Precision Aerial Delivery Systems in a Tactical Environment

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ABSTRACT

A systems level analysis of precision aerial delivery systems provides a basis for comparing the characteristics of different types of systems and the implications that component and control approach selection have on system performance. High-glide and low-glide systems types are described. The effects of glide ratio, control response and sensor selection on terminal accuracy are analyzed. Wind data is necessary for all system types. The paper discusses the use of wind data, the need for an accuracy estimate as part of the wind data and the trade between wind data accuracy and attainable offset. In tactical situations, the concept of operations and the selection of system type and desired offset performance is affected by the threat scenario, and the operator's knowledge of threats and their distribution. Several novel operational concepts are discussed, along with the implications for system performance requirements. As part of the analysis, this paper suggests new nomenclature needed to analyze systems, introduces key operational concepts, and areas for future study.

Nomenclature

ARC	Aerial Release Circle
BIT	Built-In Test capability
PI	Point of Impact
IP	Intended Point of impact
CARP	Calculated Aerial Release Point
DoD	US Department of Defense
GN&C	Guidance, Navigation, and Control
JPADS	Joint Precision Aerial Delivery System
KPP	Key Performance Parameter
$\hat{V}$	mean wind error
σ	standard deviation

I. Introduction

Interest in precision aerial delivery systems is increasing, driven by military users for whom accurate, timely delivery of equipment and supplies is critical. Development has been enabled by affordable navigation sensors based on the Global Position System (GPS). Development has also been enhanced by the parallel development of remote wind profile sensing, improvements in mesoscale forecasting, and systems capable of fusing measured wind data and forecasts from multiple sources.

Precision aerial delivery systems of a several distinct types have been developed in response to this combination of user demand and affordable enabling technology[1-4]. The objective of this paper is to suggest a framework for the systematic characterization of precision aerial delivery systems that is traceable to key performance parameters

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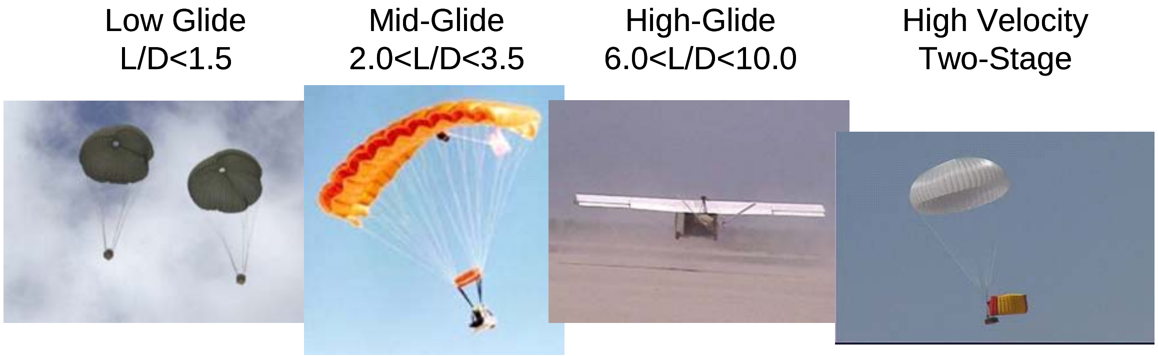
(KPPs) and that applies to all system types. As part of this objective, we will introduce nomenclature related to the concepts of operation peculiar to precision aerial delivery systems.

II. Guided Airdrop Types

It is convenient to classify precision aerial delivery system type according to their glide ratio (L/D) to the extent that present systems with similar glide ratio tend to have strong similarities in configuration and operating characteristics. Here, we suggest types according to three ranges of glide ratio and one additional type that is not easily classified buy glide ratio alone.



Low-glide types include controlled conventional cargo parachutes and single-surface gliding type parachutes. At this time only the former is represented.

Mid-glide types are exclusively ram-air inflated double surface, rectangular planform wings, commonly known as parafoils.

High-glide types include deployable high aspect ratio wings. Several examples have been demonstrated, but none are technically mature or operational at this time.

High velocity, two-stage types can use a guided first stage of any of the preceding types and a second stage comprising conventional cargo parachutes appropriate for the payload weight. The first stage is relatively small and highly loaded, resulting in high speed guided descent. The second stage is deployed at low height above the ground and descends without guidance.

