Thesis

Preliminary sizing of parachute systems

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1 Introduction to parachutes and the tool

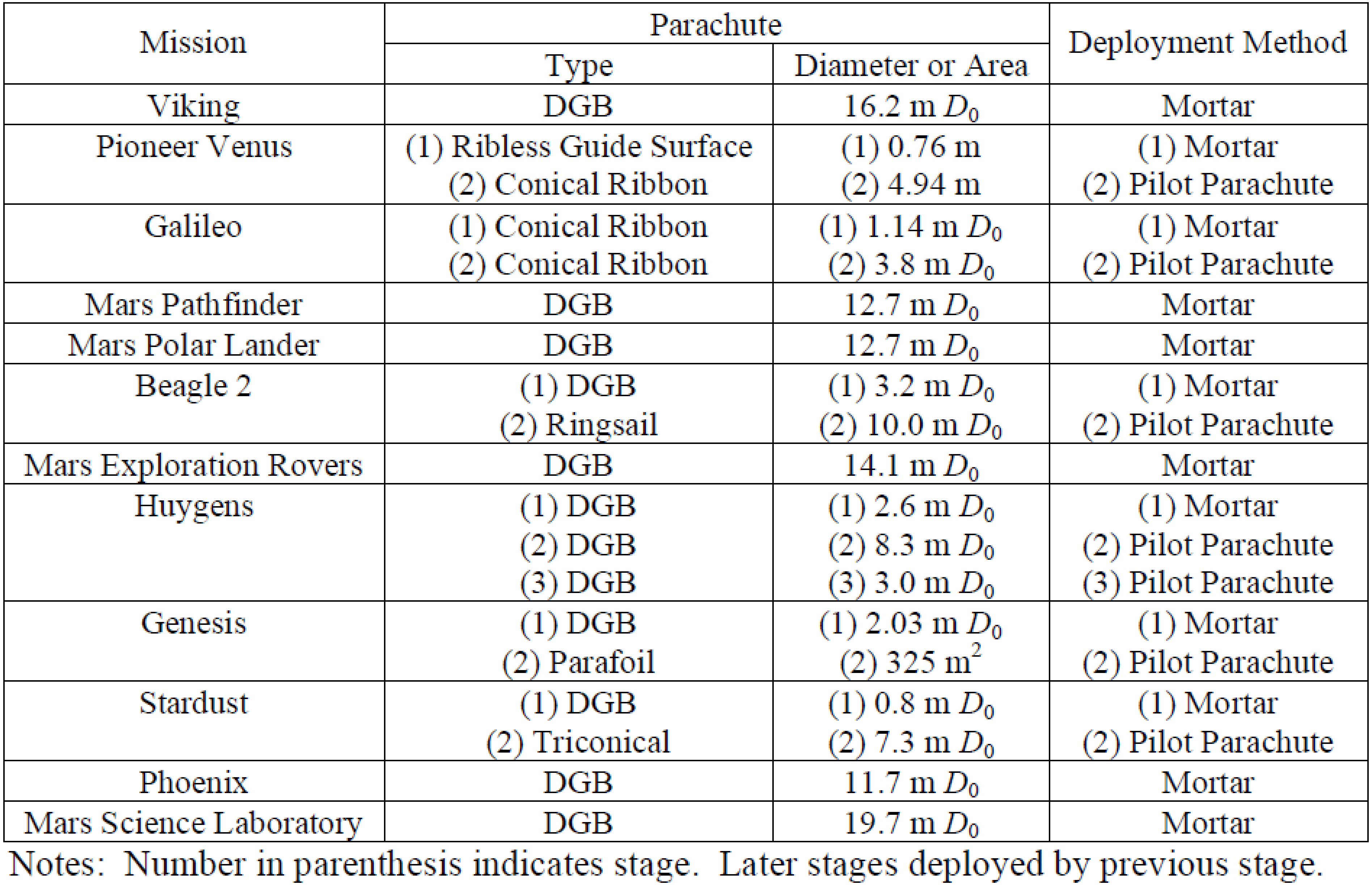
1.1 History

The first modern parachutes used for material drop and personal descent were born in the '20. During WWII parachute technology significatly progressed in order to guarantee a safe platform for soldiers deployement. After the end of the war, parachute diffused also for sport and recreational application.
Anyway only since the '60, with high module material introduction, parachute application for high mass object descent diffused. In this period also many wind tunnel and drop tests were made in order to undestand geometry and Mach number effects on stability, inflation and drag coefficient of different parachute types. Parachutes were widely applied for re-entry space system and also at the moment, since STS disposal, they rapresent the only space landing systems.

1.2 Applications

- Material drop
- Sport activity
- Emergency escape
- Military units deployement
- Weapons drop
- Small airplane recovery
- Re-entry of space vehicles

For this treatement only space application will be considered. For this kind of application Earth and Mars have particularly interesting application, this because they are among the few planets to have an atmosphere dense enough to permit a reasonable and relaiable application. Anyway on Mars final slow down system, as rockets systems or airbags, are required in order to avoid too large diameter parachutes. Historically applications can be reminded as US Gemini, Mercury and Apollo capsules, Soviet Soyouz (still operative) and Mars robotic missions.



