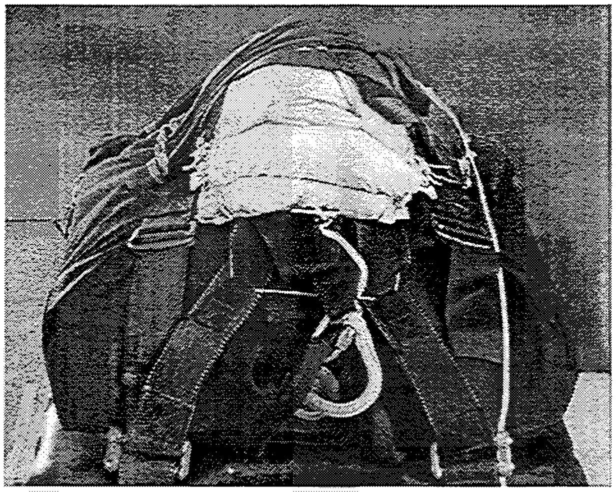

Figure 7. Packed Parachute Deployment Bag

The payload attachment harness, seen in the lower portion of Figure 6., is used to attach and orient the guidance unit. Additionally, the harness is used to suspend the payload below the parachute and guidance system.

Functional Description of the PEGASUS 500 System

Initialization Sequence

The Static Line, which is attached to the aircraft using a 220 (lb) nylon break cord, extracts the Drogue Bridle and Stabilization Drogue from its Deployment Sleeve. When introduced into the air stream, and fully extended, the Stabilization Drogue begins to inflate. Since the static line is attached to the payload through the Stabilization Drogue load path, it breaks away from aircraft after full extension of the Drogue and Bridle.

Stabilization Sequence

First, the Stabilization Drogue is fully inflated. Next, the payload extension risers become fully extended. After full extension of the risers, the drogue is then able to stabilize the Guidance Unit and Payload. This portion of the stabilization sequences occurs during a four second time delay.

Finally, the Stabilization Drogue is released from the payload using a pyrotechnic cutter in conjunction with a modified Three-Ring Release configuration.

Deployment Sequence

After the release of the Stabilization Drogue from the payload, the parachute Deployment Bag is released from the Guidance Unit, and the drogue begins to extract the suspension lines.

Upon complete extraction of the suspension lines from the parachute Deployment Bag, the parachute is extracted from the bag.

The Parachute begins to inflate and the Slider begins to move down the suspension lines. During this time the inflated drogue provides the effect of airspeed regulation over the deployment, which slows the descent of the Slider.

As the Slider overcomes the resistance of the inflated drogue, it will descend to the suspension line attachment links.

The risers become fully extended during Drogue deployment. Full extension of the risers, prior to parachute deployment, prevents the payload from accelerating and increasing the shock loads on the entire system. Also, extension of the risers is used to pull a lanyard, which in turn engages the power on the Guidance Unit.

Guidance Unit Initiation Sequence

The Guidance Unit initiates two functions upon power up. First, the unit simultaneously cycles both parachute control lines to release deployment brakes. Second, the Guidance Unit turns the parachute onto the programmed magnetic heading.

Flight Navigation and Guidance Sequence

After power-up, the AGU begins its GPS acquisition and control cycles to guide the system to the next selected waypoint. Multiple sets of waypoints can be programmed using the laptop method. However, the last set a waypoints are reserved for the landing sequence.

Landing Sequence

At 1,000 feet AGL, the system is controlled to be at the initiation point of the down-wind leg of the approach sequence. The system flies down to the base-leg turn point. Then it flies to the turn point of the final-leg. Upon entering final approach the system begins to initiate landing brakes, with full landing brakes being applied approximately 50 feet above ground level.

ACTUAL PERFORMANCE DATA

After component development was complete, the newly created PEGASUS 500 was prepared for testing. A variety of tests were performed over the Mojave Desert in central California. The overwhelming majority of these tests were performed from relatively low altitudes, less than 6,000 ft. MSL, from a Twin Otter. The airdrop velocity was limited to less than 100 knots with exits being from the side of the aircraft. After resolving a variety of system inconsistencies it began performing with a high level of accuracy. The obvious next phase of testing would include proving its performance from larger aircraft at higher airspeeds with drops from higher altitude and offset distances.