Specific descriptions of the various types of systems and their development are found in references 4 through 8. All of these systems have the potential to meet most/all KPPs for the 1st two JPADS weight classes defined by DoD[10].

III. Key System Performance Parameters

The intrinsic performance parameters that bring value to a guided aerial delivery system are accuracy, reliability, payload capacity and safety of the drop aircraft. These parameters relate directly to getting a given payload on the ground accurately.

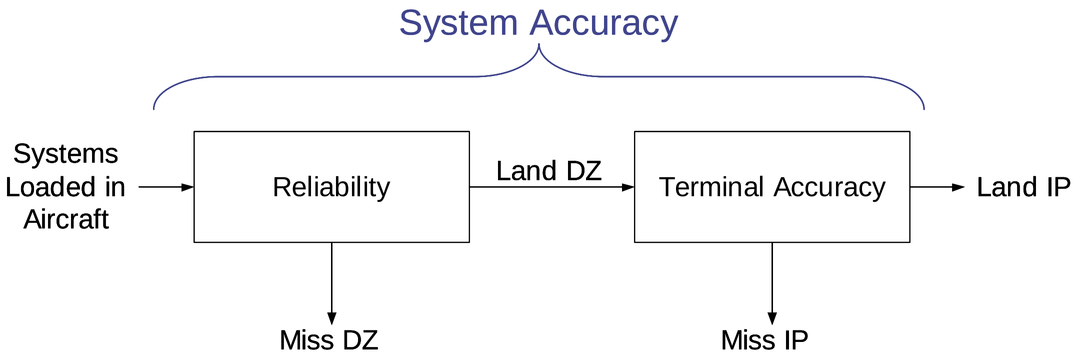
Glide ratio, or release point offset from a given height above the DZ, is a derived performance requirement based on safety of the drop aircraft. A particular threat or operational scenario would be required to derive such an offset requirement. Glide ratio and airspeed also have an effect on the use of wind data and the effect of wind data error as discussed later in this paper.

IV. Reliability and Accuracy

We wish to define several concepts and associated nomenclature related to reliability and accuracy of precision aerial delivery systems:

- Reliability The probability of the Aerial Delivery System (ADS) reaching a point in the vicinity of the DZ from which a guided approach and landing at the IP can be successfully completed.
- Terminal Accuracy For all systems that reach a point to which the IP can be reached, the distance from the IP to the nearest of all landing points falling within a specified probability level, e.g. 50% for CEP, 68% for 1σ, 95% for 2σ, 99.7% for 3σ.
- System Accuracy For all systems that are loaded on the drop aircraft, the distance from the IP to the nearest of all landing points falling within a specified probability level.

The block diagram below illustrates the relationship implied by these definitions between reliability, terminal accuracy and system accuracy. All systems, once loaded on the drop aircraft, count toward the accuracy statistics. One important point is that reliability affects system accuracy such that an unreliable system cannot be considered to be accurate.



V. Reliability: Failure Modes and Effects

The mode of failure and its effects can have a great deal to do with the outcome of an attempt to deliver critical supplies and equipment. For example, certain types of failures may still result in the payload being available to the troops on the ground if the result is degraded accuracy and a landing in the vicinity of the DZ. Other failures result in destruction of the payload or a landing so far from the DZ that it cannot be recovered in a timely manner. The table below lists and comments on a number of potential failure modes associated with precision aerial delivery systems.