Mission	Parachute		Deployment Method
	Type	Diameter or Area	
Viking	DGB	16.2 m D_0	Mortar
Pioneer Venus	(1) Ribless Guide Surface (2) Conical Ribbon	(1) 0.76 m (2) 4.94 m	(1) Mortar (2) Pilot Parachute
Galileo	(1) Conical Ribbon (2) Conical Ribbon	(1) 1.14 m D_0 (2) 3.8 m D_0	(1) Mortar (2) Pilot Parachute
Mars Pathfinder	DGB	12.7 m D_0	Mortar
Mars Polar Lander	DGB	12.7 m D_0	Mortar
Beagle 2	(1) DGB (2) Ringsail	(1) 3.2 m D_0 (2) 10.0 m D_0	(1) Mortar (2) Pilot Parachute
Mars Exploration Rovers	DGB	14.1 m D_0	Mortar
Huygens	(1) DGB (2) DGB (3) DGB	(1) 2.6 m D_0 (2) 8.3 m D_0 (3) 3.0 m D_0	(1) Mortar (2) Pilot Parachute (3) Pilot Parachute
Genesis	(1) DGB (2) Parafoil	(1) 2.03 m D_0 (2) 325 m^2	(1) Mortar (2) Pilot Parachute
Stardust	(1) DGB (2) Triconical	(1) 0.8 m D_0 (2) 7.3 m D_0	(1) Mortar (2) Pilot Parachute
Phoenix	DGB	11.7 m D_0	Mortar
Mars Science Laboratory	DGB	19.7 m D_0	Mortar

Notes: Number in parenthesis indicates stage. Later stages deployed by previous stage.

Figure 1: Example of missions using aerodynamic decelerators (Aerodynamic Decelerators for Planetary Exploration: Past, Present, and Future, 2006)

1.3 The tool

This work is focused on the possibility of developping an easy handy and quick, but also reliable enough, tool for the preliminary sizing of parachute systems. The second target of the tool is to describe with a simplified model the descent phase of an object, using the data calculeted with the first part of the tool. In any case parachutes parameters will be obtanined scaling the parameters themselves in function of the diameter, which is a common way to proceed, but obviously a deeper study will be necessary in the more advanced phases of the project.

To the tool is required to being able to give construction parameters of selected kind of parachutes, knowing initial and final condition of the descent and payload requirements. The trajectory simulation part of the tool on the other hand will be usefull for validating data and estimating a possible range of time and distance of the descent.

In order to guarantee a certain flexibility at least the parachute data estimation is made in terms of dynamic pressure, which makes possible, just changing gravity acceleration value, the use of the tool for different planets. This reasoning cannot be made for the trajectory analisis, in fact in this case an atmospheric model of the planet is required. At this moment simulation on Earth and Mars are possible. An Earth model is present yet on matlab, a Mars one has been obtained interpolating data.

The tool has been conceived in a modular way, the sizing part estimates a staging strategy, diameter and load force values, then interfaces to a function for calculating loads on parachutes elements and has a specific function for each parachute type mass calculation. The trajectory simulation part has some functions for calculation drag correction of vehicle and parachutes in function of Mach number and a specific Mars atmosphere function has been created.

Finally the possibility of describing casual variation of drag coefficient effects is foreseen, multiple descent trajectory can be plotted, considering a positive or negative variation.

1.4 Examinated examples

Two different example mission were studied. One on Mars the other on the Earth, in order to verify that the tool can be applied for both the planets. Staging strategy, diameter and masses were verified in order to validate the sizing part of the tool. Then a trajectory simulation with time condition was made for both cases.

1.4.1 Earth mission: IXV

IXV, Intermediate eXperimental Vehicle, was case studied for the Earth application of the tool. IXV was a technological demonstrator, launched in 2015 with the Vega rocket. Its aim was to validate re-entry technologies for a reusable space-plane. Its succesor Space Rider is at the moment under development.

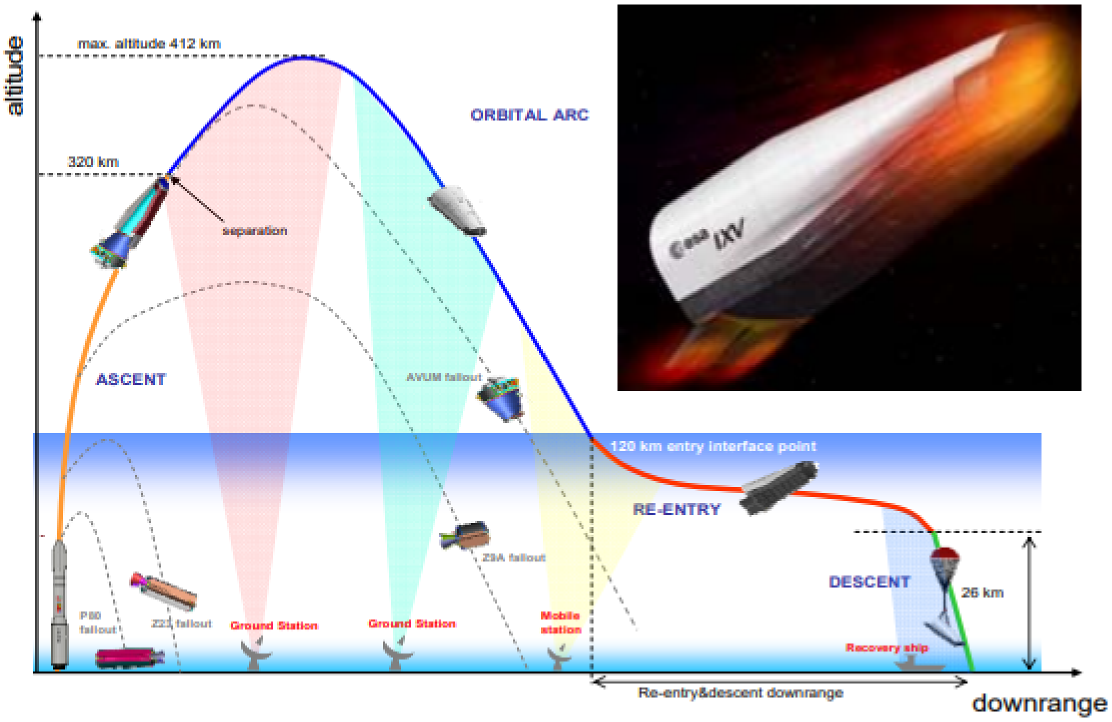


Figure 2: IXV Overall Mission Illustration (images courtesy of ESA and Thales Alenia Space)

In this case a three stage configuration was adopted, with the last parachute reefed, having the possibility of validating also the disreef transition in the tool. Once obtained the parachute dimensions and end stage conditions the trajectory simulation was made considering time and dynamic pressure as end stage conditions.

