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OPTIMIZED PARACHUTE RECOVERY SYSTEMS FOR REMOTE PILOTED AERIAL SYSTEMS

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ABSTRACT

The new RPAS (remotely piloted aerial systems) are mostly video cameras with wings whose ownership isn't enshrined in any constitution. Rulers are rushing to do regulate the lack of safety and accountability for RPAS. In Italy ENAC (aviation authority) legislated against random acts of stupidity and probable failures. For the current year of 2015, there is a forecast to sell $1bn worth of RPAS product. For these reasons the installation of RPS (Recovery Parachute System) on commercial RPAS is particularly interesting. A few RPS manufacturers have manufactured specific RPS systems for "drones" both rotary and fixed wing. However, these systems are designed with the same criteria of manned aerial vehicle. This paper demonstrates that the design criteria of RPAS are sensibly different from other applications. In particular the rate of descent during recovery should be reduced from 6m/s to 2m/s. This fact poses new challenges in parachute design. In fact RPS mass depends on parachute diameter that increases with low descent rates. This paper demonstrates that it is possible to design effectively RPS for RPAS up to 80kg by using nonwoven fabric in parachutes. In this way the RPS mass is a small fraction of the RPAS one. Deployment systems are not a problem for RPAS since masses are extremely small and the power necessity are accordingly limited.

Keywords: remotely piloted aerial systems, unmanned aerial vehicles, recovery, parachute.

REGULATIONS AND DEFINITIONS

Article 743 of the Italian navigation code "Concept of aircraft" introduces in the definition of aircraft the notion of remotely piloted aerial vehicle:

"Aircraft shall mean any machine designed for the transportation by air of persons or property. Remotely piloted aerial vehicles are also aircraft, as defined by special laws, ENAC (Italian civil aviation authority) regulations and, for the military, by decrees of the Ministry of Defense. The distinctions of the aircraft, according to their technical specifications and use shall be established by ENAC with its regulations and, in any case, by special legislation in this field".

Pursuant to the regulation of the European parliament and of the council (EC) No 216/2008, RPAS of maximum takeoff mass not exceeding 150 kg and those designed or modified for research, experimental or scientific purposes are under ENAC responsibility. This means that a remotely piloted aerial vehicle used for specialized operations or experimental activities constitute a remotely piloted aircraft system (RPAS) and the provisions of the navigation code shall apply to them, in accordance with the current ENAC Regulation. The RPAS operator's capability to fulfil the obligations of the ENAC regulation is recognized by ENAC authorization in cases of critical flight operations. For non-critical flight operations, the operator explicitly declares this capability in accordance with the provisions of this regulation. The declaration or authorization, as applicable, covers all aspects concerning the safety of the RPAS operations (airworthiness, flight operations, pilot competence). A plate attached to the RPA containing the identification of the system and the operator data must identify the RPAS. The same plate should also be clearly visible on the ground station.

Furthermore, all RPAS should have with a flight manual or equivalent document.

The RPAS that fall under the provisions of the ENAC regulation can be used in specialized operations either non-critical or critical.

Non-critical specialized operations are those operations that do not involve over flights, even in the event of failures and malfunctions, of the following:

- I congested areas, gatherings of people, urban areas and infrastructures;
- II restricted areas;
- III railway lines and stations, highways and industrial plants.

They are conducted in the volume of space "V150" and under the following conditions:

- at an adequate horizontal safety distance from congested areas, but not less than 150 m, and at a distance of at least 50 m from persons and property, which are not under the direct control of the operator;
- in daylight conditions;
- in uncontrolled airspace;
- outside the ATZ, and anyway at a minimum distance of 8 km from the perimeter of an airport and from the paths of approach/take-off to/from an airport.

b. Critical specialized operations are those operations conducted in VLOS that do not meet, even if only partially, the limitations/conditions indicated above.
Where it is not possible to ensure the above conditions or for operations in controlled airspace, the applicant must submit, in accordance with ENAC provisions, an application for the use of airspace.

Limitations/conditions are established by ENAC based on the kind of operations and the results of the risk assessment carried out by the operator.