In December 2000 the US Army sponsored a series of airdrops. The Army's objective of these tests was to demonstrate the performance of various types of autonomous guided ram-air systems. These demonstrations were provided to members of the military, industry, and other interested groups. The FXC Corporation and its Guardian Parachute Division participated in this demonstration as a means of performing high-altitude, high-offset airdrops of its PEGASUS-500 APADS.

During this demonstration the PEGASUS 500 was airdropped from C-130 aircraft to determine its performance characteristics when dropped from larger aircraft at relatively high altitude and offset distances. Overall the system performed as expected. Airdrops were made at up to 9.3 miles from the planned landing point where the system landed within 90 meters from the target. Detailed results from these tests will be further discussed in this section.

Test Conditions and Set-up

The airdrop demonstration consisted of dropping two systems onto the La Posa drop zone (DZ), with an elevation of 1,234 ft mean sea level (MSL). Drops were to be performed at altitudes up to 18,000 ft (MSL). YPG Test Directors provided the impact point (IP) to which FXC personnel were to program the PEGASUS 500 APADS to land. A Global Positioning System (GPS) retransmission kit was installed into the C-130 aircraft to minimize the loss of GPS reception during deployment. However, the PEGASUS 500 does not acquire GPS until Parachute deployment.

Airdrop Instrumentation

There were several types of instrumentation used to document these demonstration tests. They consisted of ground to air video, on-board video, radar tracking, meteorological balloons and hand-held GPS receivers to record impact locations.

Ground to Air Video was provided with two stabilized Kineto Tracking Mounts (KTM's). They were set up south and east of the planned impact points, which was done to ensure adequate coverage of the deployment and flight of each system. According to the YPG report, each KTM had three cameras with multiple fields-of view, and one video stream from each site was transmitted into the DZ command center for close-up real-time drop observation.

Also provided for these airdrop tests was on-board aircraft video. Additionally, according to the YPG report, this video was encoded with IRIG-B time and audio, and was recorded to annotate any deployment anomalies, green light time and first motion.

Another important means of documenting the PEGASUS 500 during its flight was YPG's MPS-25 radar tracking system. The MPS-25 radar and YPG Mission Control were used to control the aircraft to the pre-determined release points and to track the airdrop payloads during flight. Radar beacons were not installed on the loads to eliminate the potential of RF interference with the guidance systems. The radar dish location and local terrain features prevented the radar from tracking below ≈3000 feet (MSL); therefore no tracking data was available below this altitude.

Meteorological balloons were used to monitor the wind during these airdrop tests. The balloons measured and transmitted wind speed and direction every 100 feet up to the drop altitude. A balloon was launched at the DZ approximately two hours prior to aircraft takeoff. The wind data was provided to FXC personnel so that optimum release points and flight paths could be determined.

Hand-held GPS receivers were used to mark the actual landing point of the PEGASUS 500 at the termination of its fight. Yuma Proving Grounds personnel measured and recorded the GPS coordinate at the point of landing.

Airdrop Test Summary

A summary of the PEGASUS 500 drops is described in the following section. It is important to note that winds were relatively high and therefore the release points were up-wind of the drop zone. These conditions demonstrate a practical use of the system, which could benefit from existing winds by an increase in offset capability.

Day 1

The first day of airdrops at YPG were performed on December 13, 2000. These drops were designated YPG Drop No. 00-441 and 00-442. The release point of the systems was from 7.5 miles from the planed IP.

Two PEGASUS 500 systems were dropped on separate flight passes. These two drops deployed normally from 14,000 feet MSL without issue. Both systems flew easterly arriving directly over the target at approximately 6,000 feet above ground level (AGL). As expected, the systems then turned into the wind (facing west) to scrub altitude and land. However, the winds had increased after the last reported wind information, which caused the loads to arrive at the target with excess altitude. Since the wind at that altitude was greater than what the systems could overcome, the systems continued to fly in the same direction, which was not an expectation of the algorithm at that time. While the parachute was facing into the wind, it continued to be pushed in the rearward direction. Therefore, the algorithm using GPS for tracking determined that the systems were tracking in the wrong direction (down wind). The system then executed a command to turn 180 degrees to face into the wind, which exacerbated the issue. This cycle continued until the load descended far enough until reaching a lower wind speed allowing the on-board GPS to obtain a proper ground track. Unfortunately, this caused the systems to fly well passed the planned IP before they attempted to fly back to the intended target. Because they didn't have enough altitude, they did not regain much ground, landing approximately 4800 meters downwind of the IP.

