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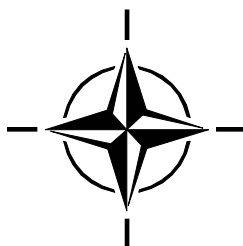
**RTO AGARDograph 300**  
**Flight Test Techniques Series – Volume 24**

**SCI-125**

# **Precision Airdrop**

(Largage de précision)

This AGARDograph has been sponsored by the  
Systems Concepts and Integration Panel.



Published December 2005

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# **Precision Airdrop**

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Systems Concepts and Integration Panel.

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# The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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## AGARDograph Series 160 & 300

Soon after its founding in 1952, the Advisory Group for Aerospace Research and Development (AGARD) recognized the need for a comprehensive publication on Flight Test Techniques and the associated instrumentation. Under the direction of the Flight Test Panel (later the Flight Vehicle Integration Panel, or FVP) a Flight Test Manual was published in the years 1954 to 1956. This original manual was prepared as four volumes: 1. Performance, 2. Stability and Control, 3. Instrumentation Catalog, and 4. Instrumentation Systems.

As a result of the advances in the field of flight test instrumentation, the Flight Test Instrumentation Group was formed in 1968 to update Volumes 3 and 4 of the Flight Test Manual by publication of the Flight Test Instrumentation Series, AGARDograph 160. In its published volumes AGARDograph 160 has covered recent developments in flight test instrumentation.

In 1978, it was decided that further specialist monographs should be published covering aspects of Volumes 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. In March 1981, the Flight Test Techniques Group (FTTG) was established to carry out this task and to continue the task of producing volumes in the Flight Test Instrumentation Series. The monographs of this new series (with the exception of AG237 which was separately numbered) are being published as individually numbered volumes in AGARDograph 300. In 1993, the Flight Test Techniques Group was transformed into the Flight Test Editorial Committee (FTEC), thereby better reflecting its actual status within AGARD. Fortunately, the work on volumes could continue without being affected by this change.

An Annex at the end of each volume in both the AGARDograph 160 and AGARDograph 300 series lists the volumes that have been published in the Flight Test Instrumentation Series (AG 160) and the Flight Test Techniques Series (AG 300) plus the volumes that were in preparation at that time. Annex B of this paper reproduces current such listings.

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# Precision Airdrop

## (RTO-AG-300-V24)

### Executive Summary

This AGARDograph describes the basic principles and testing considerations for precision airdrop systems. A variety of precision airdrop systems available as commercial-off-the-shelf and others in various stages of development will be described in general terms. Some of the systems described are currently in use while other systems are in development. This report also concentrates on the aircraft navigation to the airdrop release point and on the trajectory control and concepts of airdropped payloads to enable accurate ground impacts. In addition, the report outlines the need for precision airdrop systems and introduces the reader to potential Concepts of Operations.

Of particular note is the recent growing interest in precision airdrop by NATO. The NATO Conference of National Armaments Directors (CNAD) has recently prioritized precision airdrop for Special Operations Forces (SOF) as the eighth highest priority within NATO for Defence Against Terrorism (DAT). Other current activities within NATO to meet this short term requirement will be outlined.

A list of useful reference documents is included in the report. These can be helpful to the reader looking for appropriate details if the full background should be needed for information contained in this AGARDograph.

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# Largage de précision

## (RTO-AG-300-V24)

### Synthèse

Le présent AGARDograph décrit les principes de base et les conditions d'essais des systèmes de largage de précision. Il donne une description générale d'un certain nombre de systèmes de largage de précision disponibles dans le commerce et de systèmes à différentes étapes de développement. Certains de ces systèmes sont actuellement utilisés et d'autres sont en cours de développement. Ce rapport est également ciblé sur la navigation vers le point de largage et sur le contrôle de trajectoire et les concepts de charges utiles larguées permettant un impact au sol précis. En outre, ce rapport souligne le besoin en matière de systèmes de largage de précision et présente les concepts d'opérations potentiels.

L'intérêt croissant de l'OTAN pour le largage de précision est à noter. La Conférence des directeurs nationaux des armements (CDNA) a récemment accordé au largage de précision pour les forces d'opérations spéciales (FOS) un niveau de priorité huit dans le cadre de l'OTAN pour la lutte contre le terrorisme (DAT). D'autres activités actuelles au sein de l'OTAN en vue de répondre à cette exigence à court terme seront présentées.

Ce rapport contient une liste des documents de référence utiles. Ceux-ci peuvent s'avérer utiles si vous recherchez des détails particuliers au cas où le contexte global serait nécessaire pour les informations contenues dans le présent AGARDograph.

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## Acknowledgements

The authors would like to thank Mr. John Phillips, AFFTC, Edwards AFB, CA, USA for his significant contribution to the aircraft navigation sections of this report. Thanks also to Dr. Henk W. Jentink of the National Aerospace Laboratory (NLR), Amsterdam, the Netherlands, Mr. Rob Humphries of the Airborne Forces Equipment Project Team, QinetiQ Ltd, Boscombe Down, UK and Mr. Mark Kuntavanish of the USAF Air Transportability Test Loading Agency (ATTLA), Wright-Patterson AFB, OH, USA for their outstanding support in providing material and reviewing the paper. In addition, the authors would like to thank members of the U.S. Army Natick Soldier Center, Natick, Massachusetts, and the U.S. Joint Forces Command (JFCOM), Norfolk, Virginia, for their contributions to the overview descriptions of many of the precision airdrop systems and the concept of operations outline. Finally we would like to thank the USAF Air Mobility Command for their support in the development of precision airdrop systems.



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## Biographical Sketch

### **MICHAEL R. WUEST**

Mr. Michael Wuest is an aerospace engineer in the Engineering Directorate, U.S. Air Force Flight Test Center, Edwards AFB, California, USA. He graduated with a Bachelor of Science in Aerospace Engineering from the University of Arizona in 1968. Mr. Wuest is an Associate Fellow of the American Institute of Aeronautical and Astronautics (AIAA) since 1990. He has served three terms on the AIAA Aerodynamic Decelerator Systems Technical Committee.

Mr. Wuest began his government career in 1974 with the 6511th Flight Test Squadron at the National Parachute Test Range located at El Centro, California, USA. He worked as a flight test engineer in support of cargo aerial delivery systems projects. His first projects included supporting the successful effort to air-launch a Minuteman III missile from a C-5 aircraft and evaluating the aerial delivery system of the lengthened C-141B aircraft. He continued as a flight test engineer until 1989, when he was appointed chief of the Mission Systems engineering branch, 6520 Test Group at Edwards AFB. In this position, he supervised engineers and technicians as they evaluated missions systems and aerial delivery systems on C-17, C-130, C-141, C-5 AND UH-1 aircraft. Since 1996 through 2005, he has worked for the 412th Test Wing at Edwards AFB serving as an Avionics Engineering Branch Chief. He and his teams have evaluated various avionics systems on virtually all of the cargo, fighter, tanker, bomber and unmanned aircraft tested at Edwards AFB during that time. He also continues to support parachute test projects for the USAF.

### **RICHARD J. BENNEY**

Mr. Richard J. Benney is an aerospace engineer in the Airdrop/Aerial Delivery Directorate, U.S. Army Natick Soldier Center, Natick, Massachusetts, USA. Mr. Benney graduated from Northeastern University with a Bachelor of Science in Mechanical Engineering in 1987, and a Master of Science in Mechanical Engineering in 1989. In addition, he received his Master of Science in Applied Sciences from Harvard University in 1990.