1.4.2 Mars mission: Exomars 2020

For the mars application of the tool validation, data from Exomars 2020 were used. The aim of this mission is to bring a rover on the Mars surface. This mission is successor of Exomars 2016.

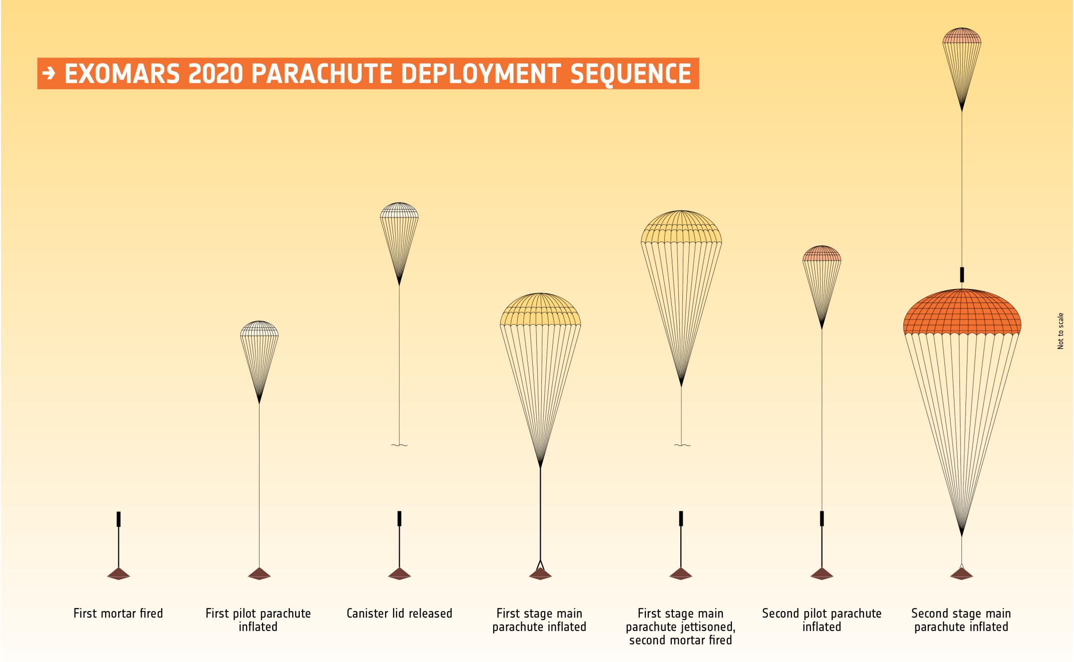


Figure 3: ExoMars parachute sequence

In this case a two stage configuration was adopted with no reefed stage. Also for this validation a dynamic pressure and a time end stage condition were used. Also an investigation on Cd variation effects was made, finding that the parachute Cd variation is much more important then the vehicle one. Obviously a Cd decrease involves a descent time reduction and a dynamic pressure and Mach number increase. The descent and parachute sizing were studied not considering pilot chute, which are not possible to estimate with this reasoning and are almost not influent on the drag.

2 Main components

In this section main components of parachute will be analized. In particular canopy, suspension lines, parachute reinforcements, bridle and risers. The first three mentioned are also calculeted in this developed preliminary sizing tool. Bridle and riser are not treated because their geometry is strictly linked to the vehicle and cannot be easly studied with a fixed model, but can change based on the application. Anyway even if their mass cannot be considered null it is not so significant compared to the other parachute components.

