Wind Forecast Accuracy and PADS Performance Assessment

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If the wind is known and the navigation and guidance logic of a parachute system leads it close to the drop zone (DZ) for final approach, a good guidance and control scheme can make it land a few yards from the IP. Yet when winds change and the system's flight software is not robust enough, however fine the guidance and control part of the algorithm, the airdrop error can become very large. Weather forecast agencies can give at best a good evaluation of an average wind field in a given area for a given period of time. Wind is seldom stationary, and its fluctuations are such that two wind profiles measured 30 minutes apart can show a difference of roughly 4 m/s over a height span of 1000 m (observed July 6, 2005 during a Precision Airdrop Capability Demonstration (PACD) in Biscarosse, FR). The direct consequence is that even with the best forecast system and drop sondes used just prior to the airdrop, Precision Air Delivery Systems (PADS) will face winds different from what was used in the mission planing. Therefore a class of models was developed in ASTRAL software that simulates accurately generic navigation logic with simplified guidance and control models. They are valid as long as the navigation logic plans trajectories with few turns and lots of straight branches, or smooth curves that allow the system to make turns in almost stabilised turn configurations. Therefore they can be simulated with only speed and turn rate performance data on the systems (1st order dynamics with 3 DoF, as opposed to the 2nd order 6 DoF dynamics model also available in ASTRAL), and are highly representative of the main part of the descent, the homing? phase, and can be correctly representative of some final approach logic, except in cases where highly dynamic manoeuvres are implied (by extension, those model cannot determine if a self guided system is stable in turbulent wind conditions). Assuming the system guidance is effective, the ASTRAL models allow simulating a mission plan with an "expected" wind forecast, then simulating an airdrop mission with a "real" wind forecast, then verifing if the flight logic is robust to the wind change. The major advantages and opportunities of the numeric analysis are : the possibility to choose planing as well as real wind profiles, which is not possible in real-time airdrop testing; a significant amount of forecast and sensed wind data is available thanks to a preceding work; the detail level chosen for the models (1st order) makes it easy to physically interpret the simulation results, which facilitates formal demonstrations to assess the PADS ability to reach the DZ at the end of the flight, hinted by the pure numerical output, and for some to assess the performance of the final approach logic. In a specific case, it was possible to show a system was able to reach the Impact Point (IP) in wind conditions so varied that flight tests could have never covered them all. It was also possible for other systems to demonstrate that forecast wind data were insufficient and drop sondes were needed.

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Nomenclature

IP   =   intended point of impact
PI   =   actual point of impact
$CARP_p$ =   Computed air release point

I. Introduction

Self guided and precision airdrop systems are based on a parachute system, a mission planing system that requires wind data, and automatic actuation devices that improve the accuracy as compared to classic ballistic airdrop. When using non-guided, immediate opening systems, the parachute system experience the effect of wind drift to the fullest extent, which means any airdrop position error, wind forecast error, or system sink rate variation leads to loss of landing precision.

During the 90', a 4 power long term technology project known (LTTP) as Precision Airdrop Improvement (PAI) was initiated to identify and conduct preparatory work for future precision airdrop applications.

One of the most basic precision systems is the HALO airdrop system, for High Altitude Low Opening, that aims at increasing precision by minimising the time of descent, thus limiting exposure to winds, while maintaining an impact speed comparable to the classic solution by opening the main parachutes close to the ground. PAI LTTP needed figures to assess the concept's potential, and in the early 2000's ASTRAL proved to be convenient software to generate both figures and illustrations. ASTRAL stands for Analyse Statistique des Trajectoires pour l'AéroLargage.

Early in 2005, PAIc, the continuation of the PAI 4 powers LTTP, decided to focus on guided systems with the same techniques. The work to be done was twofold: gathering information about the statistical accuracy of wind data used for airdrop applications, and modelling the behaviour of self guided systems at a level both simple enough not to need too much manufacturers' data and elaborate enough to be representative of how wind changes affect Self Guided Systems, at <u>navigation</u> level. The second fold is the purpose of the current paper.

For the purpose of this paper, navigation, guidance and control are defined as follow :
- Navigation is the highest level of trajectory management : it involves positioning and planning a route.
- Guidance is an intermediary trajectory management level : it consists in choosing an instantaneous direction to go or attitude to keep that will generate the transitory trajectory back to the planned route, of just keep the system on route ("flight director").
- Control is the law that defines command actions to execute the guidance objective ("autopilot").