In summary the offset distance was planned to be 7.5 miles from the IP but the actual flight with winds were over 9.5 miles. The wind speed was measured at ~30 knots at an altitude 6500 ft. MSL and were at a direction of ~310 degrees.

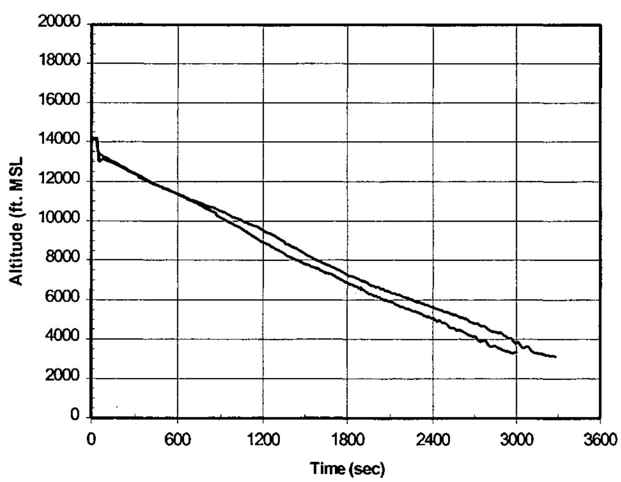

Chart 1
Descent Rates for Drop 441 and 442

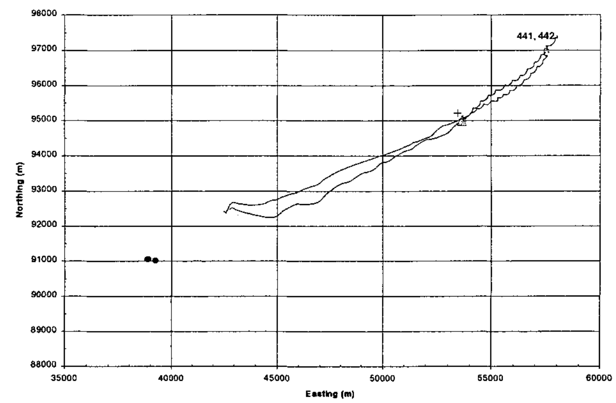

Chart 2
Flight Paths for Drop 441 and 442

It can be seen that the guidance system was expecting to obtain a reading that it was tracking forward across the ground but since winds were significantly high, ~30 (Kt.), they continued tracking the same direction. The system turned again to attempt to find a forward ground track. This continued until the ground track criteria were met, which was at approximately 500 (ft AGL), which caused the actual landing point to be significantly downwind. Notice that both systems flew approximately the same flight path to the target and then circling until the winds became penetrable by the parachute.

Day 2

Day two of the demonstration airdrop testing was performed on December 14, 2000. These drops were designated YPG Drop No. 00-447 and 00-448. The release point of the systems was from 9.3 miles from the planed IP.

Both of the airdrop tests performed on day two were outstanding in terms of overall performance. Regressing to a previous version of the control algorithm seemed to solve the continual turning cycle that caused the two systems on Day 1 to land east of the IP. The two systems dropped on Day 2 landed 287 and 82 meters from the IP, respectively.

The systems performed in an outstanding manner from an orderly deployment to a relatively soft touchdown of the payload. As can be seen in Chart 3, that the descent rate throughout the flight was between 8 and 14 feet per second.