He began his government career in 1991 as an aerospace engineer in the Engineering Technology Division at Natick, where he served as a highly successful research engineer making breakthrough advances in high performance computer modeling of parachute systems, work for which he received an Army Research and Development (R&D) Achievement Award in 1994. Mr. Benney was promoted in 1999 to Team Leader, Airdrop Technology Team (ATT), where he took on additional responsibilities for research and technology development for all ATT projects, as well as the corresponding supervision of approximately 15 research engineers. Mr. Benney is currently the Technical Manager for the Joint Precision Airdrop System (JPADS) Advanced Concept Technology Demonstration (ACTD) Program.

Mr. Benney is an Associate Fellow of the American Institute of AIAA, of which he has been a member since May 1992. He has served as Treasurer of the AIAA Aerodynamic Decelerator Systems Technical Committee (ADC-TC) since 1989 and as Chairman of the ADS-TC from June 1999 – June 2001. Mr. Benney has been recognized for his accomplishments with numerous awards throughout his career, including: Ten Outstanding AMC Personnel Of The Year, 2005; Army Materiel Command (AMC) Small Business Award, 2004; AMC Top 10 Inventions Program – Certificate of Excellence, 2003; U.S. Army Soldier Systems Center Outstanding Team Leader, 2002; Civilian graduate of the U.S. Army Airborne School, 1999; Department of the Army R&D Achievement Award, 1994; Certificate of Achievement, 1993 and 1994; and Natick Soldier Center Technical Director's Award for Research Silver Pin, 1993. He has published over 60 technical papers on airdrop systems to include a number of refereed journal articles.

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## List of Acronyms

AATV	Airborne All-Terrain Vehicle
ACTD	Advanced Concept Technology Demonstration
ADS	Aerial Delivery System
AFFTC	Air Force Flight Test Center
AFWA	Air Force Weather Agency
AGAS	Affordable Guided Airdrop System
AGL	Above Ground Level
AGU	Airborne Guidance Unit
AMC	Air Mobility Command
ATR	Airborne Trailer
ATTLA	Air Force Air Transportability Test Loading Agency
CARP	Computed Air Release Point
CEA	Computed/Circular Error Average
CEP	Computed/Circular Error Probable
CNAD	Conference of National Armaments Directors
CNIU	Common Navigation Interface Unit
CPU	Central Processing Unit
CTII	Combat Track II
DAT	Defense Against Terrorism
DGPS	Differential Global Positioning System
DZ	Drop Zone
ECDS	Enhanced Container Delivery System
FSS	Force Sustainment Systems
GAINR	GPS-Aided Inertial Navigation Reference
GDS	Generic Delivery System
GN&C	Guidance, Navigation and Control
GPS	Global Positioning System
HARP	High-Altitude Release Point
HD	High Drag
HMD	Helmet-Mounted Display
HMMWV	High-Mobility Multiwheeled Vehicle
HUD	Head-Up Display

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JAAWIN	Joint Air Force Army Weather Information Network
JPADS-MP	Joint Precision Airdrop System-Mission Planning
KIAS	Knots Indicated Air Speed
LAPES	Low-Altitude Parachute Extraction System
LCAT	Low-Cost Actuator Technology
LTCR	Long-Term Capability Requirement
LIDAR	Laser Radar
MEW	Mean Effective Winds
MFD	Multiple Flight Display
MP	Mission Planner (includes aircraft mission computer)
MSL	Mean Sea Level
NATO	North Atlantic Treaty Organization
NLR	National Aerospace Laboratory, The Netherlands
NSC	Natick Soldier Center
OUE	Operational Utility Evaluation
PATCAD	Precision Airdrop Technology Conference and Demonstration
PDA	Personal Data Assistant
PI	Point of Impact
PIP	PADS Interface Processor
PM	Product Manager
RAD	Ram-Air Drogue
RDECOM	Research Development and Engineering Command
RTK	Retransmission Kit
SBIR	Small Business Innovative Research
SOCOM	Special Operations Command
SOF	Special Operations Forces
SPADES	Small Parafoil Autonomous Delivery System
TRL	Technology Readiness Level
TSPI	Time, Space and Position Information
UAV	Unmanned Aerial Vehicle
YPG	Yuma Proving Ground

## **Chapter 1 – INTRODUCTION**

Today, most airdrops are conducted by flying to a computed air release point (CARP) that is based on winds, system ballistics and airspeed. A ballistic table (based on the average ballistic characteristics of the given parachute system) dictates the CARP, where the load is released. This average is often based on a data set that includes variations up to 100 meters (328 feet) standard deviation. The CARP is also often calculated using an average of the winds (at altitude and surface winds) and assumes a uniform profile of the wind from the drop altitude to the ground. Wind profiles are rarely uniform from ground level up to higher altitudes, with variations coming from terrain effects and natural variable meteorological characteristics of wind currents like wind shear. Since most present threats to military aircraft are from ground fire, modern thinking is to have aircraft airdrop at high altitudes and with horizontal offset, putting the aircraft out of harm's way. This has obvious consequences of exacerbating the effects of varying winds. To meet the need of airdropping from higher altitudes and preventing deliverables from falling into the wrong hands, precision airdrop has been given a high priority by the NATO Conference of National Armaments Directors (CNAD). Modern technology has made the realization of many new innovative methods of airdrop possible. In order to mitigate the effects of all the variables that hinder precision ballistic airdrop, systems are being developed to not only increase the accuracy of CARP calculations by more accurately profiling the wind, but also to guide the airdrop system to a predetermined ground impact point regardless of the variations in wind.

### **1.0 BACKGROUND**

Variation is the enemy of precision. The less a process varies, the more precise the process is; airdrop is no exception. There are many variables in the airdrop process. Among these are parameters that cannot be controlled, like weather, human factors such as rigging variations and crew/timing procedures, the porosity of individual parachutes, parachute manufacturing differences, differences in opening dynamics of individual and/or groups of parachutes, and the effects of wear. All of these and many more factors have an effect on the achievable accuracy of any airdrop system, ballistic or controlled. Some parameters can be partially controlled, like airspeed, heading, and altitude. But due to the very nature of flight, even these will vary to some extent during most airdrops. That said, precision airdrop has come a long way in the past few years and is likely to mature rapidly as NATO Nations invest more funding in precision airdrop technologies and testing. Many advances to precision airdrop systems are under development and many others are planned in the near future in this rapidly expanding capability area. This AGARDograph will describe the state of precision airdrop.

### **1.1 AGARDOGRAPH OBJECTIVE**

The objective of this AGARDograph is to discuss the current state-of-the-art in precision airdrop technology/systems and to identify considerations for evaluating the performance of related systems.





## Chapter 2 – AIRCRAFT NAVIGATION TO A PRECISION AIRDROP OVERVIEW

This chapter discusses the procedures and algorithms used by the U.S. in navigating an aircraft to perform an airdrop. These are given in U.S. Air Force Instruction (AFI) 11-231, *Computed Air Release Point Procedures (CARP)*. [1] This paper describes the C-17 automated process as used by the USAF. The airdrop navigation methods used by other USAF aircraft are described in Annex B.

### 2.0 NAVIGATION

The C-17 aircraft has an automated capability for the navigation part of the precision airdrop process. Precision airdrops from the C-17 aircraft are conducted using CARP, high-altitude release point (HARP), or low-altitude parachute extraction system (LAPES) algorithms. This automated airdrop process considers ballistics, winds, release location computations, time-to-go cues, and recording key data at release.

For low-altitude airdrops in which the recovery system is deployed in conjunction with the load exit, CARP is used. For high-altitude airdrops, HARP is used. Note that the difference between CARP and HARP calculations involves the trajectory during the freefall stage of a high altitude airdrop.

The C-17 Mission Airdrop Database contains the ballistics of various types of loads such as personnel, containers, or equipment and their associated parachutes. The computers allow ballistics information to be updated and displayed at any time. The database maintains the parameters shown in table 1 as inputs to ballistics computations made by the aircraft mission computer. Note that the C-17 allows ballistics to be maintained not only for discrete personnel elements and discrete equipment/cargo elements, but also combination elements of people exiting the aircraft with their equipment/cargo.