INTRODUCTION

An airframe parachute or a Parachute Recovery System (PRS) gives the remote pilot one last but extremely valuable option. However, these systems add mass to the aircraft; this additional mass is not only the PRS itself, but also the installation with steel wires, connections, structure reinforcements etc. Usually four steel wires connect to the vehicles. This system gives the correct attitude to hit the ground with the undercarriage. On RPASs (Remotely piloted aerial system) the maximum allowed mass is 150kg. The PRS mass should not interfere with the aerial performances of the vehicle. However, the touch-down position is casual and further dangers may be faced at the impact with the ground. In fact, the parachute trajectory is usually uncontrolled. In commercial RPS for ultralight and small aircrafts, the design vertical speed is usually vi_n=6-8 m/s. This value is calculated at ISA+0, sea level. However, the vertical speed depends on the air density. For example, a parachute system designed for 6 m/s ISA+0 will descent 30% faster at ISA+25°C@3000m.

DESIGN VERTICAL VELOCITY

To avoid damages to people it is important to limit the speed at touch-down. If the landing gear/device/cushion, which absorbs most of the impact energy, is 0.1m, the collapsing of s=0.1m means an average deceleration *a* of 18g (1):

$$a = \frac{v_{in}^2}{2s} = \frac{6^2}{0.1 \times 2} \approx -18g \qquad (1)$$

This value is not acceptable, so a much smaller design vertical velocity is necessary. Figure-1 shows the average negative acceleration with v_{in}.

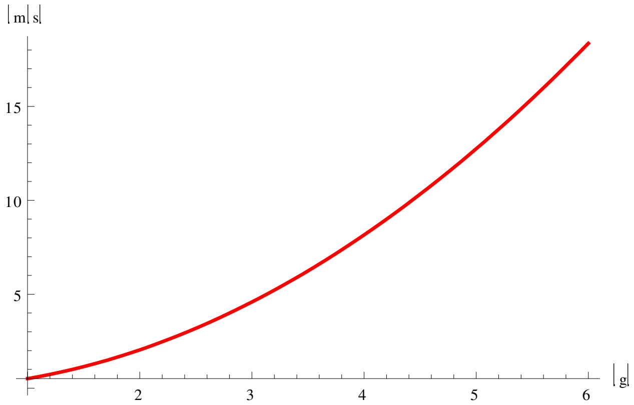

Figure-1. Vertical speed (m/s) vs. average negative acceleration (g).

As shown in Figure-1, an acceptable vertical speed (rate of descent) is then very low. At v_{in} =2 m/s, the average deceleration is about 2g.

If the undercarriage is taller, the situation changes in a significant way (Figures 3 and 4).

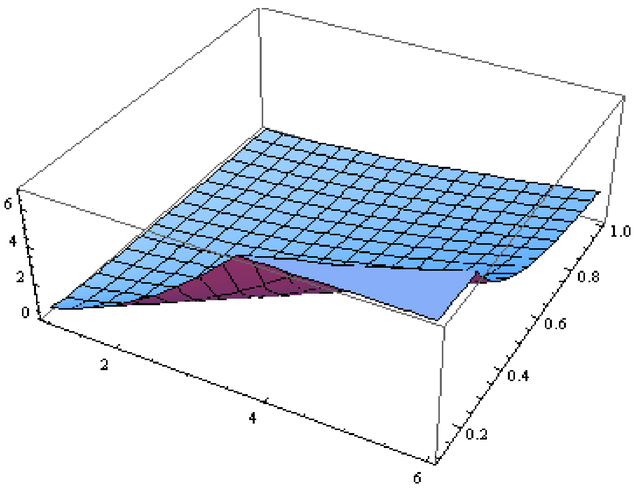

Figure-2. Vertical deceleration g vs. v_{in} (m/s) and undercarriage height (m).

In particular, it is convenient to have an undercarriage with a minimum height of 0.5m (Figure-3).

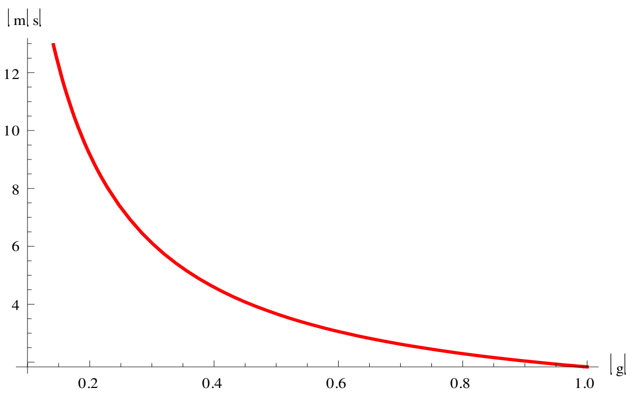

Figure-3. Vertical deceleration (g) at v_{in}=6 m/s vs undercarriage height (m).