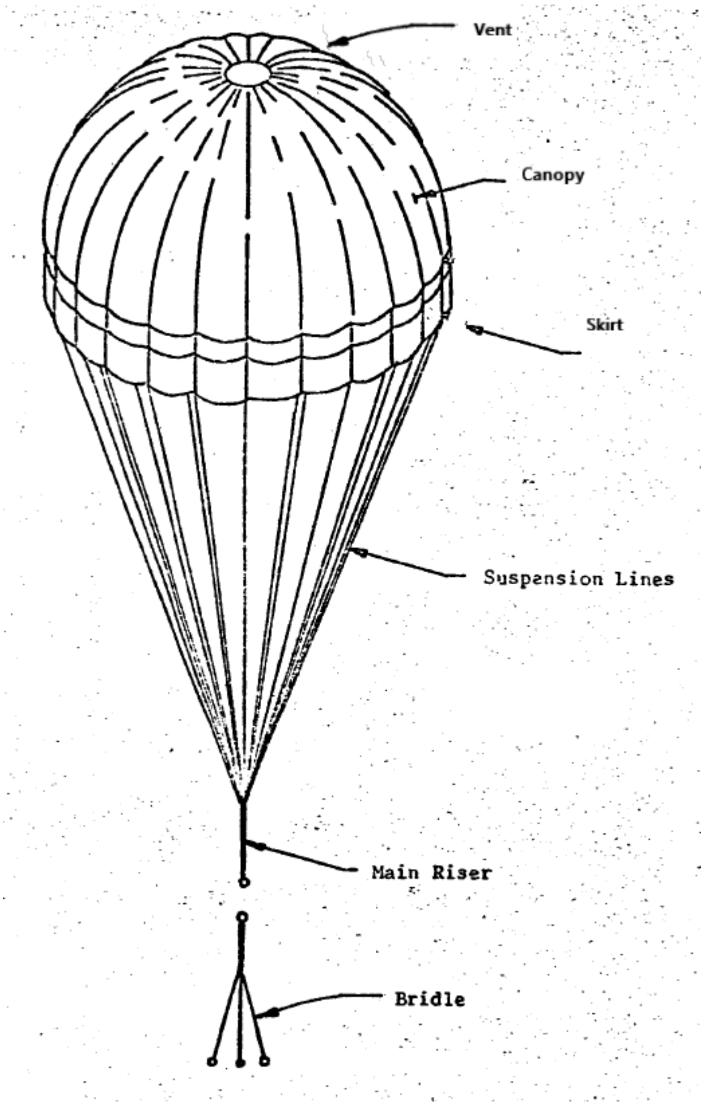


Figure 4: Main components of a parachute

2.1 Canopy

The canopy is the upper part of a parachute, can be fabric made as DGB type for example, or bands made like ribbon type. The lower part of the canopy is called skirt, the upper opened zone vent. This two parts are particulary stressed and a dedicaded reinforcement is placed there. The fabric or the band of the canopy are sewed directly to the lines. Terminated the inflation the diameter can have little changes from nomial value and the parameter D/D0 is specified for each kind of parachute. The canopy is divided in gores which are delimited from lines, the number of gores, like many other parameters can be calculated scaling similar parachute in function of the diameter.
A very important property of the canopy is the porosity, wich is defined like the open area to the total area of the canopy ratio. Porosity can influence the stability and the inflation of a parachute. Usually porosity assumes values of 15-20%. Desired porosity can be obtained changing the dimension of the vent or number or dimensions of gaps in the canopy.
In case of fabric made canopy the material used is usually nylon, its density is measured in oz/yd^2. In case of ribbon type parachutes the canopy is made of kevlar or nylon made bands, their density is measured in Denier: 1 Denier=1 gram / 9000 meters.
On fabric made parachute stress on canopy can be calculated as load on parachute divided by the canopy total surface.

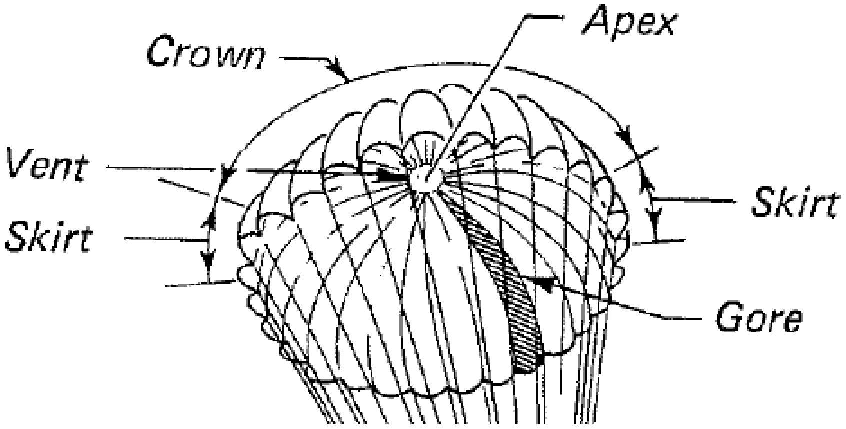


Figure 5: Parachute canopy

2.2 Lines

Lines are bands which link the parachute to the riser if present or to the bridles, lines converge to a point called confluence point. Also the number of lines can be scaled from similar parachute, and their number is equal to gores one. Usually lines number is an even number. The length of the lines can be supposed to be a multiple of the diameter value, often is two times the diameter. The stress on the lines can be easly calculated knowing the total load on the parachute, divided by number of lines and the cosine of the angle between lines and parachute axis.

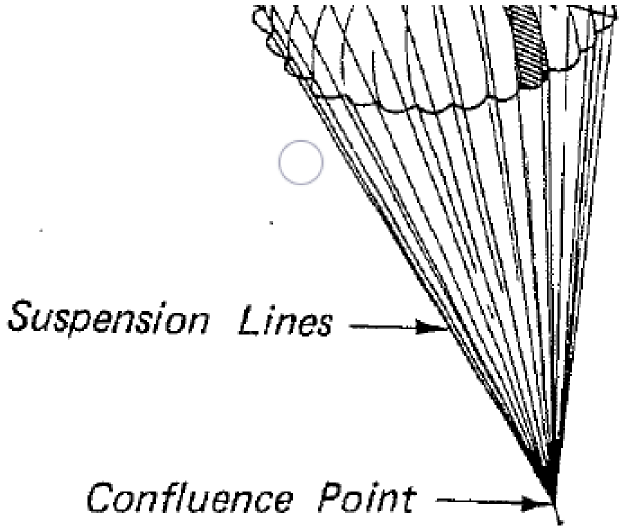


Figure 6: Parachute canopy

2.3 Reinforcements

In this tool also skirt and vent reinforcements are calculated. These reinforcements consist in band just like lines ones, sewed in particularly solicited parachute areas, in this case the skirt and the vent. In this case stresses cannot be easly calculated as made for canopy and lines, but trigonometric and semi-empirical relations are required. Anyway this topic will be treated more deeply in the sizing section.