In the case of airliner automated flight management, the "flight director" executes the guidance level and defines a bank and pitch to keep that lead to the planned route defined in the navigation management system. The "autoplilot" stricto sensu keeps the prescribed attitude. In the case of self guided airdrop systems, either attitudes or heading or bearing can be used as guidance parameters, depending on the system's avionics equipment : 3 axes inertial platforms, 1 axis heading reference or only GPS with no orientation data. The 3 trajectory management level are often more difficult to differentiate in SGS as compared to planes for multiple reasons : real-time trajectory re-planning blurs the frontier between navigation and guidance, and guidance base on directions to go instead of attitudes to keep blurs the frontier between guidance and control.

II. Simulation architecture, cases and models

A. ASTRAL architecture

ASTRAL is a software application allowing to define airdrop systems models with the equation of mechanics of their successive phases of operation, and to link those to environmental data (atmosphere, terrain) and system data (masses, drag areas, opening time) in an ergonomic interface.

The simulations are run with either deterministic or random input data. The automatic running of hundreds simulations allows one to estimate the system's performance when data is available about the probable variations on each parameter. In the current work, based on a statistical sample of forecast and measured wind, the analysis is not based on the random input data option but on deterministic simulation ran with actual statistic wind data taken from the PAIc database.
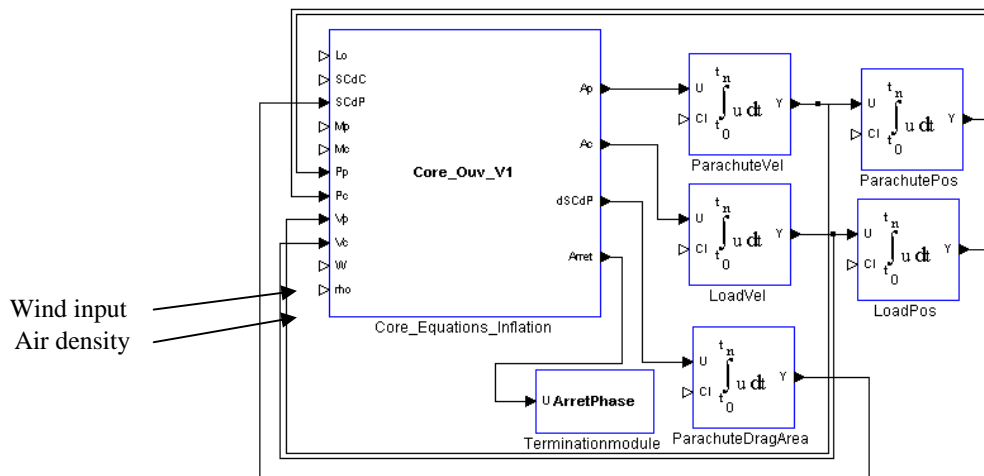
Figure 1: ASTRAL graphic interface for model assembly. This assembly integrates the equations of motion and the parachute inflation model defined in the core equations module. Links with additional modules (weather, terrain, Guidance and Navigation Unit model) allow one to build a full simulation.

B. Guided hemispherical parachute case

The guided hemispherical parachute model is based on the ballistic characteristics of a G-12 parachute loaded at 600 Kg, assuming it can be steered with a glide ratio of 0.5 (this is hypothetical and not based on existing systems), and the steering is directed to move the parachute toward a planned trajectory. The planned trajectory is based on a wind forecast and built bottom-up from the planned Impact Point (IP). The instantaneous position of the system is compared to the planned position at the current altitude, which gives a direction to drive toward the planned trajectory. The steering is applied in that direction. The model does not simulate the transitory phase between two different steering commands, which is not significant at navigation level. It happens only when the parachute crosses or gets near to the planned trajectory, and thus has the lesser effect when the guidance impact is the more important.

The simulation is conducted in 3 runs. The first run uses the forecast wind, provided by one of the PAIc nations, to generate the CARP and planned trajectory with no guidance. The second run uses the planned CARP and an actual wind profile measured at the time and place of the forecast. It does not have any guidance and provides a reference for the guided case. The first run uses the planned trajectory and CARP, the actual wind profile and the navigation capability. Compared to the first two trajectories, it shows how well a guided hemispherical system could perform when using wing forecasts.
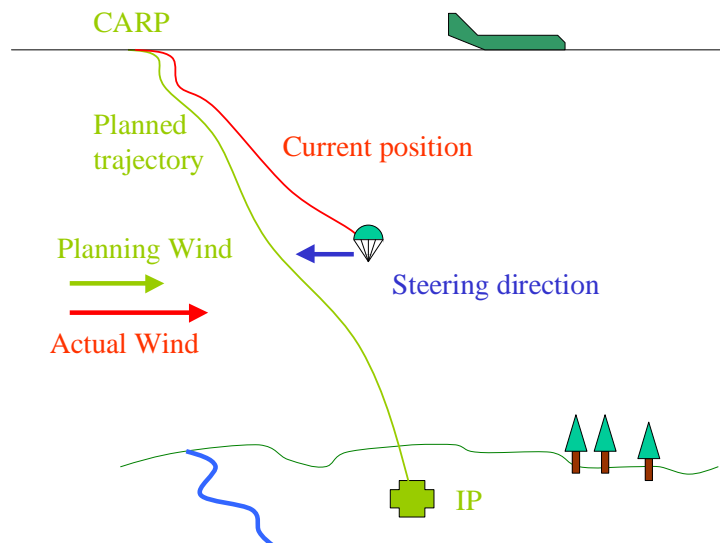