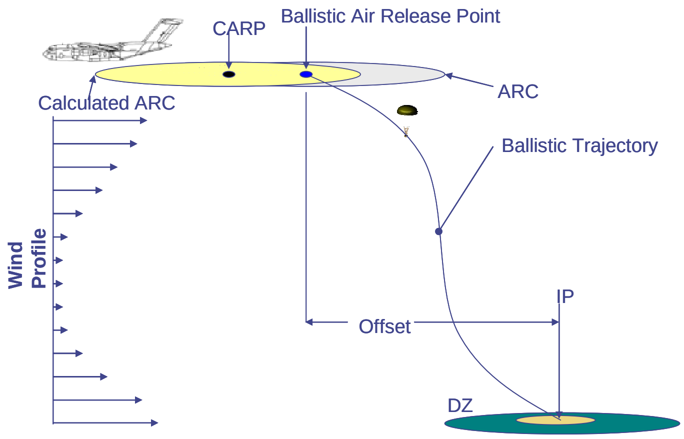
Failure Mode	Effect	Comment
Fails BIT	Payload not available	Not a failure mode of unguided systems. Can drop low glide system unguided.
Parachute fails to open	Payload destroyed	Also a failure mode of unguided systems. A function of parachute type, training, maintenance, etc.
Aircraft misses CARP	Miss DZ, payload unavailable or damaged	Also a failure mode of unguided systems. Mitigated by guided systems.
Wind Data Error>System Horizontal Authority	Miss DZ, payload unavailable or damaged	Low glide system needs 10 kt accuracy. High glide system accuracy requirement depends on release offset.
Control System fails after deployment	Miss DZ, payload unavailable or damaged	High glide system lands far from DZ. Low glide system reverts to no-glide, lands near DZ.

VI. Air Release of Aerial Delivery Systems: Defining Terms

We wish to define terms related to air release and the effects of wind:

- **Impact Point (IP)** – designated point of intended landing.
- **Point of Impact (PI)** – actual point of landing
- **Air Release Point (ARP)** – point of release of the airdrop unit from the drop aircraft.
- **Ballistic Trajectory** – trajectory along which an unguided, drag-only body would fall in order to reach the IP.
- **Ballistic ARP** – the intersection of the delivery aircraft flight path with the ballistic trajectory, i.e., a theoretically perfect release point
- **Calculated ARP (CARP)** – standard airdrop terminology for the calculated location of the air release point based on estimated winds.
- **Air Release Circle (ARC)** – a circle at the release altitude, centered on the Ballistic ARP, within which the glide performance of the system is sufficient to reach the IP.

The difference between the "Ballistic Air Release Point" and the "Calculated Air Release Point" is the error in the wind data used to calculate the CARP. If we had perfect knowledge of wind, there would be no need for guided airdrop systems when dropping one payload. Clearly all guided systems with a large enough altitude release and glide ratio will be able to overcome the natural "spread" which is related to the speed of the aircraft and the time it takes to deploy all payload units.



VII. Wind Estimation Error

Wind varies in space and time, making exact knowledge of wind velocity along a particular trajectory impossible. However, various methods of measurement and analysis are available to aid in estimating wind.

Sources of error include the very causes of wind: movement of weather systems and associated pressure gradients; orographic influences, both meso- and micro-scale effects; convection, which causes the most rapid time variation; terrain variations, and other diurnal thermal effects.

Even direct measurements of the wind by dropsonde are inexact for precision airdrop purposes. Sources of measurement error are associated with time and location. Winds will change between the time of the measurement and the time of the airdrop. The shorter the interval between measurement and release, the more accurate will be the result. Location errors come from an inability to drop along the exact intended trajectory and tend to be greatest for the low altitude portion of the data and in mountainous terrain.

Three equations are shown, each defining “average” wind estimation error.

The first equation simply calculates the unguided ballistic landing error, over the time of flight, to arrive at the average wind error. This might be an appropriate definition for assessing unguided systems, but note that the estimated wind could be substantially incorrect at all times and still “average” to zero. A guided system in such a wind could accumulate substantial error trying to chase the erroneous wind estimate even though the wind estimate was “perfect” by this definition.

$$\hat{V} = \left| \frac{\int \overline{V}_{true}\,dt - \int \overline{V}_{estimated}\,dt}{T} \right|$$

The second equation avoids this problem by averaging the absolute value of the estimating error over the time of flight. This does not allow errors of the opposite direction to cancel. This definition might be more useful in characterizing the performance of guided systems.

$$\hat{V} = \frac{\int \left| \overline{V}_{true} - \overline{V}_{estimated} \right| dt}{T}$$

The third equation is an RMS version of the second, which may or may not be more useful statistically. More statistical analysis is needed to resolve this question.

$$\hat{V} = \sqrt{\frac{\int \left| \overline{V}_{true} - \overline{V}_{estimated} \right|^{2} dt}{T}}$$