2.4 Bridles and riser

Bridles are bands used to connect the parachute to the vehicle, being necessary to adequately connect the two objects, number, length and geometry must be studied case by case and a general treatment is not possible. In literature sometimes is suggested to set their mass as a fraction of the canopy and lines mass. Anyway the mass of bridles should be not so significant respect to total parachute one and in the tool is not considered.
Almost the same reasoning can be made for the riser, it could be necessary in some cases in order to keep the canopy over the vehicle wake. In literature is suggested to set riser lentgh as a fraction of vehicle diamter. Anyway also this component is not easly predictable in such a preliminary study and its mass should be a secondary contribution to the total, just like bridles is not considered in the tool.

3 Database

For the required sizing and trajectory simulation some data are necessary. In particular for the strategy and diameter estimation parachutes coefficients are necessary. Then material mechanical skills are useful for the mass estimation of the parachutes of estimated diameter. Finally aerodynamic coefficients of parachutes and vehicle are used in the trajectory simulation part.

3.1 Vehicles

The considered vehicle in this work are capsules or spaceplanes. Referring to capsule is easy to individuate a typical diameter, for spaceplanes not but an equivalent diameter can be estimated. A medium Cd can be found but it is important remembering that it will be corrected in function of Mach number. In general it is possible to say that vehicle drag is particularly important during the first phase of the descent, when Mach number is high. Being the main mass component is essential indicating the vehicle mass.