BASIC CONCEPTS

The deployment is the process from the initiation of the system to deploy the parachute and recover the vehicle. An emergency recovery parachute system for aerial vehicles has a large, strong, canopy to withstand the high dynamic pressure necessary to slow down quickly the aerial vehicle. It should be noted that the wing loading of the parachute should be an order of magnitude lower than the one of the aerial vehicle; otherwise the aerial vehicle will impair the floating capability of the parachute with deplorable results.

In any case, recovery systems should develop sufficient force to decelerate the vehicle and to counter the yawing, roll and pitch moments of the vehicle even when operating within is aerodynamic wake. In any case, recovery systems should reliably deploy the parachute into cleanest air areas possible. They should also provide simple and safe systems to check the entire system, either visually or by some other means during the pre-flight operations.

A disarming system should also be provided to prevent accidental deployments on the ground.

The system should be easy to operate with the minimum possibility of improper operation inadvertently defeating the system.

There are several systems of deploying a PRS. The “classic” system is with a mortar deployed pilot chute. It uses an explosively ejected "slug". This mass forces the ejection of a pilot chute. This first pilot chute inflates and pulls out the main parachute, which is stored in a deployment bag. A designing problem for controlled deployment is the size of the pilot chute. It has to provide enough power at low speeds to pull out the parachute assembly but at high speed, it could exceed the opening force tolerances itself. Therefore, deployment velocity range is restricted. Another main problem is the presence of the “pyrotechnic charge” and the ejection of the slug. A gas pressure or a spring loaded system can easily replace the pyrotechnic charge but the speedy slug is extremely dangerous for people in the area of the recovery. This system is then unsuitable for RPAS. In fact, in hang gliders and light aircraft, a 0.5 kg slug leaves the mortar muzzle at more than 200 km/h. The recoil force on the lightweight structure is not negligible and the potential damage of the projectile is high.

An improved recovery system ejects the recovery chute with is deployment bag directly from the mortar tube. This method ensures that the recovery chute goes directly into the clean air. However, the packed parachute may have a mass that results into a force on the aircraft structure may require structural reinforcements. The parachute bag is pressure packed to a very high density (above 50 kg/m^3) to save mortar mass and to increase parachute pack resistance during initial acceleration. The shape of the packed parachute is restricted to cylindrical shapes in order to fit into the mortar. However, the velocity of the deploying parachute reaches its maximum as the bag clears the muzzle and then rapidly decreases as the chute clears from the vehicle. In many cases, additional ballast ensures a residual inertia to continue the deployment of the parachute bag up to line stretch. A further improvement is the substitution of the mortar with a rocket. This solution reduces the recoil loads and the PRS mass.

The rocket provides an average acceleration of 60 m/s^2 and burns long enough to continue beyond line stretch even at the coldest temperatures and lowest vehicle speeds. However, this solution seems to be impractical for RPAS, due to fire hazards and size. In alternative, the aerodynamic forces may throw the pilot chute that deploys the bag containing the canopy and suspension lines. A very small spring or the air pressure on a flap deploys the bag clear of the aircraft, and thereafter the airstream would extract the parachute canopy and suspension lines from the deployment bag. This system has proven to be unsafe in aircrafts. In certain situations, the deployment bag, the harness, the suspension lines or the chute itself would foul on the aircraft structure or on the propeller, rendering the parachute system inoperable. In any case, air deployed emergency parachutes were ineffective below a certain altitude, because of the time required to complete the deployment sequence, and for the canopy to fully inflate and slow down the maimed aircraft [2-16].

MINIMUM HEIGHT EVALUATION

For a very fast PRS cross wind deployment system, the mortar system will take approximately t_d=0.5s to extract the parachute and stretch its line and the harness. In this time, the vehicle will lose h_d height (2).

$$h_d = v_{v0} t_d \tag{2}$$

Equation (3) outputs an approximate time to open the parachute at a horizontal velocity of about v_{s0} and vertical velocity of v_{v0}.

$$t_a = \frac{D}{\sqrt{v_{s0}^2 + v_{v0}^2}} \tag{3}$$

During t_a the vehicle will lose (4):

$$h_a = v_{v0} t_a \tag{4}$$

The recovery parachute will typically be a parachute with a drag coefficient C_d that varies from 0.55 up to 0.85 for parachute sizing calculations. In this case, due to the limited size, the smaller value is closer to the real one. The parachute diameter can be evaluated with expression (5)

$$Mg = \tfrac{1}{2} C_d \rho S v_{in}^2 = \tfrac{1}{8} C_d \rho \pi D^2 v_{in}^2 \Rightarrow \\ D = \sqrt{\frac{Mg \times 8}{v_{in}^2 C_d \pi \rho}} \tag{5}$$

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Then the recovered aircraft should decelerate down to the design recovery speed *v*.