**Table 1: Mission Airdrop Database, Ballistics**

Input Data Name	Description
Location Element Exit	Where the element will exit the aircraft
Location Element Exit Combination	Where the element (combination of people and equipment) will exit the aircraft
Pressure Barometric Drop Zone Surface	Atmospheric Barometric pressure at the drop zone
Quantity Chutes Drogue	Number of drogue chutes per element
Quantity Chutes Extraction	Number of drogue chutes per element for a parachute extraction from the aircraft
Quantity Chutes Main	Number of main chutes per element
Quantity Elements	Number of discrete elements that will exit the aircraft
Quantity Elements Combination	Number of discrete elements (combination of people and equipment)
Station Number Element Center of Gravity	Where the element cg is located by aircraft station number
Station Number Element Center of Gravity Combination	Where the combination element cg is located by aircraft station number
Type Chute Drogue	Type of drogue chute employed with the element
Type Chute Extraction	Type of extraction chute employed with the element
Type Chute Main	Type of main chute employed with the element
Type Chute Main Combination	Type of main chute employed with the combination element
Weight Element	The weight of the element
Weight Element Combination	The weight of the combination element

## AIRCRAFT NAVIGATION TO A PRECISION AIRDROP OVERVIEW

Based on the inputs from the Mission Airdrop Database (table 1) the mission computer software computes these ballistics outputs for use in further continuous calculations of air release point, shown in table 2.

**Table 2: Ballistics Computation Outputs**

Output Data Name	Description
Distance Element Forward Travel	Horizontal distance travelled by the element after release
Distance Element Forward Travel Combination	Horizontal distance travelled by the combination element after release
Distance Vertical Actuate-Deploy	Vertical distance (altitude difference) from element chute actuation to full chute deployment
Distance Vertical Stability	Altitude difference from release point to point where element is under stable descent
Distance Vertical Stability Combination	Same as above, only element is combination of personnel and equipment/cargo
Time Element Exit (TEE)	Time to exit for the element
Time Element Exit Combination	Time to exit for the combination element
Time Forward Travel (TFT)	Total time the element travels forward under inertia from aircraft velocity (sum of TEE and TFTD)
Time Forward Travel Combination	Total time the combination element travels forward under inertia from aircraft velocity, after release
Time Forward Travel Deceleration (TFTD)	Time the element travels forward under inertia from aircraft velocity, after exit from aircraft
Time Forward Travel Deceleration Combination	Time the combination element travels forward under inertia from aircraft velocity, after exit from aircraft
Time of Fall Constant	Constant for particular element; time from drop altitude to stabilization altitude
Time of Fall Constant Combination	Constant for particular combination element; from drop altitude to stabilization altitude
Velocity Down Deployed	Downward velocity of the element under deployed chute
Velocity Down Deployed Combination	Downward velocity of the combination element under deployed chute
Velocity Down Free Fall	Downward velocity of the element during free fall (for a HARP computation)

### 2.1 WINDS

After the airdrop load is released, winds affect the direction of travel and time of fall. The C-17 mission computer computes winds using data from the aircraft's various airspeed, pressure, and temperature sensors, as well as navigation sensors. Wind data may also be entered manually using information from the actual drop zone (DZ) or from weather forecasts. Each type of data has benefits and drawbacks. Aircraft sensor winds are very accurate but may not reflect the weather conditions over the DZ because the aircraft is not able to fly from the ground to altitude over the DZ. Ground wind data are usually not the same as winds at altitude, particularly at high altitude. Forecast winds are predictions and do not reflect wind speeds and direction at the different altitudes. Actual wind profiles are usually not linear versus altitude. If the actual wind profile is not known and entered into the mission computer, the default assumption of a linear wind profile adds to errors in CARP computation. After those computations are made (or data entered), their results are written to the Mission Airdrop Database (table 3) for use in further computations of the CARP, or HARP, based on mean effective winds (MEW). Winds are not used for LAPES releases, since the aircraft releases cargo just above the ground at the desired point of impact (PI). The C-17 mission computer

calculates the net along-track and cross-track offset components of wind drift distance for CARP and HARP airdrops. Wind drift distance is a function of average wind velocity and drop element total time of fall as may be seen in the equations following table 3.

**Table 3: Mission Airdrop Database, Winds**

Input Data Name	Description
Velocity Wind	Wind velocity computed by navigation systems based on heading, airspeed, ground track, etc
Velocity Wind Airdrop Altitude	Wind velocity at the aircraft airdrop altitude
Velocity Wind Ballistic	Wind velocity for period of element travel in ballistic (no chute) configuration
Velocity Wind Chute Deployed	Wind velocity for period of element travel under deployed chute
Velocity Wind Mean Effective	Mean wind velocity vector computed from airdrop altitude to PI
Velocity Wind PI	Wind velocity on the ground at PI

### 2.1.1 CARP Winds Equations

$$\text{Distance Along Track Wind} = \text{MEW}_{\text{ALONG}} \times \text{Total Time of Fall}$$

$$\text{Distance Cross Track Wind} = \text{MEW}_{\text{CROSS}} \times \text{Total Time of Fall}$$

$$\text{Total Time of Fall} = \text{Time to Stabilization} + \text{Time from Stabilization to PI}$$

$$\text{Time from Stabilization to PI} = \text{Altitude Chute Stability} / \text{Adjusted Rate of Fall}$$

The values for the above terms are determined as follows:

$$\text{Altitude Chute Stability} = \text{Altitude Above Drop Zone} + \text{Elevation High Point Air Drop Zone} - \text{Elevation PI Air Drop Zone} - \text{Distance Vertical Stability}$$

$$\text{Adjusted Rate of Fall} = \text{Rate of Fall}_{\text{DEPLOYED}} \times \text{Air Density Correction Factor}_{\text{DEPLOYED}}$$

Rate of Fall is entered, preloaded, or computed using ballistic data as Velocity Down Deployed (see table 2).

Air Density Correction Factor<sub>DEPLOYED</sub> is determined at the average drop pressure altitude and the average temperature in the vertical region bounded by the PI elevation and the drop altitude.

### 2.1.2 HARP Winds Equations

A two-stage model is used to calculate wind drift for HARP air releases. The total wind drift is the sum of the drift encountered in the free-fall, high-velocity stage and the drift encountered during the high-drag, chute-deployed stage.

$$\begin{aligned} &\text{Distance Along Track Wind} = \\ &\text{Distance Along Track Wind}_{\text{HIGH VELOCITY}} + \text{Distance Along Track Wind}_{\text{HIGH DRAG}} \end{aligned}$$

$$\begin{aligned} &\text{Distance Cross Track Wind} = \\ &\text{Distance Cross Track Wind}_{\text{HIGH VELOCITY}} + \text{Distance Along Track Wind}_{\text{HIGH DRAG}} \end{aligned}$$

**2.1.2.1 HARP Free-Fall, High Velocity (HV) Stage**

$$\text{Distance Along Track Wind}_{HV} = \text{Velocity Wind Ballistic}_{ALONG} + \text{Total Time of Fall}_{HV}$$

$$\text{Distance Cross Track Wind}_{HV} = \text{Velocity Wind Ballistic}_{CROSS} + \text{Total Time of Fall}_{HV}$$

$$\text{Total Time of Fall}_{HV} = \text{Time to Stabilization} + \text{Time From Stabilization to Actuation}$$

The wind drift component of the time of fall from aircraft exit to stabilization is entered, preloaded, or computed from ballistic data as Time of Fall Constant (see table 2).

$$\text{Time from Stabilization to Actuation} = [(\text{Altitude Chute Stability} - \text{Altitude Indicated Chute Actuation}) / \text{Adjusted Rate of Fall}_{HV}] + \text{Time Delay Chute Actuation}$$

The values for the above terms are determined as follows:

$$\text{Altitude Chute Stability} = \text{Altitude Pressure at Release Point} + \text{Altitude Difference True} / \text{Pressure} - \text{Distance Vertical Stability} - \text{Elevation PI Airdrop Zone}$$

$$\text{Adjusted Rate of Fall}_{HV} = \text{Rate of Fall}_{HV} \times \text{Air Density Correction Factor}_{HV}$$

Rate of Fall is entered, preloaded, or computed from ballistic data as Velocity Down Free Fall (see table 2).