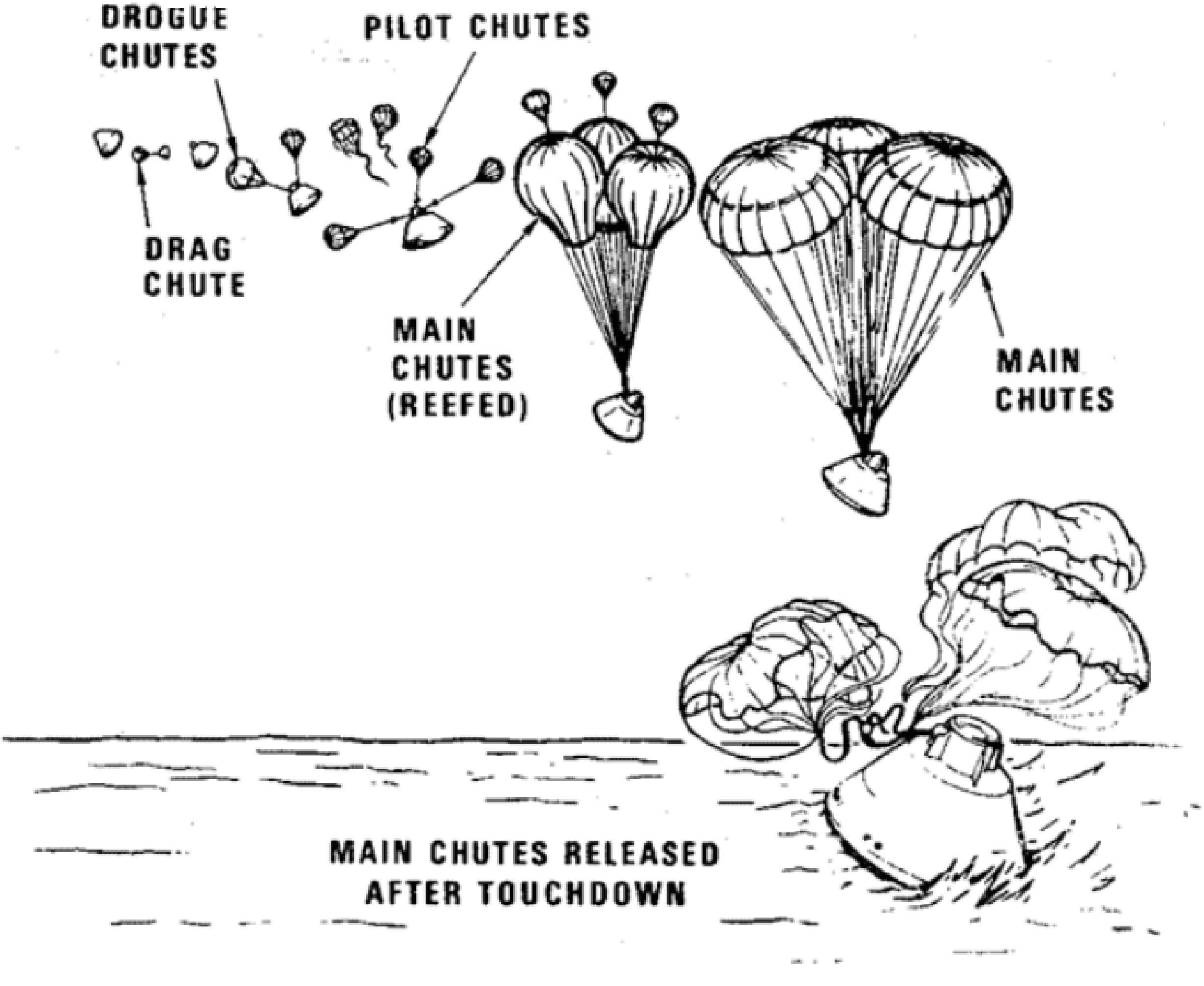


Figure 7: Capsule example

3.2 Parachutes

3.2.1 Ribbon type parachute

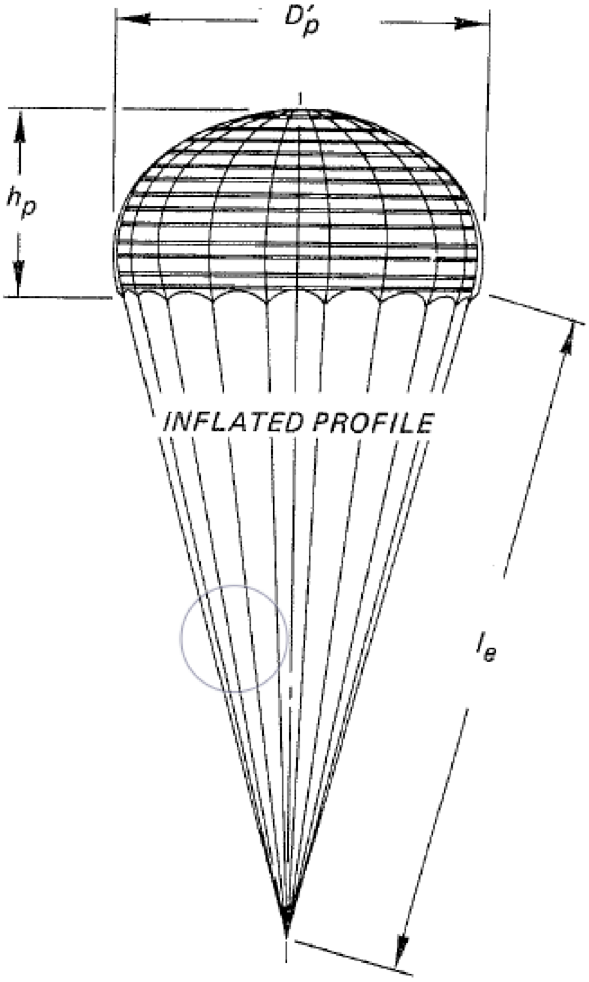


Figure 8: Ribbon type parachute scheme

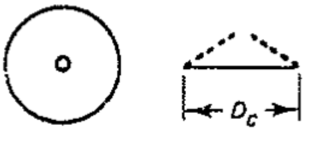


Figure 9: Ribbon type parachute section

Informations

- Cd: 0.55
- Cx: 1.05
- Dp/D0: 0.7

- Dc/D0: 0.97
- Applications: deceleration, descent, supersonic phase

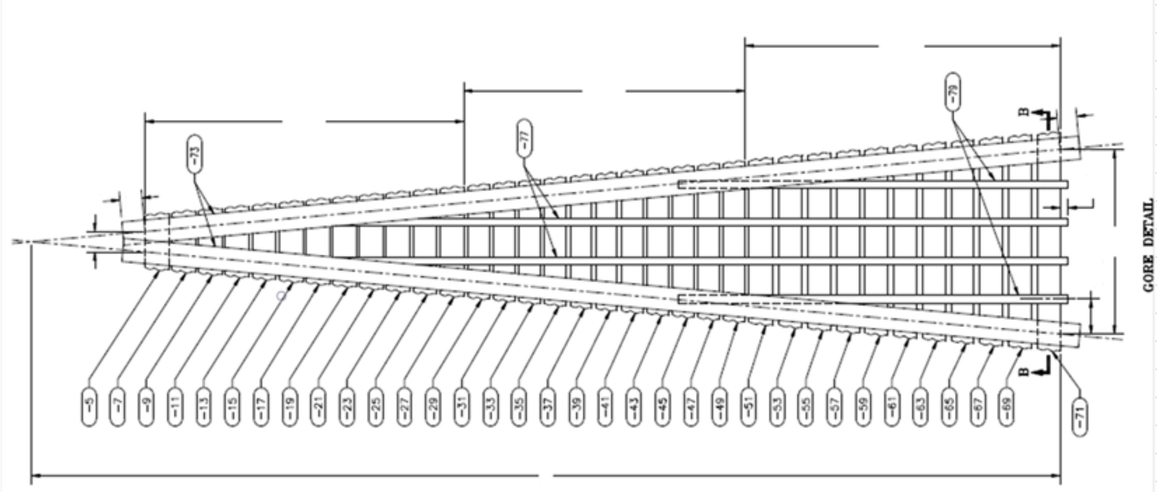


Figure 10: Ribbon type parachute, gore scheme

Parameters scaled to D0

- Lines length
- Number of lines and gores
- Vent diameter
- Number of horizontal ribbons
- Number of slots
- Gore height