Figure 2 : schematic of the guided G-12 guidance principle.

C. High velocity, gliding system with two stages

The second system modelled is a fast load that uses a small parafoil for substantial wind penetration, then opens a G-12 recovery parachute ~500 ft above ground level. Its typical performance is a vertical velocity of 10 m/s (2000 ft/min) in standard conditions and a glide ratio of 2. At FL 240, this corresponds to about 15 m/s vertically and 29 m/s horizontally (57 Kts). The navigation logic aims at heading toward the vicinity of the IP with a straight ground track, then orbiting around the IP until the recovery height is reached. The load then flies a few seconds toward the IP and the G-12 opens. Its performance is intended to allow nearly all weather operations (except for the usual limitations on wind speed at ground level). When the wind is too strong for the system to rule its track, the guidance rule was made to put the load headwind and thus minimize the drift. Its good glide ratio allows one to expect a significant horizontal stand-off capability, and makes it robust to wind.
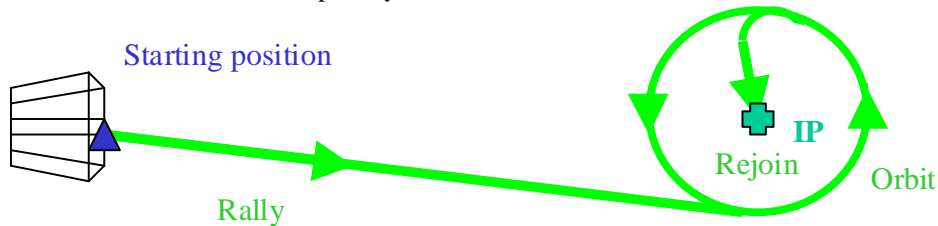

Figure 3 : Schematic of the gliding system's navigation plan.

D. Models

Both systems are based on two dynamically linked models. One integrates the equations of flight, based on speed performance data. The other simulates the guidance and navigation logic.

Equations of flight model :
Input :
- atmospheric density ρ (g/l) and wind w (3D vector) from the atmospheric data model
- heading h (degrees)

Parameters:
- sink rate and horizontal velocity (Vz_{ref} and Vh_{ref}) at standard atmospheric conditions (ρ = 1.225 g/l)

Speed computation:
- at any specific location, the atmospheric data model gives ρ (that decreases with altitude)
- with the local atmospheric density, the vertical and horizontal true speed are updated with

$$V = Vref \sqrt{\frac{1.225}{\rho}} \quad (1)$$

- wind is added to determine groundspeed

Output:
- speed is integrated and the output is a trajectory

Guidance and navigation logic for the guided hemispherical parachute:
The actual position compared to the planned position at current altitude gives the heading input for the flight model

Guidance and navigation logic for the gliding phase of the high velocity system:
Input:
- current position
- current groundspeed

Parameters:
- IP coordinates
- radius R for the orbit phase
- decision height to rejoin the IP

A mobile target is generated to determine is the system should steer right or left if above the recovery height. "Mobile target" means a geometric construction based on where the system is and its theoretical track

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(navigation plan as defined in this paper) that allows to determine the instantaneous optimal direction to steer (guidance as defined in this paper). If below, the target is the IP. If the system is slower than the wind, it can be unable to achieve the prescribed groundtrack. In this case, the guidance model is set to face the wind and thus minimise its effect.

Output:
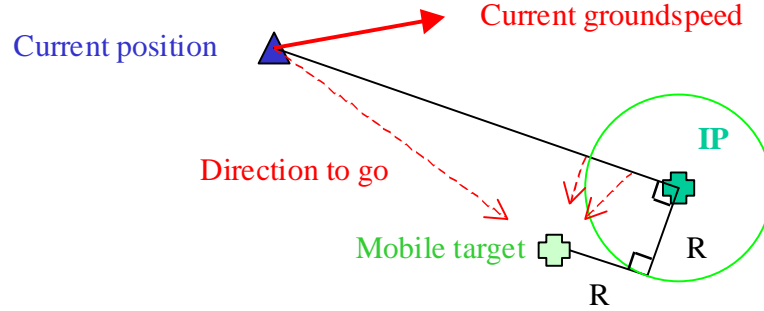- a turn rate right or left that allows to update the heading for the flight model.