According to Doherr [1], the deployed RPS takes about 1 step of non-dimensional time t_{ad} to decelerate the system with non-reefed, fully-open parachute (5).

$$t_{full\_d} = \frac{v_{in}}{g} \tag{6}$$

The altitude loss z to reach the design vertical velocity can be calculated with equations (6).

$$\bar{v}_a = \frac{v_{in}}{v_{v0}}$$

$$t_{ad} = \frac{t_{full\_d} \times g}{v_{v0}}$$

$$\bar{a} = \frac{\bar{v}_a - 1}{\bar{v}_a + 1} \tag{7}$$

$$z_{ad} = t_{ad} + \ln\left(\frac{1 + \bar{a} \times e^{-2t_{ad}}}{1 - \bar{a}}\right)$$

$$z_{ad} = \frac{z \times g}{v_{v0}^2} \Rightarrow z = \frac{z_{ad} v_{v0}^2}{g}$$

For this very performing system, the limit altitude h_l for the PRS will then be (7):

$$h_l = h_d + h_a + z \tag{8}$$

This is the minimum value; the true one is usually higher. Equation (7) includes all the phases from the deployment up to when the vertical design speed is reached. Figure-4 shows the height loss. In this case, the RPAS begins the recovery with a pure vertical velocity.

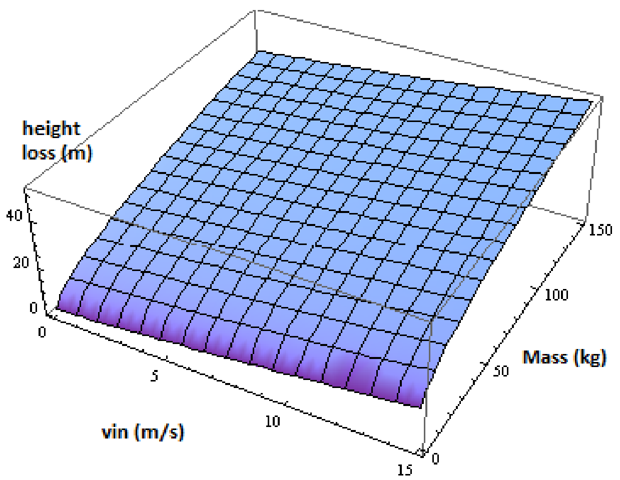

Figure-4. Height loss with mass (kg) and vertical velocity (m/s).

Figure-4 is drawn at sea level ISA condition. The design final velocity is 2 m/s. For a 150kg RPAS, the minimum altitude is 53m. Figure-5 shows that the mass is important on height loss. In this case, the initial velocity is 15m/s purely vertical.

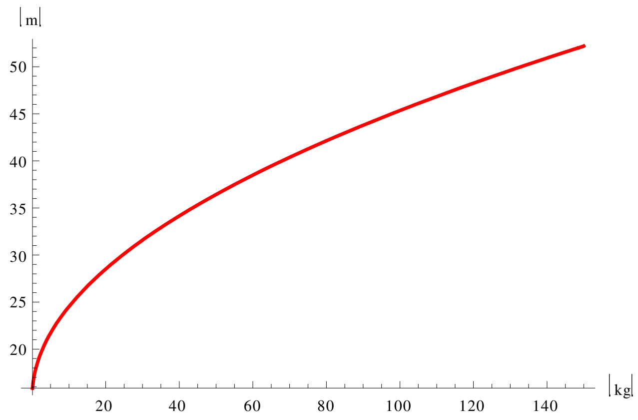

Figure-5. Height loss (m) vs. mass (kg) for an initial speed of 15m/s purely vertical and a design rate of descent of 2m/s.

Over 40 kg the curve of Figure-5 is nearly linear. The system is particularly efficient for small lightweight RPAS. For an RPAS of 10 kg, the height loss is less than 25m. The PRS is then efficient and it is cost-efficient to install them on RPAS. Figure 6 shows the influence of horizontal speed component for a 150kg RPAS.