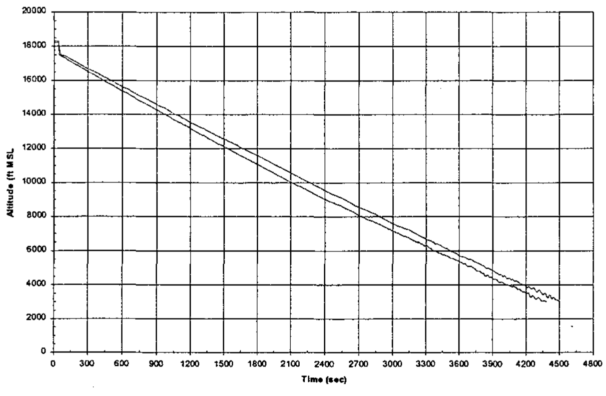

Chart 3
Rate of Descent for Drops 447 and 448

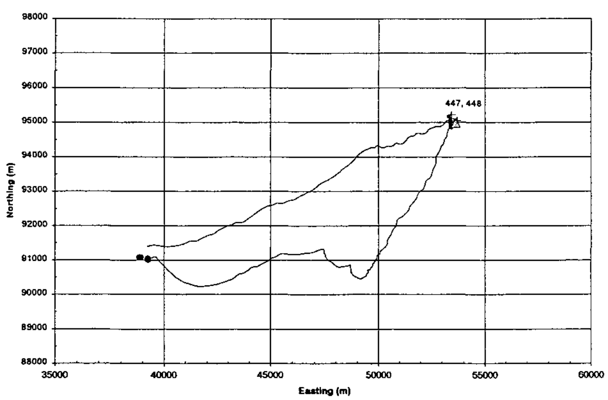

Chart 4
Ground Track for Drops 447 and 448

After visual inspection, it could be seen that the Parachute, AGU, and Payload were in excellent shape.

Day 3

Day 3, the final day of these airdrops was performed on December 15, 2000. These drops were designated YPG Drop No. 00-455 and 00-456. The release point of the two systems were 5.0 and 3.2 miles from the planed IP respectively.

The first drop landed 1,990 meters short of the IP; this was related to one end cell of the parachute hesitating to fully inflate causing approximately 1,300 feet of altitude loss. The second drop performed in an excellent manner, landing 185 meters from the IP.

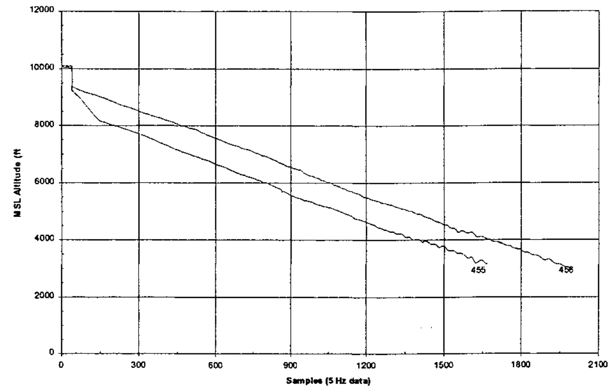

Chart 5
Rate of Descent for Drops 455 and 456

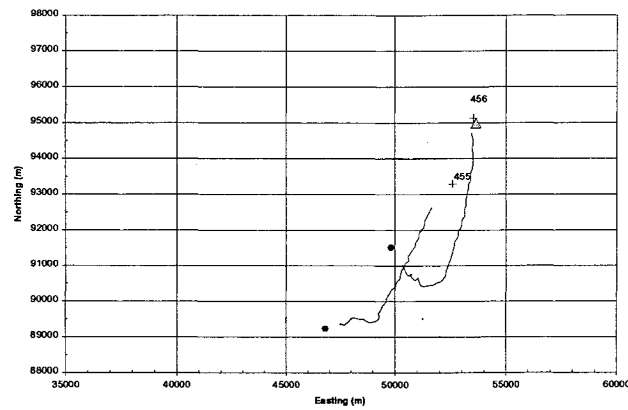

Chart 6
Ground Track of Drops 455 and 456

Overall Test Results

The demonstration airdrop testing was considered successful in that it demonstrated the performance as well as the inadequacy, which was beneficial to the continued development of the PEGASUS 500.

Landing Accuracy

A common measure of horizontal error with terminal guidance systems is Circular Error Probable (CEP). CEP is a statistical measure of horizontal precision, which is defined as a circle of the stated radius that will enclose exactly 50% of the data points. For guided air delivery missions, a common CEP requirement is 100 meters.

This airdrop series did not contain enough drops for statistical confidence, though the conclusion is that the PEGASUS-500 demonstrated the potential for meeting the CEP requirement, which is 150 meters CEP. Even though the system landed within 82 meters on one occasion, further airdrops will be required before statistical analysis can be used to determine if it will pass the 100-meter CEP requirement.