Figure 4 : Schematic of the guidance logic for the gliding system. If the distance to IP equals the orbit radius R, the direction to go will be tangent to the orbit circle. If the distance is different, the direction to go converges to the circle's tangent.

The orbit radius R is set to at least twice the turn radius at which the system is designed to operate. As long as the system is faster than the wind and the air release point is close enough, the described guidance logic generates the required flight pattern. The guidance logic to aim at a mobile target is easier to master than the guidance logic to follow a prescribed path, since the underlying mathematical model has only 1 degree of freedom (a direction to keep) instead of 2 (a direction and a cross track distance to keep): 2 DoF models, when badly parameterised, can have a built-in oscillatory behaviour that can interfere with the system's own yaw oscillations.

III. Simulation results for the guided G-12

A. Purpose
The purpose of this series of simulations is to evaluate the capability of a G-12 based precision airdrop system to operate with only wind forecast data. The wind data used to run the simulation were collected in 2005 by the PAIc nations, both to serve as a statistical sample of wind data and to develop a wind profile comparison method.

B. Wind forecast precision data
The precision of wind forecast is hardly easy of use in airdrop application when expressed in terms of velocity and direction. Indeed, a big change in direction for a low velocity may bring a minimal change in drift. A small change of direction for a strong wind may cause a big change in drift. Therefore, when analysing the wind forecast accuracy for airdrop applications, PAIc often represents wind profiles with Cartesian coordinates (east and north component, the directions the wind blows TO). A wind of force 2 m/s and direction 150° blows FROM south and east, TO north and west, its Cartesian components are east -1 m/s and north +1.7 m/s. The drift error (or difference between drift as caused by the measured wind and drift as expected from the wind forecast) can also be analysed in east and north components, with a simple integral of the wind profiles. PAIc chose to sample wind data by layers of 100 m, and the expression of the standard drift error is :

$$Derr_e(z) = \sum_{n=1}^{n=z/100} \left(Ws_e(z_a) - Wf_e(z_a)\right) \times \frac{100}{Vs} \sqrt{\frac{\rho(z_a)}{1.225}} \quad (2)$$

$Derr_e(z)$ is the Drift error, east component, for an airdrop at height z
n is the count of 100 m layers between ground level and height z
Ws and Wf are the wind profiles, sensed and forecast. e stands for east components.
Za is the average height of the atmosphere layer (nx100-50)
Vs is a reference calibrated sing rate chosen equal to 6 m/s

ρ is the atmospheric density of the standard OACI atmosphere at height Za.
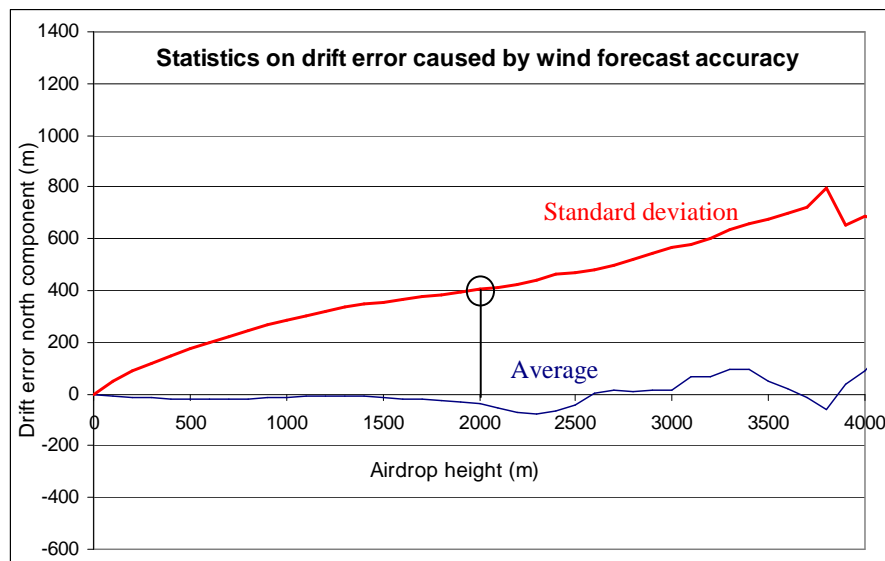The same process is applied to north components.