Air Density Correction Factor<sub>HV</sub> is determined at the average drop pressure altitude and the average temperature in the vertical region bounded by the actuation altitude and the drop altitude.

**2.1.2.2 HARP High Drag (HD), Chute-Deployed Stage**

The second stage of a HARP air release begins at parachute actuation and ends at ground impact. This region is characterized by high drag as the parachute system is fully deployed. The second stage of the HARP air release is identical to that of the single-stage CARP release except for the initial high downward velocity of the drop element resulting from the HARP first-stage free fall.

$$\text{Distance Along Track Wind}_{HD} = \text{Velocity Wind Ballistic}_{ALONG} + \text{Total Time of Fall}_{HD}$$

$$\text{Distance Cross Track Wind}_{HD} = \text{Velocity Wind Ballistic}_{CROSS} + \text{Total Time of Fall}_{HD}$$

The values for the above terms are determined as follows:

$$\text{Total Time of Fall}_{HD} = \text{Time from Actuation to Deployment} + \text{Time From Deployment to PI}$$

The time from chute actuation to full chute deployment is entered, preloaded, or computed from ballistic data as Time Actuate Deploy (see table 2).

$$\text{Time from Deployment to PI} = \text{Deployment Altitude} / \text{Adjusted Rate of Fall}_{HD}$$

$$\text{Deployment Altitude} = \text{Altitude Indicated Chute Actuation} - \text{Deceleration Distance}$$

$$\text{Deceleration Distance} = \text{Distance Vertical Actuate-Deployment} + (\text{Time Delay Chute Actuation} \times \text{Adjusted Rate of Fall}_{HD})$$

$$\text{Adjusted Rate of Fall}_{HD} = \text{Rate of Fall}_{DEPLOYED} \times \text{Air Density Correction Factor}_{DEPLOYED}$$

Rate of Fall is entered, preloaded, or computed from ballistic data as Velocity Down Deployed (see table 2).

Air Density Correction Factor<sub>HD</sub> is determined at the average drop pressure altitude and the average temperature in the vertical region bounded by the PI elevation and the actuation altitude.

**2.2 RELEASE POINT COMPUTATIONS**

Based on the location of the desired PI, the C-17 mission computer uses ballistics and wind data as described in section 2.1 and the aircraft position, altitude, heading, and velocity to compute a point in space for the aircraft to fly to release its cargo. The C-17 aircraft is capable of flying to within 100-meter computed error probable (CEP) of the optimum air release point from which the first drop element will land at the PI.

CEP is calculated as follows [2]:

n = number of PI position data points

m = horizontal error

Geometric Mean (GM):

$$GM = \sqrt[n]{m_1 * m_2 * m_3 * \dots * m_{n-1} * m_n}$$

Root Mean Square (RMS):

$$RMS = \sqrt{(\sum m^2)/n}$$

$$R = GM / RMS$$

When  $R > 0.42$  then:  $Y = -0.13R^2 + 0.89R + 0.24$

When  $0.02 < R < 0.42$  then:  $Y = 0.23R - 0.05 + 0.84R^{1/2}$

When  $R < 0.02$  then:  $Y = 0.70R + 0.40R^{1/2}$

$$CEP_{50\%} = Y * RMS$$

The C-17 computations support three different modes of release: 1) CARP, 2) HARP, and 3) LAPES.

CARP. A computed air release point is obtained using MEWs applied to the ballistics of the cargo in a single stage model from airdrop altitude to the PI altitude.

HARP. A high-altitude release point is obtained using ballistic winds and deployed winds (see table 3) applied in a two-stage model that breaks the cargo fall into 1) a high-velocity, free-fall ballistic stage; and 2) a low-velocity, high-drag deployed stage.

Note: For CARP and HARP releases, the C-17 mission computer recomputes the location of the release point each time new input data are available (Recompute Airdrop in table 4). The C-17 mission computer also recomputes the predicted PI location 30 seconds prior to release based on current cross-track and track angle errors determined by the aircraft's guidance and navigation systems. The CARP/HARP forward and lateral offsets are computed and displayed on the aircraft's head-up displays (HUDs) and MFDs.

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CARP/HARP Forward Offset = Distance Along Track Wind – Distance Element Forward Travel

CARP/HARP Lateral Offset = Distance Cross Track Wind

Distance Element Forward Travel is entered, preloaded or computed as follows:

Distance Element Forward Travel = Ground Speed Airdrop x Time Forward Travel

Ground Speed Airdrop is the desired track along track ground speed during release.

### 2.2.1 LAPES

A LAPES release point is simply a point a short distance above the runway at which the C-17 automatically deploys an extraction parachute to pull cargo out of the cargo bay. Winds are not used in LAPES release point computations. The LAPES air release point is simply the latitude and longitude of the desired PI.

Airdrop Modes (CARP, HARP, or LAPES; Automatic Release or Manual Release) and Airdrop Types (Personnel, Cargo Extraction, Container Delivery System, or Combination Personnel/Container Delivery System) are selected on the C-17 aerial delivery system (ADS) panel. The C-17 airdrop software computes the air release point location for the selected airdrop mode and airdrop type using data from the Mission Airdrop Database and navigation systems. The software then sends the airdrop location to the aircraft flight plan. The C-17 provides the aircrew steering cues on the HUD and MFD to get to the air release point. Table 4 presents inputs to the computations from the Mission Airdrop Database and navigation systems, and table 5 presents the outputs of those computations.

**Table 4: Release Point Computations Inputs**

Input Data Name	Description
Angle Track Error	Angular error between aircraft current track and desired track before release
Airdrop Mode	CARP, HARP, or LAPES selection on ADS panel
Airdrop Number	Descriptor used in flight plan used to index data in the Mission Airdrop Database
Airspeed Indicated at Release Point	Indicated airspeed
Altitude Above the Drop Zone	Self explanatory
Altitude Difference True/Pressure	Difference between aircraft altitude above datum and aircraft pressure altitude
Altitude Indicated at Release Point	Indicated altitude
Altitude Indicated Chute Actuation	Indicated altitude at element chute actuation
Altitude Pressure at Release Point	Self explanatory
Auto Select Sensor Mix	The C-17 software allows the operator to select the sensor sources of data for release point computations. Parameters include temperature, altitude and surface winds. Sources can be either manual input or aircraft sensors.
Cross Track Error	Distance between aircraft current track and desired track before release
Distance Trailing Edge to Red Light Point	Distance on the ground from the Red Light Point (termination of release) to the outer edge of the drop zone
Distance Point of Impact to Trailing Edge	Distance on the ground from the desired PI to the outer edge of the drop zone defined by the operator
Drop Zone Axis Airdrop Zone	Axis line along which the rectangular drop zone is oriented