Deployment Reliability

The system demonstrated good deployment characteristics when deployed from the C-130 aircraft. Overall, the parachute opened with a low opening shock and consistent reliability.

PEGASUS 500 SYSTEM ADVANTAGES AND DISADVANTAGES

The PEGASUS 500 has developed into a viable system that has several advantages. Some of the advantages are a relatively low cost design, high glide ratio, effective landing accuracy, low system weight and bulk, system powers-up upon main canopy deployment only, no equipment left in the aircraft, autonomous or manual control, and minimum training requirements.

Low Cost Design

Several low cost design features have been incorporated into the PEGASUS 500 APADS design. The AGU circuitry is a good example of the cost saving techniques used. The AGU circuitry is contained in one low cost circuit board with a few exceptions. The servomotors, Gyro, GPS antenna, barometric pressure transducer, and transceiver sub-system are separated from the primary circuit board. While the transducers and antennas are separate they are cost and quality efficient.

Additionally, through the use of the latest technology textile materials in the canopy and other subcomponents of the PEGASUS system, it is ensured that the materials will be readily available. Additionally, the use of these materials ensures that they will be available at the best possible price to meet the parachute industry's needs.

User Friendly

While the PEGASUS 500 has multiple methods of programming, the KEY programming method is significantly more user friendly. The user only needs to select the proper switch setting on the MPU, insert the KEY, turn and watch the LED to flash green. Then remove the KEY from the MPU insert it into one or more AGU's. However, if more complex flight programming is required, a laptop computer can be used to program the AGU.

Glide Ratio

The parachute has proven to have a relatively high glide ratio, approximately 4:1, which equates to longer standoff distances from lower altitudes. This gives the user a truly enhanced flight capability. Practical offset distances of 12 (mi) from 18,000 (ft AGL) or 18 (mi) from 25,000 (ft AGL) are capable. However, local weather patterns are a significant consideration when planning for long offset distance drops.

Landing Accuracy

The accuracy of PEGASUS 500 APADS is expected to be within 150 meters, Circular Error Probable (CEP). However, continued development of the guidance algorithm is expected achieve even greater accuracies.

From a practical standpoint, the system's intended use is a target area such as a road or tree line. Due to the parachute's high glide ratio and the current guidance algorithm, errors in landing zone altitude are magnified by the glide ratio along the flight path. Therefore, one can see that a clearing alongside a tree line or equivalent area is best suited for the current system's capability. Future developments are focused on creating a more highly sophisticated algorithm that will permit more pinpoint accuracy.

System Weight and Volume

The low system weight and bulk allow for ease of handling and an increase in payload capacity. The specific weight and volume of the system is listed below.

System Weight	
AGU	44.0 (lb)
Parachute System	29.0 (lb)
Total Weight	***73.0 (lb)***
System Volume and Height	
AGU (19 x 19 x 9 In.)	2.09 (ft^3)
Parachute System (14 x 16 x 8 In.)	1.04 (ft^3)
Total Volume	***3.13 (ft^3)***

System Power-Up

The Pegasus System does not have power applied until main canopy deployment. All mission data is stored in non-volatile memory. This eliminates interference with the on-board electronics as well as minimizing batter power consumption. The system uses approximately 0.1 Amp Hours from 18,000 feet (MSL). Additionally, all mission data is stored in non-volatile memory.

No Equipment Left In Aircraft

Through the use of a breakaway static line, there is no equipment left in the aircraft. The static line is attached to the aircraft using an Air Force approved method, including the use of a clevis connect around the aircraft static line cable and the typical 220 (lb) nylon cord. Once the system exits the aircraft the nylon cord breaks and the static line exits with the other items.

CONCLUSIONS

In conclusion, the PEGASUS 500 (APADS) system development has shown that autonomously guided ram-air parachute systems are a viable approach to precision aerial delivery of cargo. In fact this development has proven that this approach to aerial delivery can also be economical, especially when precious items are the primary cargo.

Future development of this type of system will include larger scale parachutes with significantly increased payload capacities. Additionally, more sophisticated methods of programming the system are being developed with significantly more precision as an expected result.

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