Figure 5 : an example of statistics on drift error profiles. This data is representative of the french civilian weather agency forecast in France. The average drift error is smaller enough than the standard deviation for the sample used to be representative. The red curve reads as follows: for airdrop at 2000 m (circle marker), with a parachute loaded so as to fall at 6 m/s at sea level, the standard drift error is 400 m on the north-south axis. With the hypothesis of a gaussian distribution, this means 68% probability to fall closer than 400 m north or south of the IP. A factor 2 is needed to reach a 95 % probability and a factor 2.6 (1040 m) to reach a 99 % probability.

The drift error expression raises two other difficulties related to wind profiles, be they Cartesian or polar :

First, a wind forecast error may have opposite directions at different altitudes. When a parachute is dropped in such conditions, wind forecast errors at a given altitude can be compensated at a lower altitude. If a statistical analysis is made on wind profiles, the information about error direction change with altitude is lost and the effect on drift can not be determined. The drift error function includes the effect of error direction (the sign of Ws-Wf and the integral form) and statistics on drift error are then useful for airdrop applications.

Moreover, a parachute does not have a constant rate of fall with altitude: the effect of wind forecast errors at high altitude are therefore a little attenuated by higher sink rates, related to the decrease in atmospheric density.

The reference sink rate of 6 m/s was chosen as a good base value, making conversions easy for various classes of systems. For example, for the slower gliding systems known (with sink rates of 3 or 4 m/s), the drift error shall be multiplied by 2 and 1.5 respectively. For a Container Delivery System (CDS), falling closer to 9 m/s, remove one third. For a HVCDS, divide by three. For a HALO, divide by up to ten.

These statistics are used to know the likeliness of a certain amount of forecast error, in terms of drift.

C. Example simulation cases

In a first case where the biggest forecast error happens 3,500 m above ground level, the system proves to be able to enhance precision: without control, the impact would be more than 3 Km away from the IP. Guidance allows the system to land within 200 m of the IP.
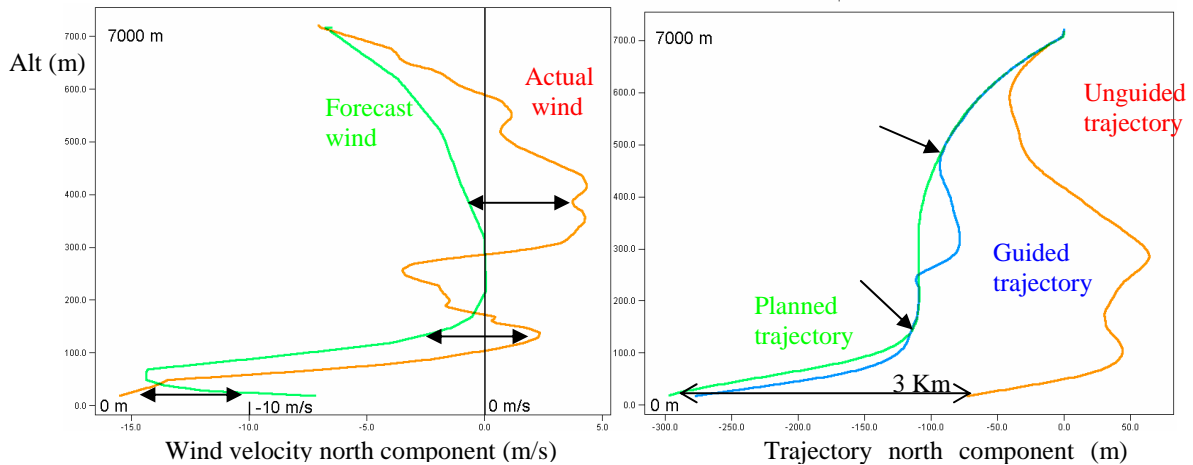
Figure 6 : Wind data used in a simulation and simulation result. The greatest local wind forecast errors are marked with arrows on the left graph. The first and second encounters of errors greater than the system's compensation capability cause the system to leave the planned trajectory (arrows on the right graph).

In a first case where the biggest forecast error happens 3,500 m above ground level, the system proves to be able to enhance precision: without control, the impact would be more than 3 Km away from the IP. Guidance allows the system to land within 200 m of the IP.