3.2.2 Ringslot type parachute

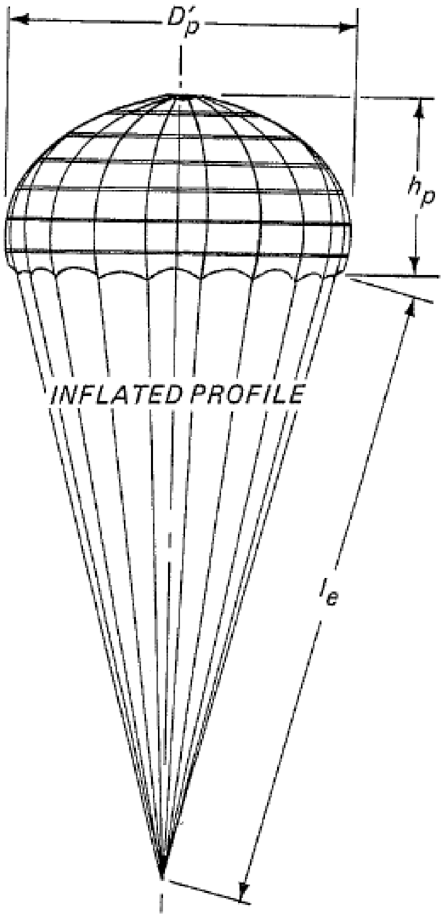


Figure 11: Ringsolt type parachute scheme

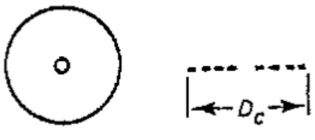


Figure 12: Ringslot type parachute section

Informations

- Cd: 0.65
- Cx: 1.05
- Dp/D0: 0.7
- Dc/D0: 1

- Applications: estraction, deceleration

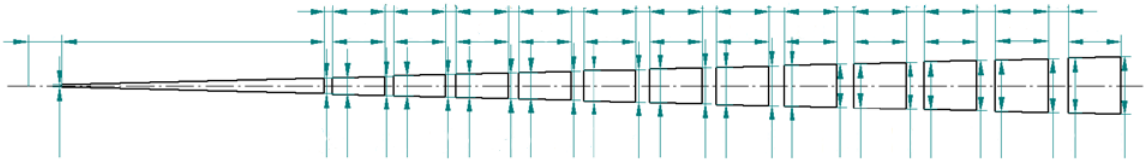


Figure 13: Ringslot type parachute, gore scheme

Parameters scaled to D0

- Lines length
- Number of lines and gores
- Vent diameter
- Gore width at the vent
- First ring height
- Other rings height
- Number of rings
- Gore total height

3.2.3 Disk-gap-band type parachute

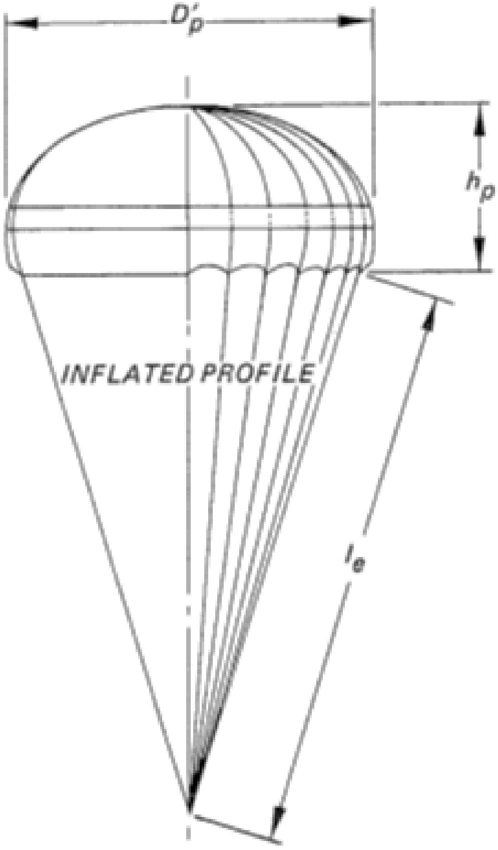


Figure 14: DGB type parachute scheme

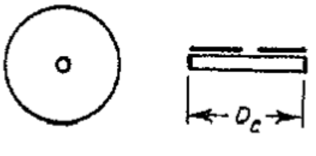


Figure 15: DGB type parachute section

Informations

- Cd: 0.58
- Cx: 1.3
- Dp/D0: 0.65
- Dc/D0: 0.73
- Applications: descent, supersonic in some cases

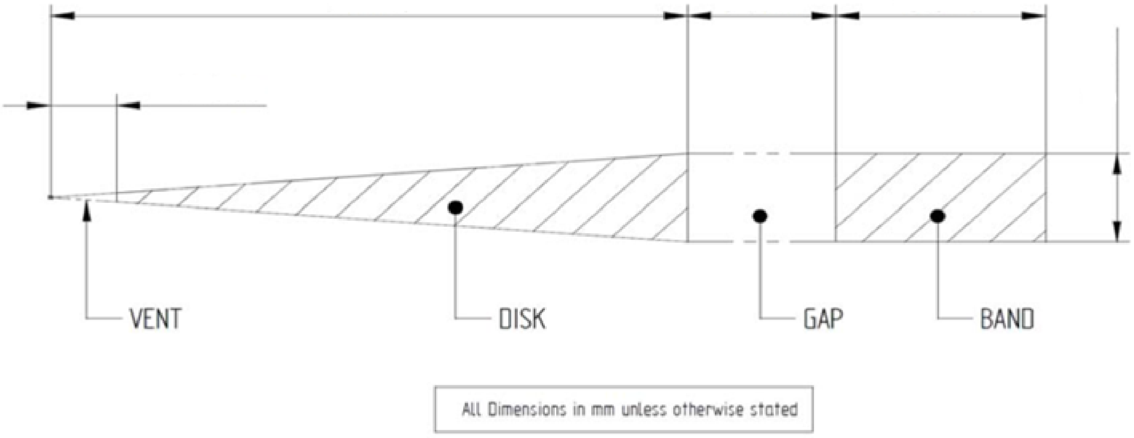


Figure 16: DGB type parachute, gore scheme

Parameters scaled to D0

- Lines length
- Number of lines and gores
- Vent diameter
- Band width
- Disk height
- Gap height
- Band rings