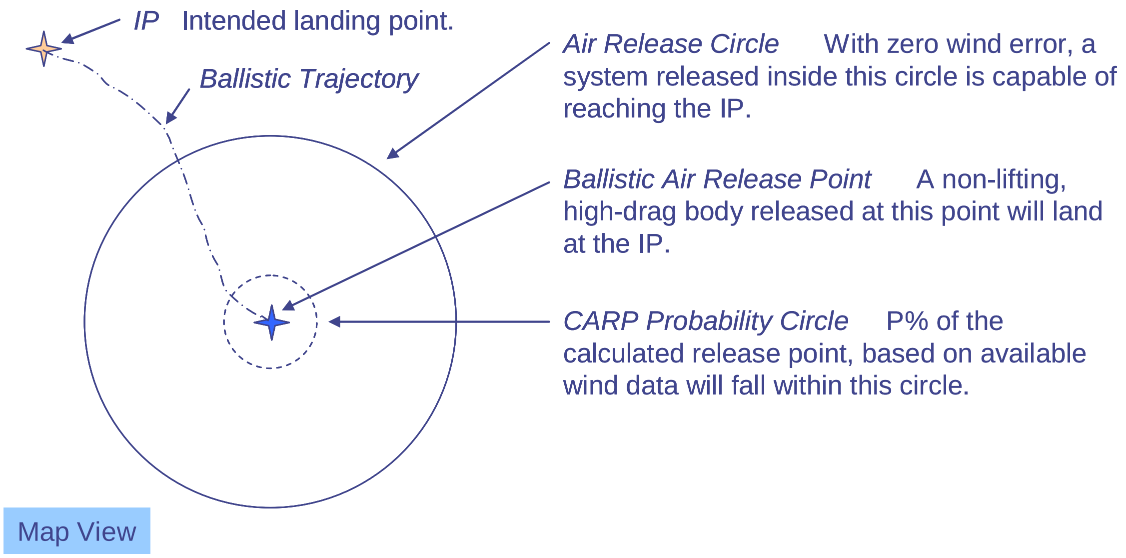
VIII. Wind Estimation Error Effect on Guided Systems

The radius of the Air Release Circle is proportional to system glide ratio and the difference in altitude between release and landing.

$$R_{ARC} = \left(z_{release} - z_{IP} \right) L/D$$

The diagram below shows the air release circle relative to the IP and the ballistic trajectory. The dashed circle represents the CARP probability circle, whose interior will contain a given percentage of calculated air release points for a given uncertainty in available wind data. The radius of the CARP probability circle is proportional to the wind uncertainty, proportional to the release height, and inversely proportional to descent velocity.

$$R_{CARP\_probable} \propto \frac{\left(z_{release} - z_{IP} \right)}{V_z} \hat{V}$$

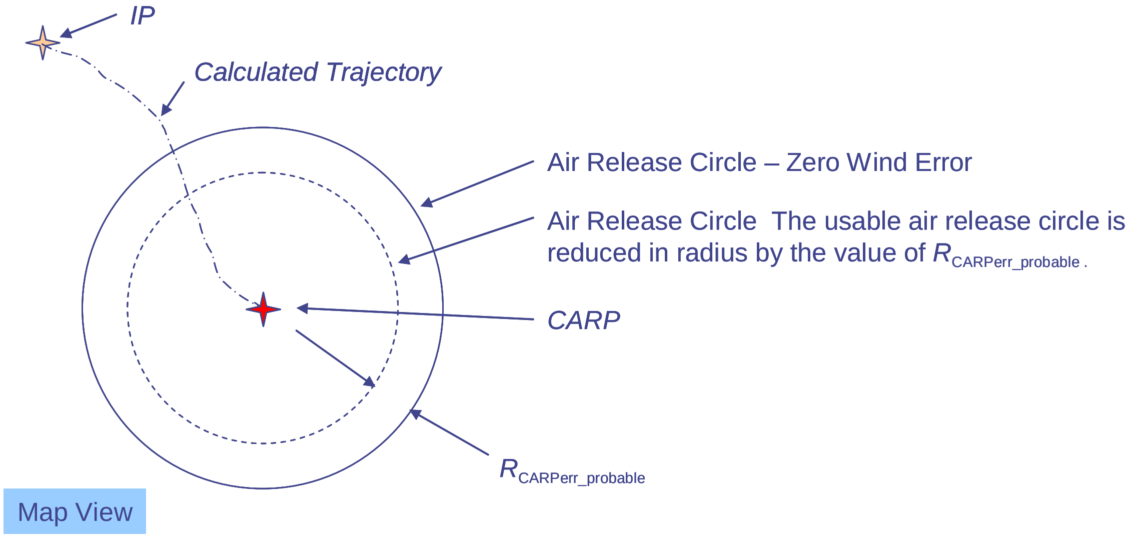


Air Release Circle With zero wind error, a system released inside this circle is capable of reaching the IP.