In a second case, the biggest forecast error happened to be close to ground level. In such a case, once the system leaves the planned trajectory, there is no possibility to subsequently return to it. This case was based on a wind forecast generated by a foreign forecast system for a region in France influenced by the local geography. Mountains in the south of France and a valley that goes from Toulouse to the Mediterranean cause a local increase of wind at ground level 2 days out of 3. The foreign agency probably did not use a fine enough numerical terrain model or a boundary condition to its weather simulation; the same result would be expected for any nation that uses rough terrain data for areas outside their own territory: the wind forecast is the worst close to ground level, where it is more difficult to handle.
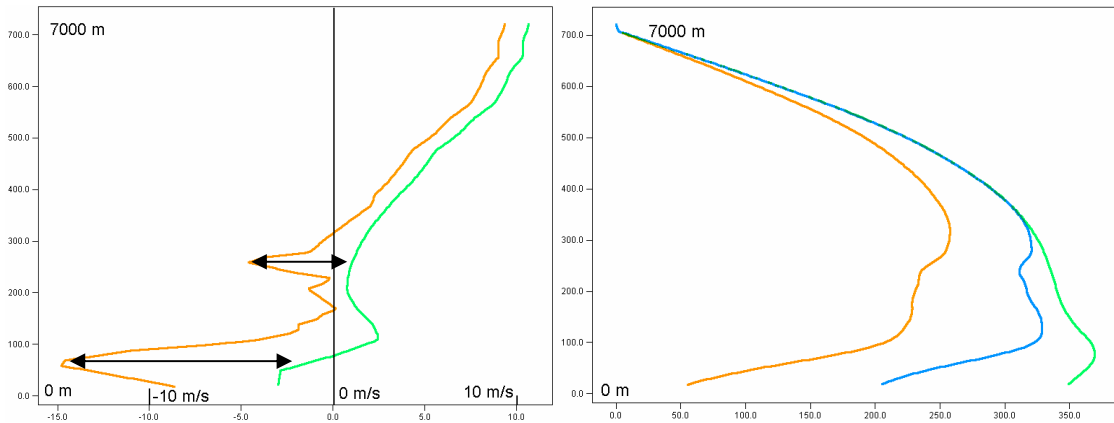

Figure 7: Wind data used in a simulation and simulation result. The greatest local wind forecast errors are marked with arrows on the left graph. The greatest forecast error happens close to the ground, so that the system cannot compensate it.

D. Performance analysis

Cases with a large range of unguided drift error were tested to estimate the correction capability of the steered G-12. If the drift error due to the forecast quality is lower than 2,000 m, the system is able to compensate.
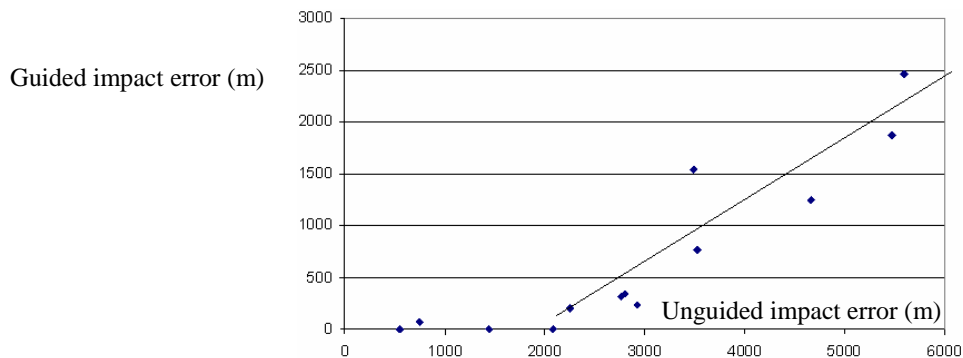
Figure 8: guided system precision vs. unguided system precision for a G-12 model for airdrop at 7,000 m.

For unguided impact errors greater than 3,000 m, the guided system could fail by more than 500 m. Using data such as presented in figure 5, French civilian forecasts in France with a 6 hours term would allow optimal precision with a probability of 85 %. This kind of analysis demonstrates that precision airdrop with a guided G-12 parachute based on wind forecasts is successful only with a top quality weather forecast system. Since few nations have so far the ability to check their forecasts' precision on any area of the world, and it can hardly be expected to be better than the forecast they make for they own territory, the use of drop sondes is for most users the only means to make the concept effective.

IV. Simulation results for the fast gliding system

A. Purpose

The analysis purpose is to check the capability of the system to operate without wind forecast and evaluate its precision if the final turn toward the IP is not adapted to the encountered wind. The goal of the system design is to allow a 100% accurate airdrop with 0% mission planning. It shall allow vertical airdrop with no more information than the wind at flight level obtained with the plane's navigation data and a wind at ground level compatible with the G-12 final stage.