**Table 4: Release Point Computations Inputs (Concluded)**

Input Data Name	Description
Elevation High Point Airdrop Zone	Elevation of the highest terrain in the drop zone
Elevation PI Airdrop Zone	Elevation of the PI inside the drop zone
Greenwich Mean Time	Self explanatory
Ground Speed	Self explanatory
Heading True Inertial Reference Unit (IRU)	Aircraft true heading as measured by IRU
Latitude Present Position	Aircraft latitude
Longitude Present Position	Aircraft longitude
Location PI Airdrop Zone	Latitude and longitude of the desired PI (within 10 meters CEP)
Pressure Altitude Variation	Difference between mean sea level pressure altitude and navigation standard datum altitude
Recompute Airdrop	Function which updates the release point location based on any sensed change or operator entered change in the data that drives the release point location computation
Temperature at Chute Actuation Altitude	Atmospheric temperature at element chute actuation altitude
Temperature at Drop Altitude	Atmospheric temperature at release altitude
Temperature at PI	Atmospheric temperature on the ground at PI
Temperature Static Air	Atmospheric temperature of static air as measured by aircraft sensors
Time to Green Light	Time to start of an airdrop.
Time Red Light to Drop Zone Escape	Time from termination of release to a waypoint defined as the Drop Zone Escape waypoint
Type of Airdrop	Personnel, Cargo Extraction, Container Delivery System, or Combination Personnel / Container Delivery System

**Table 5: Release Point Computations Outputs**

Output Data Name	Description
CARP Forward Offset	Along track distance of the release point relative to the desired PI
CARP Lateral Offset	Cross track distance of the release point relative to the desired PI
Distance Along Track PI Correction	For combination element releases, the C-17 checks to insure the PI is inside the drop zone; if not, the distance along track to move the PI into the nearest drop zone edge is computed and displayed
Distance Cross Track PI Correction	For combination element releases, the C-17 checks to insure the PI is inside the drop zone; if not, the distance cross track to move the PI into the nearest drop zone edge is computed and displayed
Distance Drop Zone Escape	Distance from PI to the Drop Zone Escape waypoint
Drift Airdrop Wind Adjusted	Aircraft drift angle based on winds
Heading Airdrop Wind Adjusted	Aircraft heading
Location PI Airdrop Zone	The updated location of the desired PI within the drop zone

### 2.3 TIME-TO-GO CUES

The C-17 provides aural and visual cues to the crews during the airdrop, which give the crew ‘time-to-go’ to the air release point. At the release point (time-to-go = zero), the aircraft can automatically release the cargo, or the crew may release the cargo manually, depending on the type of cargo and mode of release.



**Table 6: Time-to-Go Cues**

Cue	Description
Audible Warnings	Audible countdown to release at 30, 20, 10, 6, and 1 minutes; then 10, 5, 4, 3, 2, 1 seconds
Visual Time	Visual indications of time-to-go on HUD and multifunction displays (MFDs)
Green Light	Aircraft has reached release point
Red Light	Aircraft is outside release area
Green Light Warning	Audible warning that Green Light is lit
Red Light Warning	Audible warning that Red Light is lit
No Autodrop	Visible indication that expected impact location is outside a 300-yard distance from desired PI
No Autodrop Warning	Audible warning when expected impact location is outside a 300-yard distance from desired PI
Airdrop Cue Type	Horizontal and vertical steering cues (Forward and Lateral Offsets) displayed on HUDs and MFDs
Time Duration Greenlight	Usable Drop Zone Length / Ground Speed Airdrop

## 2.4 RECORDING RELEASE DATA

At the release point, a green light comes on to indicate that the aircraft is releasing the cargo automatically, or to give the crew the go-ahead to release manually. The green light stays on throughout the release until the red light comes on, indicating end of an airdrop or the aircraft overflying the end border of the DZ. The C-17 aircraft is capable of releasing cargo day or night at various altitudes and in various weather conditions. It is important to record the specific conditions of the aircraft at actual release. Sometimes the aircraft may be slightly out of position, or winds may have changed somewhat. The C-17 automatically records data about winds, actual aircraft position, and other parameters, giving the air and ground crews required information about the release. This automatic-record feature is known as green light processing. The green light records are listed in table 7.

**Table 7: Green Light Processing**

Green Light Records	Description
Altitude at Green Light	Aircraft altitude at release
Angle Drift at Green Light	Aircraft drift angle at release due to winds
CARP Forward Error at Green Light	Distance error along drop zone axis at release
CARP Lateral Error at Green Light	Distance error perpendicular to drop zone axis at release
Ground Speed at Green Light	Aircraft ground speed at release along the desired track
Heading at Green Light	Aircraft heading at release
Location at Green Light	Aircraft latitude and longitude at release
Time at Green Light	Time of release

## 2.5 NAVIGATION TESTING CONSIDERATIONS

Details on navigation systems test methods and procedures can be found in *Flight Testing of Radio Navigation Systems* [3] and in chapter 3 of *Introduction to Avionics Flight Test* [4]. Additional test considerations can be found in the proceedings of the multiple Saint Petersburg International Conferences on Integrated Navigation Systems [5]. Basically the general method involves flying to a specific point, such as the CARP, using specific navigation system modes, maneuvering using pitch, bank and yaw, approaching



the point from various compass headings. As the tests are conducted, the resultant spatial and temporal navigation errors are measured and tracked. This requires using a very accurate truth source.

The measurements for the required parameters, such as the time, space, and position information (TSPI), velocities, and deck angle (pitch), must be accurate. Using cinetheodolites or differential GPS is crucial for accurate TSPI data. One such system, used at the U.S. Air Force Flight Test Center as an accurate truth source, is the GPS-Aided Inertial Navigation Reference (GAINR) system.

The GAINR equipment consists of three major components: airborne equipment, data link, and ground support equipment. The airborne equipment consists of a high-dynamic GPS receiver, inertial unit, and solid state recorder. The data link transceiver is also carried by the aircraft and provides a dedicated, duplex, GPS link to the ground. The data link can support up to 25 simultaneous participants at a 10 Hz rate, provide automatic air-to-air relay capability when out of line of sight (LOS) with ground stations, and encrypt the down-linked data. Air-to-ground range has been demonstrated to 100 statute miles, with the potential for extended range using relay aircraft. The ground equipment consists of four remote data link ground stations, control/display processors, and a GPS reference receiver. Real-time aircraft trajectories can be provided to the control rooms for map displays or statistical analysis. Data can also be postprocessed to allow for additional filtering and smoothing for increased accuracy. Maximum accuracy trajectory estimates using GPS data are achieved by the incorporation of differential corrections. This method, referred to as Differential Global Positioning System (DGPS), makes use of a ground reference receiver at a known location to estimate errors and correct GPS observation data in real time and/or postflight. In real time, the corrections can either be made in the ground processing or up-linked for airborne processing. The GAINR incorporates high-rate (256 Hz) inertial sensor data with 1-Hz GPS pseudo-range and 5-Hz delta-range data into a tightly coupled/integrated system. The final TSPI products are produced by the Multisensor Optimal Smoother Estimation Software (MOSES), which employs the Carlson-Bierman factorized method in a Kalman filter/smoothen. During its certification it produced position accuracies of ~1.7 meters (5.6 feet) horizontally and 2.5 meters (8.2 feet) vertically, and velocity accuracies of ~0.0038 meters per second (0.0012 feet per second).