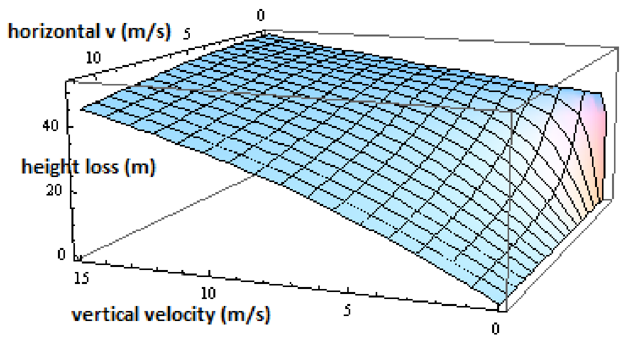

Figure-6. Horizontal velocity influence on a 150kg RPAS.

Figure-6 shows that horizontal velocity improves RPS performance. In fact, parachute opening time depends on the airspeed vector module (see equation (3)). As usual it was drawn with a design rate of descent of 2m/s.

Weight considerations

PRS mass depends essentially on parachute mass. A small design v_{in} (rate-of-descent) requires a large parachute that takes more time to open t_a. While the mortar/rocket travel time t_d and the relative height loss h_d can be reduced by using more powerful devices, the opening time varies with parachute area (Figure-7).

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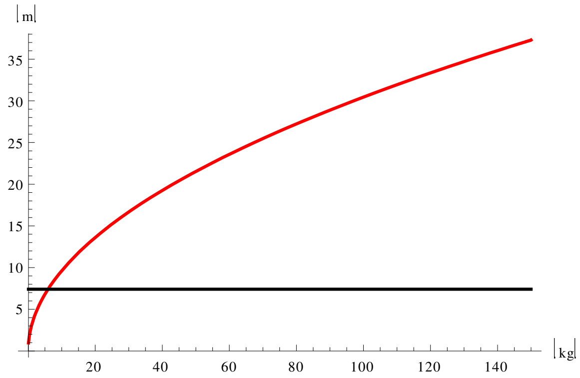

Figure-7. Height loss [m] due to parachute opening (red) and deceleration (black) vs. RPAS mass [kg].

The deceleration after the parachute opening (black) is nearly constant and depends only on the ratio v_{in}/v_{vo}.

Figure-4 was drawn with v_{in}=2m/s and v_{vo}=15 m/s. In the RPAS the deceleration time becomes negligible over 80 kg. Parachute area/mass is then critical. For this reason, PRS manufacturer tend to adopt quite high v_{in}, in order to have a fast responding system. Another consideration is lateral wind influence on the RPAS once inflated. Low wing loading of the parachute means long flying time and higher dependency on lateral wind speed. Since the parachute system is not controlled the touch-down site depends on the airspeed vector at deployment and on airspeed history during flight. In this case, the shorter is the flight the better. However, as previously discussed, RPAS should have low touchdown speed with an optimal rate of descent v_{in}=2m/s. This low speed is chosen to reduce harm to people and damage to things in the touchdown area. The RPS system weight can be calculated statistically with equation (8).

$$M_{RPS} = 0.8065\,D^2 \quad (9)$$

Figure-8 demonstrate the good matching of (8). The black dots are the averaged mass of commercial RPS systems for a given parachute diameter.

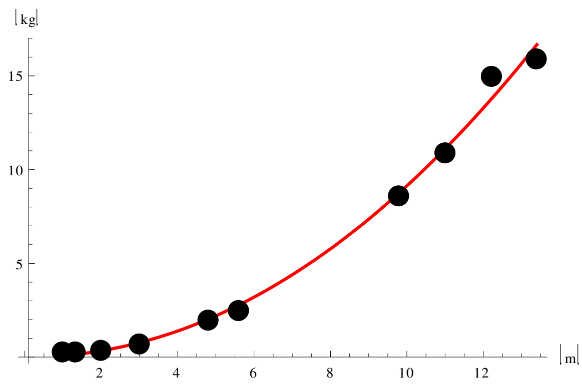

Figure-8. RPS Mass (kg) vs. parachute diameter (m).