B. Wind sample

To determine the « vertical airdrop » capability, the strongest profile was chosen, valid for March 30, 2005 at 0900 UTC. With 10 m/s at ground level, 15 m/s at 500 and 3,000 m, 23 m/s at 5000 m and 52 m/s at 7,200 m, it is as strong a wind as can be expected that allows a G-12 to land (10 m/s at ground level). Two simulations are presented here, the first for an airdrop facing north, the second for an airdrop facing east.
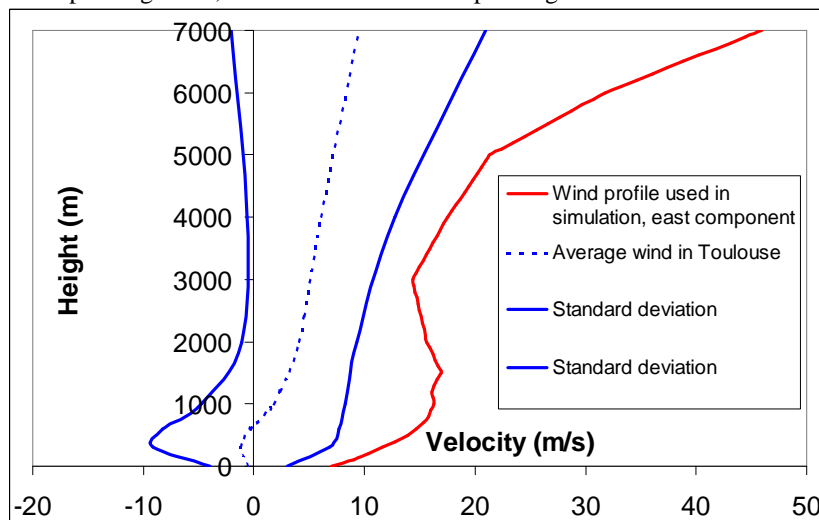

Figure 9 : East component of the wind profile used to check the vertical airdrop capability for a fast gliding system.

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In France, such winds happen no more than a few days a year (except for actual storms, when airdrop is anyway impossible). The north component is about half the east component (wind blows from direction 300°).

C. Vertical airdrop simulation result

In the initial part of the descent, the system faced the wind with a heading 300°, and yet was unable to land close to the DZ. Below 5000 m, the wind decreases, allowing the system to start rallying its waiting pattern.
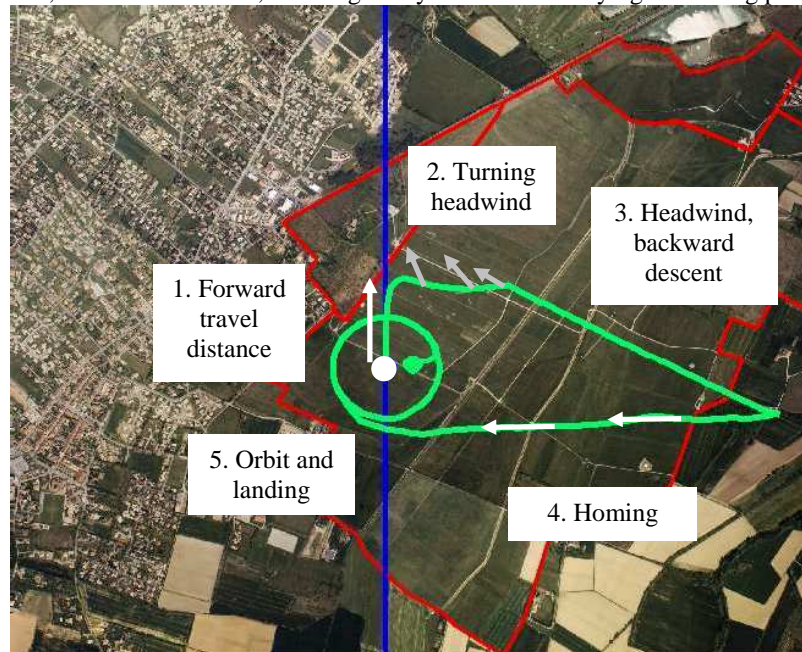

Figure 10 : Top down view of the fast gliding system's trajectory over the CEV drop zone near Toulouse. The Air release poi
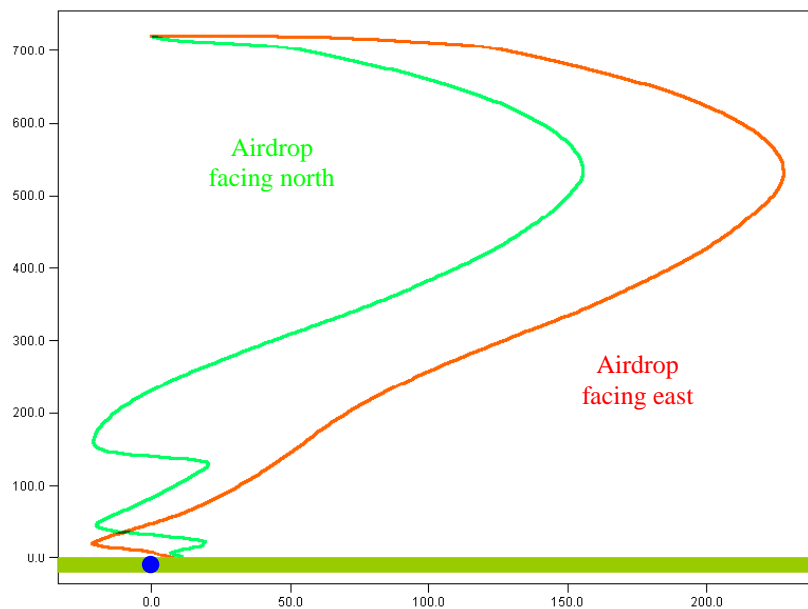