## Chapter 3 – TRAJECTORY CONTROL OVERVIEW

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

### 3.0 ON-AIRCRAFT PERIOD CURRENT AND FUTURE SYSTEMS

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

#### 3.0.1 Gravity Airdrop

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

#### 3.0.2 Power Extraction

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

#### 3.0.3 Drogue Extraction

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

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

### **3.1 RECOVERY PERIOD: CURRENT AND PROPOSED SYSTEMS**

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

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

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

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

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

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

#### **3.1.1 Parachute**

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

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

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

### **3.1.2 Airborne Guidance Unit (AGU)**

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

### **3.1.3 Cargo Container/Pallet**

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

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

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

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

## TRAJECTORY CONTROL OVERVIEW

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

### 3.1.4 Mission Planning

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

### 3.1.5 International Precision Airdrop Demonstrations

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

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

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

More PATCAD information is available at the following website:

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

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

[Richard.Benney@Natick.army.mil](mailto:Richard.Benney@Natick.army.mil)

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

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



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

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

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

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

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

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

## TRAJECTORY CONTROL OVERVIEW

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



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

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

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



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

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



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

## **3.2 WIND SENSING SYSTEMS**

### **3.2.1 Rawinsonde**

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

### **3.2.2 Light Detection and Ranging (LIDAR)**

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

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

### **3.2.3 GPS Dropsonde**

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

## **3.3 PRECISION AERIAL DELIVERY – CURRENT AND FUTURE SYSTEMS**

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

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

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

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

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

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



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



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

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



**Figure 5: Snowbird in Flight.**

**3.3.2 Strong Enterprises SCREAMER**

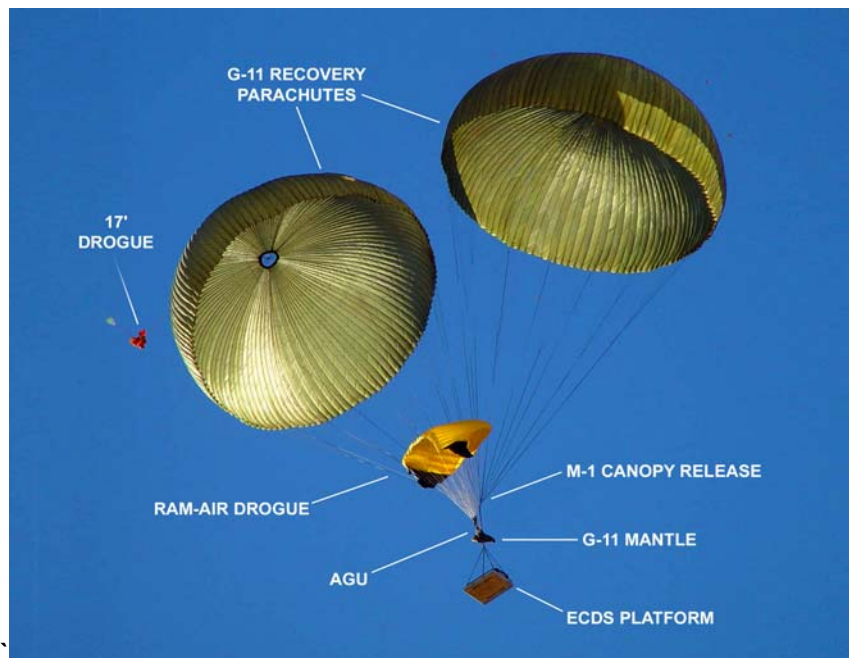
The SCREAMER concept was developed by Strong Enterprises, Orlando, Florida, and first produced in early 1999. The SCREAMER system is a hybrid JPADS that uses a ram-air drogue (RAD) canopy for controlled flight throughout the vertical descent and also uses traditional, round, uncontrolled canopies for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

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



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

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



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

### 3.3.3 DRAGONFLY 10,000-pound Capacity Parafoil System

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

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

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

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



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

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

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

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



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

### **3.3.4 Capewell and Vertigo AGAS**

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

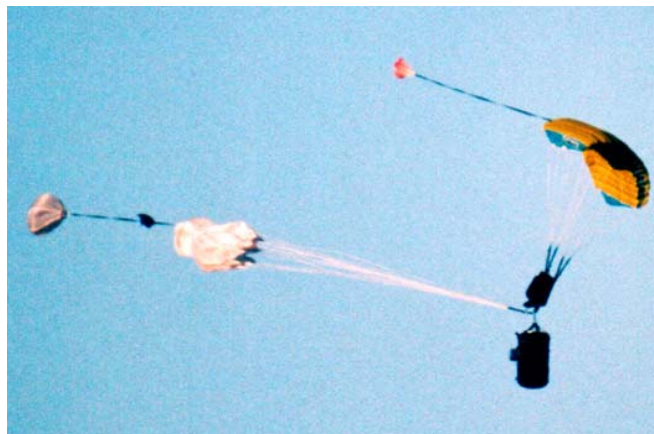


**Figure 9: Two AGAS Systems in Flight and During a Double and Single Riser Slip.**

### **3.3.5 Atair ONYX**

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

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



**Figure 10: Onyx System – Recovery Chute Opening.**

### **3.3.6 SPADES**

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



**Figure 11: SPADES Airdrop.**



### 3.3.7 Free Fall Navigation Systems

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

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

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

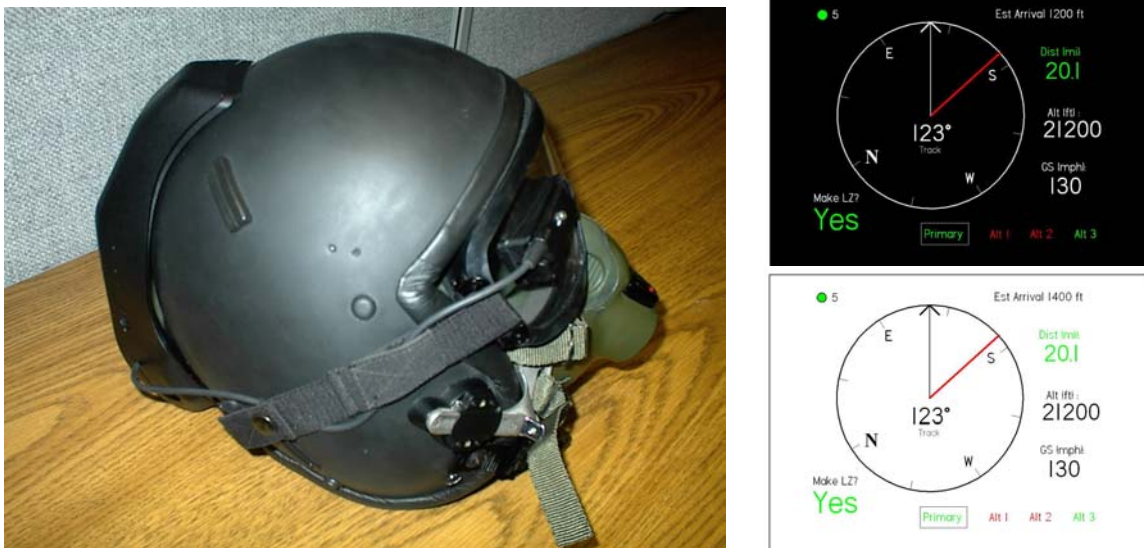


Figure 12: USMC/Coastal System and Day and Night Screens.

#### 3.3.7.2 NanΩhmics Inc.

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

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



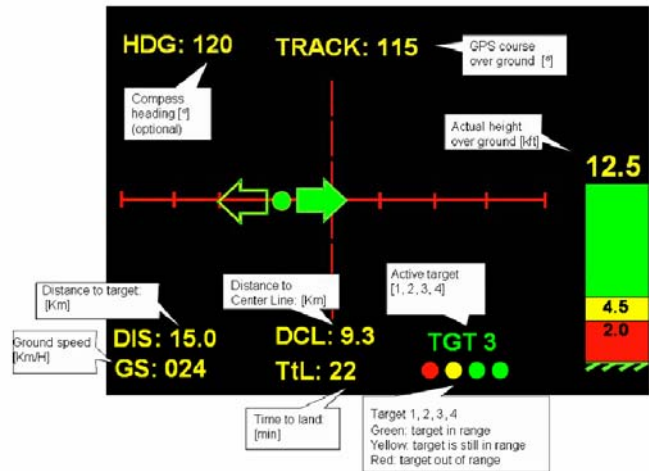
**Figure 13: NanΩhmics Free Fall Navigation System.**

### 3.3.7.3 EADS ParaFinder

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



1 User Interface HAHO Display



Pic. 1 ParaFinder HAHO-Display with explanation

Figure 14: EADS ParaFinder Airdrop and Display.