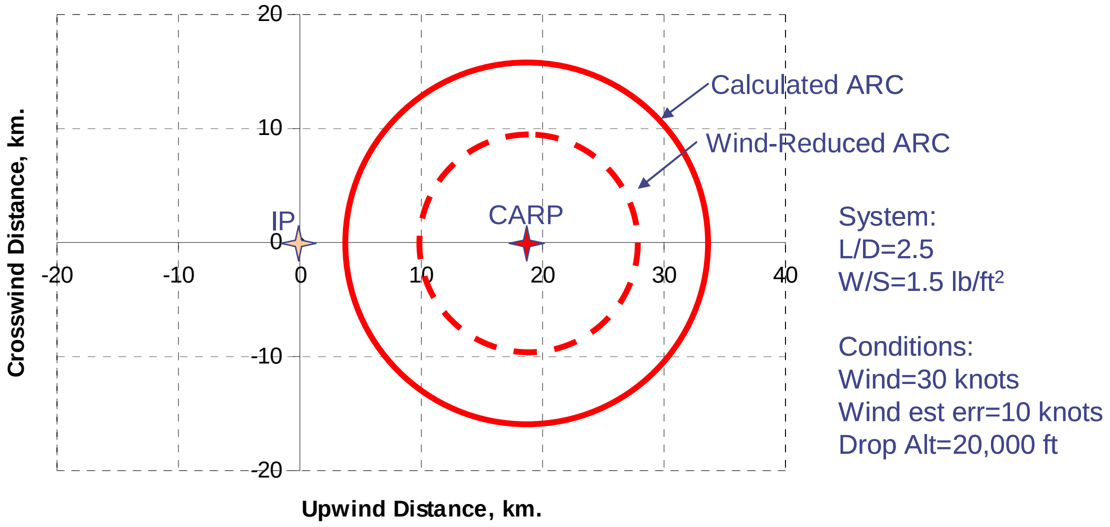
Ballistic Air Release Point A non-lifting, high-drag body released at this point will land at the IP.

CARP Probability Circle P% of the calculated release point, based on available wind data will fall within this circle.

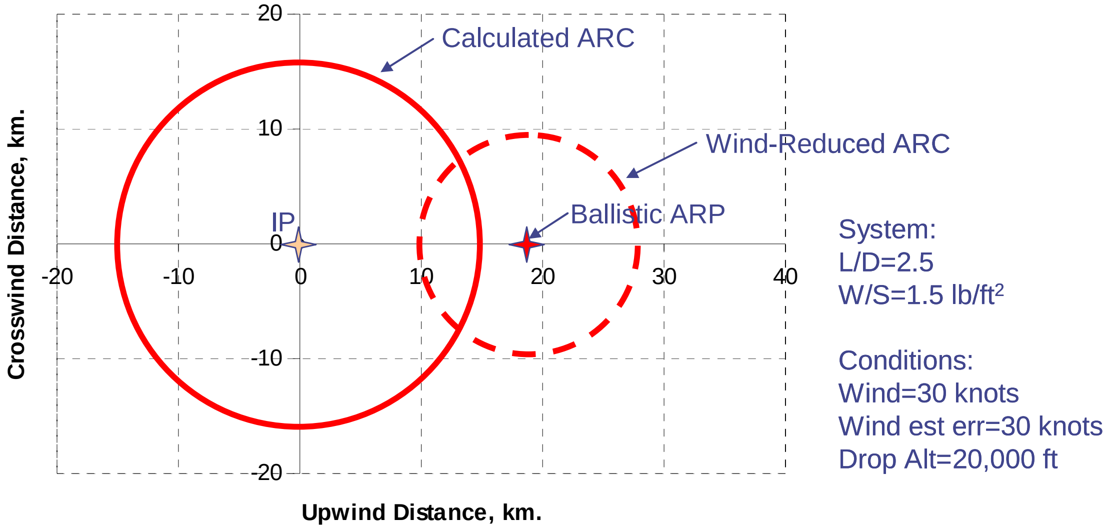
Because the Ballistic Air Release Point is a theoretical point in space that cannot be determined by any practical means, the diagram below is modified to place the Calculated Air Release Point at the center of the map view. The usable portion of the Air Release Circle is reduced in radius by the value of the radius of the CARP probability circle.