Figure 11 : Trajectory of the fast gliding system, east component (seen from south). When facing east, the exit time and forward travel in the wind's direction cause the system to drift further away from the IP (marked in blue).

The concept of fast gliding systems is adapted for vertical airdrop with the strongest wind profile recorded by PAI, with a glide ratio of 2 and a sink rate of 10 m/s at sea level.

C. Stand-off capability assessment

The modeled design was aimed at a vertical airdrop capability, yet it may still have some horizontal stand-off capability. Two drawbacks were identified in the guidance and navigation logic. First and obvious, the headwind waiting phase against strong winds does not allow one to make the best use of the gliding capability in the downwind direction. Second and less evident, the logic is based on navigation with a direct ground track. This implies that when the system encounters winds of varying cross-track velocity, it has to use a varying drift correction angle over the descent to maintain a direct track. As a result, it cannot use its maximum gliding potential that can only be achieved with a constant heading.
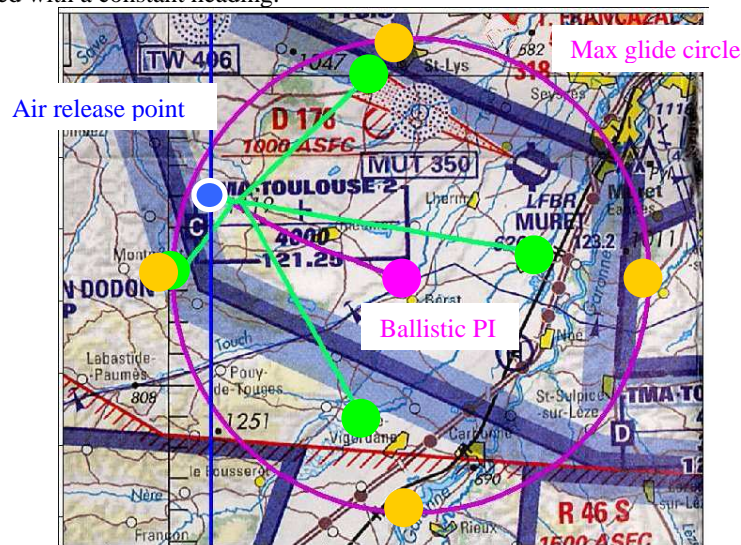

Figure 12 : Top down view of 4 simulation runs to assess stand-off capability. Air release point is blue. The ballistic point of impact (purple) is the centre of the maximum gliding distance circle.

4 IP were tested (orange points) to check how much of its maximum gliding capability the system can use. The actual PI are green. The worst performance happens when the PI is downwind, as was expected (eastern IP and PI). Nevertheless, even with the time passed facing the wind at high altitudes, the system is able to glide 8 Km out of a maximum 14, and to cover a ground distance of 20 Km downwind.

V. Perspectives

The continued use of such models and the acquisition of additional forecast and measured wind data will allow airdrop engineers to check the limits of use of all SGS concepts in terms of trajectory correction capability, maximum sustainable wind or horizontal offset capability. These limits are closely related to each nation's weather forecast ability. For that reason, government self sufficiency to conduct these evaluations helps to protect general information related to general defense capabilities. Such analyses are accessible only through simulation, where it is possible to control the atmospheric condition input: even the most extensive testing program would not guarantee that the system's domain of use is fully investigated. The result is an improved confidence in the horizontal margin used for the CARP. The major advantage of the modeling level of detail chosen is that it requires only speed performance data and high level information about the navigation logic, not detailed guidance and control information that industry may want to protect or dynamic 6 DoF flight models that are seldom available. Thus evaluation teams can be self sufficient in their analysis.

A 6 DoF dynamic flight model also exists in ASTRAL, but does not give a specific evaluation capability that industry testing or simulation would not fully provide.

Acknowledgements

References

[1]de Lassat de Pressigny Y., Tavan S. and Wheeler R., "Wind forecast error and effects on self guided systems," LTTP PAIc report 2005.