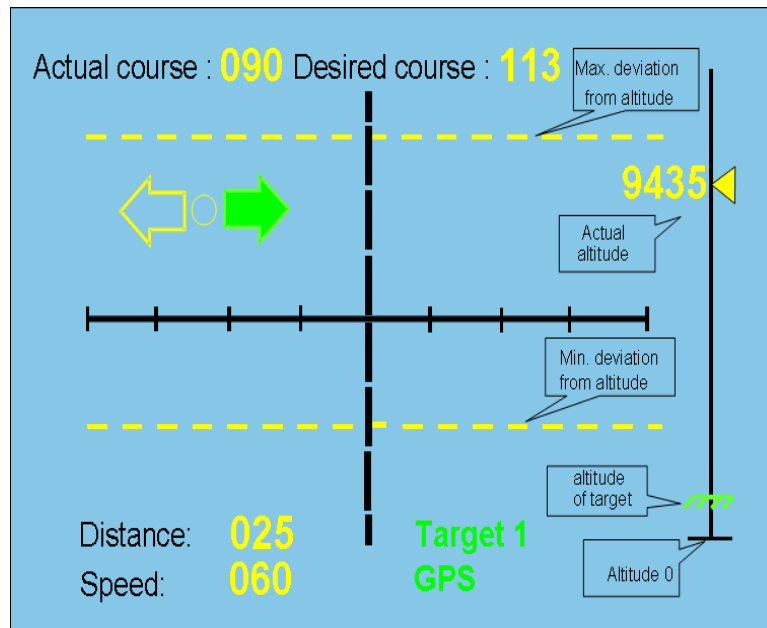


Figure 15: Typical HUD Display.

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

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



**Figure 16: EADS ParaLander.**

### **3.3.8 Stara Generic Delivery System (GDS)**

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



**Figure 17: GDS Airdrop.**

### **3.3.9 4,200-foot<sup>2</sup> Parafoil System**

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

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



**Figure 18: 10,000-pound Payload Delivered by a 4200-foot<sup>2</sup> Parafoil.**

### **3.3.10 Strong Enterprises Airborne All Terrain Vehicle and Trailer**

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



**Figure 19: Flight of Powered AATV.**



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



**Figure 20: ATR in Flight.**

### 3.3.11 MMIST Snowgoose

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

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

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

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



**Figure 21: Snowgoose Ground Launch from HMMWV.**



**Figure 22: Leaflet Cloud dropped by Snowgoose.**

### **3.4 AIRDROP TESTING CONSIDERATIONS**

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

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

## **TRAJECTORY CONTROL OVERVIEW**

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

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



## Chapter 4 – CONCLUSIONS

Precision airdrop has rapidly matured since 2001 and will likely become more common in military operations for the foreseeable future. Precision airdrop is a high-priority, short-term requirement for DAT and a Long Term Capability Requirement (LTCR) within NATO. Many NATO Nations' investments in these systems/technologies are growing. The need for precision airdrop is clear: we must protect our aircrews and transport aircraft by providing them the ability to avoid ground threats while concurrently providing pin-point-accurate delivery of supplies, equipment, and personnel over a widely dispersed and rapidly changing battle field.

Improved aircraft navigation using GPS has increased airdrop accuracy and weather forecasting and in-situ measurement technologies are providing significantly more accurate and higher fidelity weather information to aircrews and mission planning systems. The future of precision airdrop will focus on controllable, high-altitude-deployable, GPS-guided, high-performance airdrop systems that utilize advanced mission planning capabilities and provide focused logistics to the warfighter at an affordable cost. The ability to provide resupply and equipment anywhere, anytime and in nearly all weather conditions will become a reality for NATO in the very near future. Some of COTS and rapidly maturing national systems like, and including, those described in this report, are being utilized operationally in small quantities now. Further enhancements, refinements, and improvements can be expected over the coming years as the importance of getting materials where and when they are needed is critical in all military operations.

## CONCLUSIONS

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## Annex A – AERIAL RELEASE PROCESSES BY AIRCRAFT TYPE

This table briefly compares methods by aircraft type for the five basic elements of the air release process (ballistics, winds, computations, steering, and release).

**Table A1: Airdrop Elements of the Air Release Process**

Aircraft Type	Ballistics	Winds	Computations	Steering	Release
C-17	--Computer Database --Data entered manually or automatically updated from sensors	--Inertially Sensed --Automatic update to computations, or --Manually entered right up to release	--Computer calculates release point location	--Multi-Function Displays, and --Heads Up Displays provide steering info for pilots	--Automatic Mission-Computer Controlled, or --Manually accomplished by Loadmaster --Control Panel in cockpit for auto/manual selection
“Green” C-130 (a.k.a “Slicks”)	--Paper/Pencil computed and maintained by Navigator	--Paper/Pencil --Inertially sensed via Self-Contained Navigation System (SCNS) --No automatic update to release point computations	--Paper/Pencil computations by Navigator	--Navigator Steering Commands to Pilots	--Manually accomplished by Loadmaster
C-130J (no combination personnel / equipment elements like C-17)	--Computer Database --Data entered manually or automatically updated from sensors	--Inertially Sensed --Automatic update to computations, and/or --Manually entered right up to release	--Computer calculates release point location	--Multi-Function Displays, and --Heads Up Displays provide steering info for pilots --Radar enables position updates	--Automatic Mission-Computer Controlled or --Manually accomplished by Loadmaster --Control Panel in cockpit for auto/manual selection
MC-130H (Special Operations Aircraft)	--Computer Database --Data entered manually or automatically updated from sensors	--Inertially Sensed --Automatic update to computations, and/or --Manually entered right up to release	--Computer calculates release point location	--Multi-Function Displays --Radar and Infrared Sensor enable position updates prior to release	--Automatic mission-computer-controlled Green Light, but --Release manually accomplished by Loadmaster

## ANNEX A – AERIAL RELEASE PROCESSES BY AIRCRAFT TYPE

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## **Annex B – AGARD and RTO Flight Test Instrumentation and Flight Test Techniques Series**

### **1. Volumes in the AGARD and RTO Flight Test Instrumentation Series, AGARDograph 160**

Volume Number	Title	Publication Date
1.	Basic Principles of Flight Test Instrumentation Engineering (Issue 2) Issue 1: Edited by A. Pool and D. Bosman Issue 2: Edited by R. Borek and A. Pool	1974 1994
2.	In-Flight Temperature Measurements by F. Trenkle and M. Reinhardt	1973
3.	The Measurements of Fuel Flow by J.T. France	1972
4.	The Measurements of Engine Rotation Speed by M. Vedrunes	1973
5.	Magnetic Recording of Flight Test Data by G.E. Bennett	1974
6.	Open and Closed Loop Accelerometers by I. McLaren	1974
7.	Strain Gauge Measurements on Aircraft by E. Kottkamp, H. Wilhelm and D. Kohl	1976
8.	Linear and Angular Position Measurement of Aircraft Components by J.C. van der Linden and H.A. Mensink	1977
9.	Aeroelastic Flight Test Techniques and Instrumentation by J.W.G. van Nunen and G. Piazzoli	1979
10.	Helicopter Flight Test Instrumentation by K.R. Ferrell	1980
11.	Pressure and Flow Measurement by W. Wuest	1980
12.	Aircraft Flight Test Data Processing – A Review of the State of the Art by L.J. Smith and N.O. Matthews	1980
13.	Practical Aspects of Instrumentation System Installation by R.W. Borek	1981
14.	The Analysis of Random Data by D.A. Williams	1981
15.	Gyroscopic Instruments and Their Application to Flight Testing by B. Stieler and H. Winter	1982
16.	Trajectory Measurements for Take-off and Landing Test and Other Short-Range Applications by P. de Benque D'Agut, H. Riebeek and A. Pool	1985
17.	Analogue Signal Conditioning for Flight Test Instrumentation by D.W. Veatch and R.K. Bogue	1986
18.	Microprocessor Applications in Airborne Flight Test Instrumentation by M.J. Prickett	1987
19.	Digital Signal Conditioning for Flight Test by G.A. Bever	1991
20.	Optical Air Flow Measurements in Flight by R.K. Bogue and H.W. Jentink	2003

**2. Volumes in the AGARD and RTO Flight Test Techniques Series**

Volume Number	Title	Publication Date
AG237	Guide to In-Flight Thrust Measurement of Turbojets and Fan Engines by the MIDAP Study Group (UK)	1979

The remaining volumes are published as a sequence of Volume Numbers of AGARDograph 300.