The quadratic low of the RPS mass with parachute diameter can be compared with the square root law of parachute diameter with RPAS mass. An approximate relation (9) between RPS mass and RPAS mass is obtained by combining equations (8) and (5).

$$M_{RPS} = 0.021\frac{Mg}{v_{in}^2 C_d \rho} \quad (10)$$

Figure-9 shows the linear relationship between M_{RPS} and M_{RPAS}.

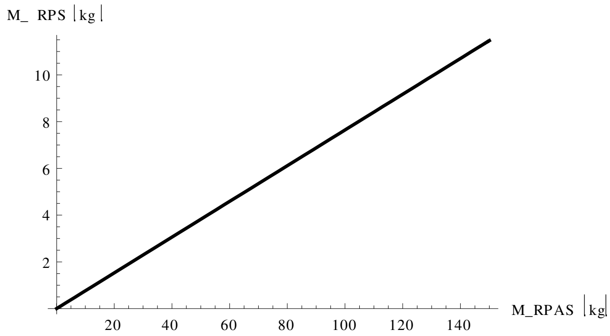

Figure-9. M_{RPS} (kg) vs. M_{RPAS} (kg).

Due to the low rate of descent v_{in} the mass of the RPS system is about 10% the mass of the RPAS. So efforts should be made to reduce this mass in RPAS. This is possible by design simplifications and lighter canopy materials. For lighter RPAS it is also possible to use nonwoven fabric with Cd values up to 0.9 in this case the parachute will be smaller and lighter.

A reasonable curve with nonwoven fabric canopy is shown in Figure-10.

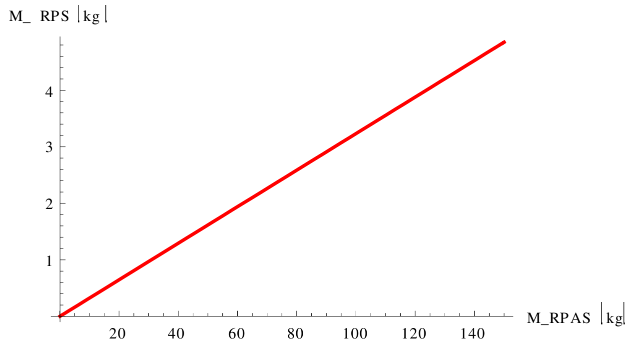

Figure-10. M_{RPS} (kg) vs. M_{RPAS} (kg) with nonwoven canopy.

However, for the larger RPAS these nonwoven materials are not commercially available and they should be manufactured for this specific application [17-28].

CONCLUSIONS

RPS can be successfully applied to RPAS with large differences from manned aerial vehicles. To avoid damage to people and things on touch-down the rate of descent should be reduced from 6m/s and 2m/s. Therefore, high drag parachutes are necessary. Since the RPS mass goes with parachute diameter, highly optimized parachutes are used. For the lighter RPASs it is possible to use no woven fabrics that have an extremely low permeability and high tensile strength. The extremely thin non tissue makes it possible to contain RPS mass. For the heavier RPAS from 80 to 150 kg, these fabrics are not commercially available. Then, they should be manufactured for this specific task. Minimum "decision" heights are acceptable for any mass from 0.1 up to 150kg. Deployment systems are easy to design due to the relatively low mass of the parachute bag, even for rotary wing vehicles.

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Symbols

Symbol	Description	Unit	Value
M, M_{RPAS}	RPAS mass	kg	-
m_{PRS}	PRS mass (maximum)	kg	-
s	Crash length	m	0.1
a	acceleration	m/s^2	-
h_d	Height loss during t_d	m	-
t_d	Deployment time	s	-
t_a	Parachute opening time	s	-
h_a	Height loss during t_a	m	-
D	Parachute nominal diameter	m	-
a	Negative acceleration	m/s^2	-
ρ	Air density	kg/m^3	1.225

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C_d	Drag Coefficient	-	
g	Gravity acceleration	m/s^2	9.81
v_{in}	Descent (final) velocity with chute open -descent rate	m/s	2
v_{v0}	Vertical speed at recovery	m/s	15
v_{s0}	Horizontal speed at recovery	m/s	-
z	Height loss from parachute opening to v_{in}	m	-
S	Parachute surface	m^2	-
t_{full_d}	Time to final speed after the parachute opening	s	-
t_{ad}	Dimensionless time	-	-
$\bar{a}$	Dimensionless acceleration	-	1.7
$\bar{v}_a$	Dimensionless v_a	-	
z_{ad}	Dimensionless height loss	-	-
k	Deceleration at parachute opening	m/s^2	-