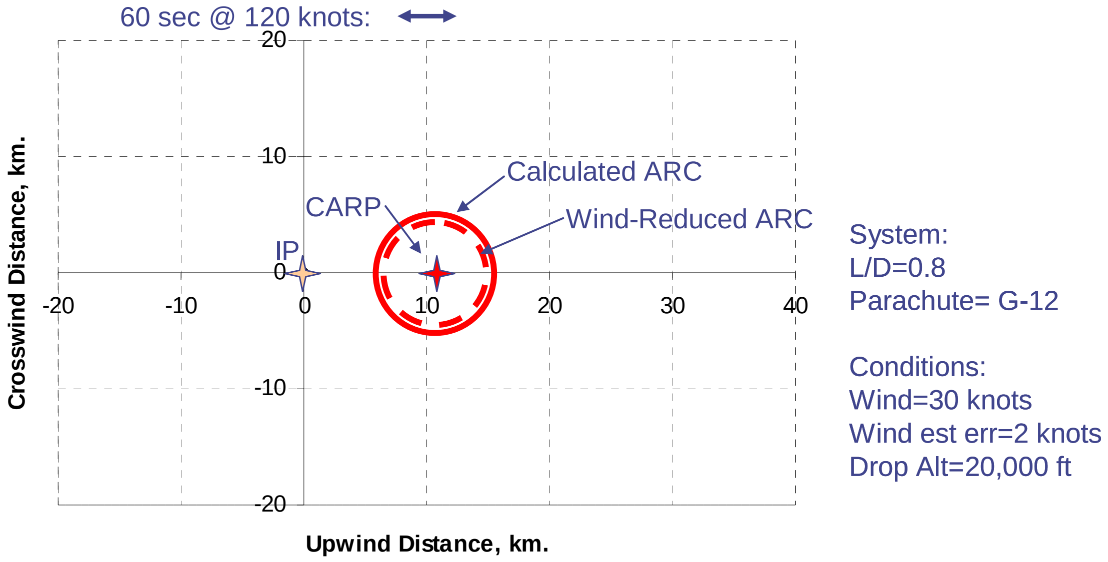
A few examples are useful to illustrate how the effects of wind, wind uncertainty, glide ratio, and true airspeed are combined in an ARC diagram. The first example is for a mid-glide system descending 20,000 feet through a mean wind of 30 knots with an uncertainty of 10 knots. One-third of the available offset is needed to overcome wind uncertainty.