1.	Calibration of Air-Data Systems and Flow Direction Sensors by J.A. Lawford and K.R. Nippres	1988
2.	Identification of Dynamic Systems by R.E. Maine and K.W. Iliff	1988
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11.	The Testing of Fixed Wing Tanker & Receiver Aircraft to Establish Their Air-to-Air Refuelling Capabilities by J. Bradley and K. Emerson	1992
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23.	Flight Test Measurement Techniques for Laminar Flow by D. Fisher, K.H. Horstmann and H. Riedel	2003
24.	Precision Airdrop by M.R. Wuest and R.J. Benney	2005





## REFERENCES

- [1] AFI 11-231, Computed Air Release Point Procedures, 7 Jul 2004.
- [2] Air Standard 70/16B, Air Standardization Coordination Committee, October 2002.
- [3] Flight Testing of Radio Navigation Systems, RTO AGARDograph 300 Flight Test Techniques Series – Volume 18, ADA380950, by Helmut Bothe, April 2000.
- [4] Introduction to Avionics Flight Test, AGARDograph 300 Flight Test Techniques Series – Volume 15, ADA322378, by James N. Clifton, PhD, March 1996.
- [5] 6th Saint Petersburg International Conference on Integrated Navigation Systems, RTO-MP-43, AC/323(SCI)TP/13, by various authors, October 1999.
- [6] Bagdonovich B., Desabrais K., Benney R., Fossar F., Vallance M., Carlsson P., “Overview of the Precision “Airdrop Improvement 4-Powers Long Term Technology Project”, AIAA paper 2003-2102 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 20-23, 2003, Monterey, California, USA.
- [7] M. Seeger, H. Eulenbach, P. Carlsson, Y. Bury, C. Delwarde, R. Benney, “Four-Powers Long Term Technology Projects,” AIAA paper 2005-1602 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [8] R. Benney, J. Barber, J. McGrath, J. McHugh, G. Noetscher, S. Tavan, “The Joint Precision Airdrop System Advanced Concept Technology Demonstration,” AIAA paper 2005-1601 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [9] R. Benney, J. McHugh, J. Miletti, P. Mortaloni, “Planning, Execution, and Results of the Precision Airdrop Technology Conference and Demonstration (2003),” AIAA paper 2005-1668 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [10] Philip D. Hattis, Thomas J. Fill, David S. Rubenstein, Robert P. Wright, and Richard J. Benney, “An Advanced On-Board Airdrop Planner to Facilitate Precision Payload Delivery,” AIAA paper 2000-4307 presented at the AIAA Guidance, Navigation, and Control Conference, August 14-17, 2000, Denver, Colorado.
- [11] Philip Hattis, Thomas Fill, David Rubenstein, Robert Wright, Richard Benney, David LeMoine, “Status of an On-Board PC-Based Airdrop Planner Demonstration,” AIAA paper 2001-2066 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 22-24, 2001, Boston Massachusetts.
- [12] Philip Hattis, Kai Angermueller, Thomas Fill, Robert Wright, Richard Benney, and David LeMoine, “An In-Flight Precision Airdrop Planning System,” presented at the 23rd Army Science Conference, December 2-5, 2002, Orlando, Florida.
- [13] R. Wright, et al, “Precision Airdrop System,” AIAA paper 2005-1644 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [14] Action Item Response to NATO Air Force Armaments Group (NAFAG) Air Group 5 on Avionics and Landing Systems Precision Airdrop Technologies by Carr and Benney.
- [15] U.S. Air Force Ballistic Wind Program, by R. Richmond, D. Jewell, J. Carr and J. Root.

## REFERENCES

---

- [16] S. Kaesemeyer “Testing of Guided Parafoil Cargo Delivery Systems (2005),” AIAA paper 2005-1668 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [17] R. Benney, J. Barber, J. McGrath, J. McHugh, G. Noetscher, S. Tavan, “The Joint Precision Airdrop System Advanced Concept Technology Demonstration,” AIAA paper 2005-1601 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [18] J. McGrath, T. Strong, R. Benney, “Status of the Development of an Autonomously Guided Precision Cargo Aerial Delivery System,” AIAA paper 2005-1625 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [19] J. Berland, S. George, J. Barber, “Development of a Low Cost 10,000 lb capacity Ram-Air Parachute,” AIAA paper 2005-1626 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [20] Carter, D., George, S., Hattis, P., Singh, L., Tavan, S., “Autonomous Guidance, Navigation, and Control of Large Parafoils” AIAA paper 2005-1643 presented at the AIAA Aerodynamic Decelerator Systems Conference, Munich, Germany, May 23-26, 2005.
- [21] S. Dellicker, R. Benney, S. Patel, T. Williams, C. Hewgley, P. Yakimenko, R. Howard, and I. Kammer, “Performance, Control, and Simulation of the Affordable Guided Airdrop System,” AIAA paper 2000-4309 presented at the AIAA Guidance, Navigation, and Control Conference, August 14-17, 2000, Denver, Colorado.
- [22] V. Dobrokhodov, O. Yakimenko, I. Kammer, R. Howard, S. Dellicker, and R. Benney, “Development and Flight Testing of the Affordable Guided Airdrop System for G-12 Cargo Parachute,” AIAA paper 2001-2060 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 22-24, 2001, Boston Massachusetts.
- [23] B. Gilles, M. Hickey, W. Krainski, “Flight-Testing of a Low-Cost Precision Aerial Delivery System,” AIAA paper 2005-1651 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [24] J. Wegereef, H. Jentink, “Parafoil Characteristics Tests with SPADES,” AIAA paper 2005-1650 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [25] H. Altmann, J. Windl, “ParaLander: A Medium-Weight Demonstrator for Autonomous, Range-optimized Aerial Cargo Delivery,” AIAA paper 2005-1627 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [26] T. Bennett, R. Fox, “Design, Development, and Flight-Testing of the U.S. Army 4200 ft<sup>2</sup> Parafoil Recovery System,” AIAA paper 2005-1628 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [27] J. Stein, C. Madsen, A. Strahan, “An Overview of the Army’s Guided Parafoil System Derived from X-38 Experience,” AIAA paper 2005-1652 presented at the AIAA Aerodynamic Decelerator Systems Conference, May 23-26, 2005, Munich, Germany.
- [28] AGARD Flight Test Techniques Series Volume 6 on Developmental Airdrop Testing Techniques and Devices, by H. J. Hunter, ADA189621, September 1987.

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Cargo transportation	Stability																
<b>14. Abstract</b> <p>This AGARDograph describes the basic principles and testing considerations for precision airdrop systems. A variety of precision airdrop systems available as commercial-off-the-shelf and others in various stages of development will be described in general terms. Some of the systems described are currently in use while other systems are in development. This report also concentrates on the aircraft navigation to the airdrop release point and on the trajectory control and concepts of airdropped payloads to enable accurate ground impacts. In addition, the report outlines the need for precision airdrop systems and introduces the reader to potential Concepts of Operations. A list of useful reference documents is included in the report. These can be helpful to the reader looking for appropriate details if the full background should be needed for information contained in this AGARDograph.</p>																	





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