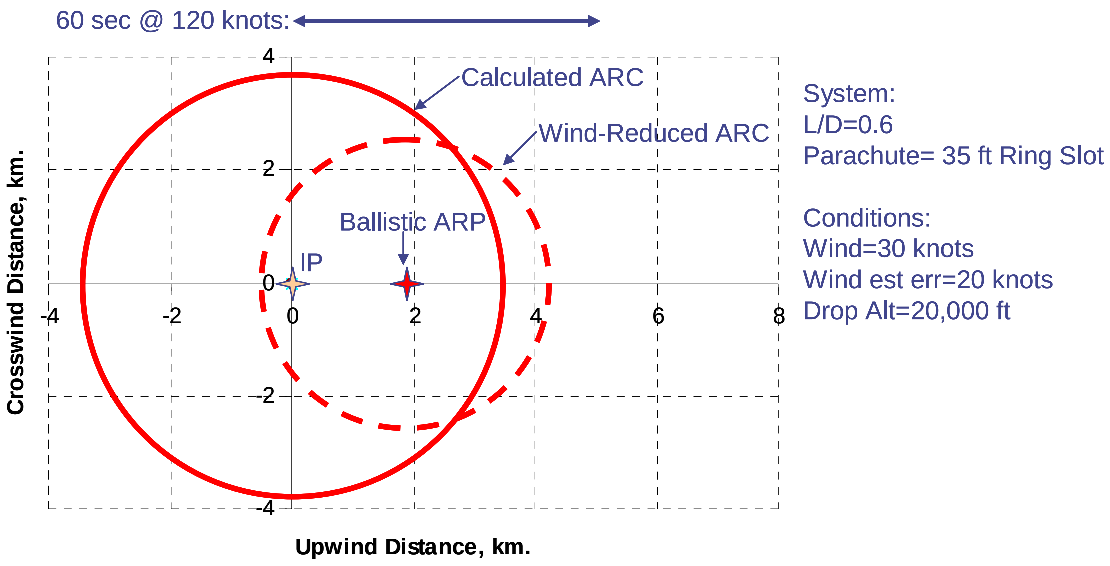
The next example is for the same system and drop conditions, but without any available wind data. The release circle from which the IP can be reached remains the same. However, without wind data, the flight planner has no way of knowing where to drop within the zero-wind glide circle centered on the IP. Most release point within that circle will not result in a landing at the IP. The point being that glide performance, expressed as release point offset, must be allocated between range and wind uncertainty. Maximum range is only available when wind is known very accurately.



The next example is for a low-glide system with low wind uncertainty, typical of using a dropsonde within 10 minutes of release. The raw release circle is much smaller than the mid-glide system and good wind data is needed to maximize the wind-reduced release circle. The usable air release circle would take approximately 120 seconds to traverse at 120 knots.

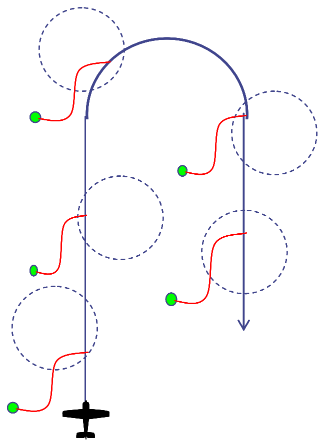


Now consider a high-velocity (160 f/s) two-stage system with low L/D using "aged" winds with high uncertainty. The flight planner could choose to ignore the forecast and drop directly over the IP and still have a successful delivery. Note the change of scale. Both the circle sizes and the ballistic offset are reduced because of the high vertical velocity. The additional landing dispersion during unguided final descent is not included in the diagram.

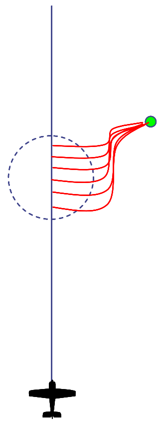


IX. Types of CONOPS

The concept of operation, the way in which a system is utilized to meet the objective of the operation, has an effect on the desired characteristics of a precision aerial delivery system. For example, consider two concepts of operation, "one on many" and "many on one", as illustrated below.



"One On Many"



"Many On One"

In each diagram the aircraft flies into a calculated air release circle, shown as dashed circles, releases one or more cargo units within that circle in order to deliver to the IPs, shown as small circles.

The "One on Many" type of operation may benefit from offset capability if the multiple release circles can be reached with less maneuvering of the drop aircraft.

The "Many on One" type of operation is a mass re-supply scenario, and stresses terminal accuracy and the ability to drop multiple units without mid-air collisions.

X. Terminal Accuracy

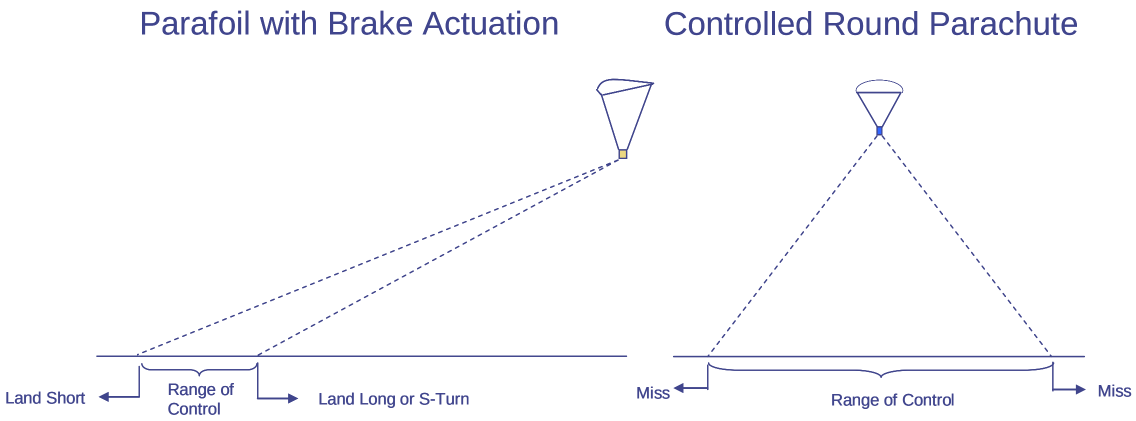
The terminal phase of flight starts after the system has flown to a point from which the IP can be reached. During this phase the system maneuvers to hit the IP as accurately as possible. Some general observations concerning terminal accuracy are:

- The effects of errors in wind data are more severe near the ground than early in the descent because there is less time to correct.
- Lateral errors are generally much smaller than longitudinal errors for mid- and high-glide systems.
- Vertical errors become amplified landing errors with high-glide approach angles.

Several different methods of path control are used by the various types of systems. Lateral control methods are generally consistent within the type classification by glide ratio. Low-glide systems use a glide-on-command approach that reverts to a ballistic trajectory except when horizontal velocity is needed. There is no “forward” body axis direction. Control is not by “steering” of an always forward moving body, but by modulation of the magnitude and direction of the lift vector. Mid-glide systems steer by turns that are initiated by skidding and continue to skid in a fully developed turn (under-banked compared to a coordinated turn) to a degree determined largely by system mass and wing loading. High-glide systems will generally steer by banked turns much as a conventional aircraft.

Vertical control, by which we mean control of the path angle to affect the longitudinal location of the point of impact, also has a variety of forms. Low-glide systems using glide-on-command do not distinguish between lateral and vertical control. The fact that the path of such systems is nearly vertical, normal to the target plane, is an advantage in the terminal phase. Mid-glide systems use a variety of control laws that lengthen the path in order to effectively reduce glide ratio, for example by adjusting the base-final turn point or by flying S-turns. Some systems also apply “brakes” by deflecting both steering lines together. High-glide systems have not yet addressed vertical control effectively, but one can look to manned glider techniques for some possibilities.

One of the largest improvements in mid-glide systems would be more effective vertical control. Some research is underway now on that subject.



XI. Ground-Air Threats to Drop Aircraft

The threats to cargo aircraft engaged in airdrop operations over hostile territory can be classed as either IR-guided man-portable air defense systems (MANPADS) or radar-guided surface-air missiles (SAMs). It is assumed that cargo aircraft will not operate in areas were air-air threats exist. The principle distinguishing characteristics of these threats are summarized below:

- IR-guided shoulder-fired weapons
    - World-wide proliferation
    - Not possible to identify potential launch sites
    - Threat mitigated by flying above 15,000 ft AGL
- Radar-guided anti-aircraft weapons
    - Threat reaches above 20,000 ft
    - Known threats are eliminated before cargo-type aircraft enter airspace.

Vertical Offset, the difference between the drop aircraft altitude and the ground elevation of the drop zone, provides effective threat avoidance for drop aircraft for IR-guided weapons.

Horizontal Offset could provide additional threat avoidance for radar-guided weapons, but only if their locations are known. Known radar weapon sites are usually taken out before cargo aircraft are cleared into an area. However, there may be special instances, such as covert operations, in which radar weapons are left in place and cargo needs to be inserted, where horizontal offset capability becomes useful.

XII. Conclusions

We have suggested nomenclature to assist in comparing the characteristics and performance of precision aerial delivery systems of different types.

The importance of wind data for all types of systems is emphasized. We note that the availability of accurate wind profile data is rapidly improving and will continue to improve in the future.

In order to use wind data effectively for flight planning a measure of the uncertainty of the data at the time of system release is needed along with the data itself.

This work is intended as a framework for further analysis of aerial delivery systems. In particular, we hope that work will proceed to establish a rigorous statistical basis for analyzing these systems.

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