3.2.4 Ringsail type parachute

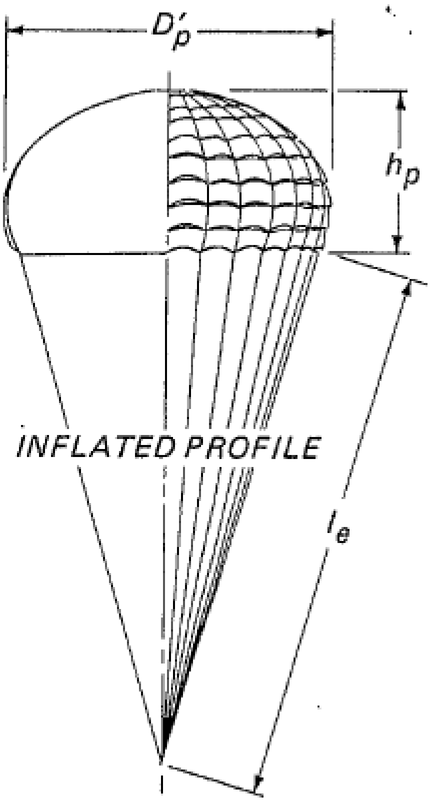


Figure 17: Ringsail type parachute scheme

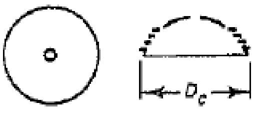


Figure 18: Ringsail type parachute section

Informations

- Cd: 1.2
- Cx: 1.1
- Dp/D0: 0.69
- Dc/D0: 1
- Applications: descent

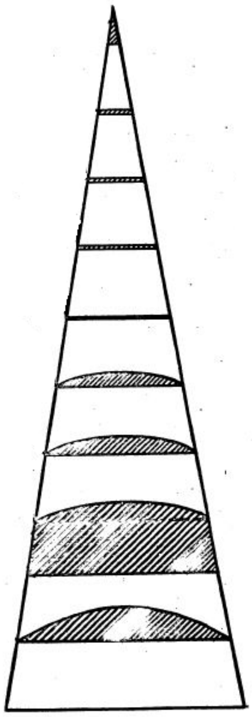


Figure 19: Ringsail type parachute, gore scheme

Parameters scaled to D0

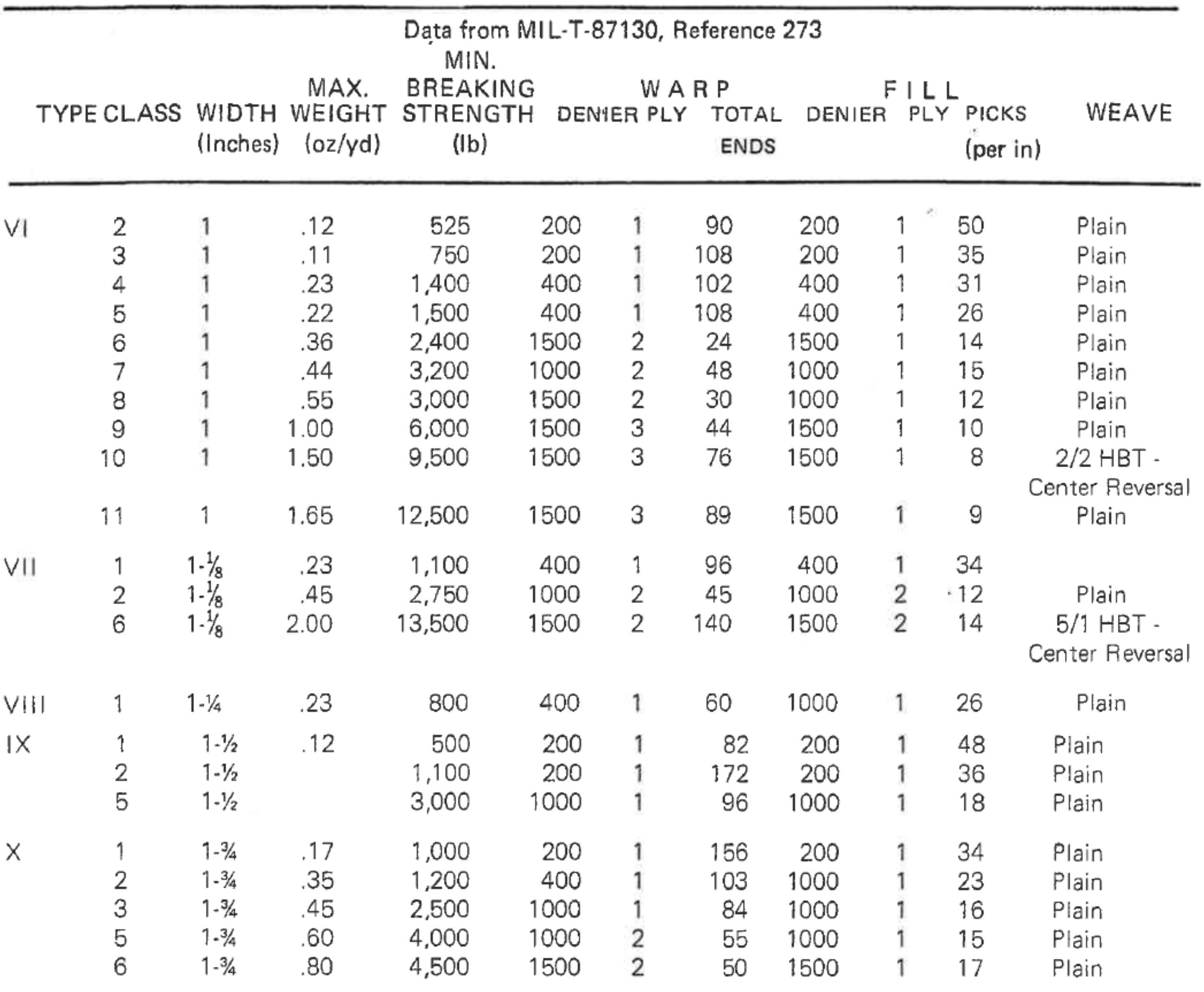
- Lines length
- Number of lines and gores
- Vent diameter
- Gore width at the vent
- First ring height
- Other rings height
- Number of rings
- Gore total height

3.3 Materials

For the materials database data were found in the Irvin guide book tables and in technical datasheets. For these applications kevlar and nylon were used for bands and nylon for fabric.

For band material the mass property is expressed in denier which is equal to 1 gram on 9000 meter, or 0.11 mg/m. The linear density must be multiplied for the number of ends in the selected kind of material and the length of the band. The maximum admissible load is expressed in pounds.

For material used in the fabric the density is expressed in ounces per squared yard, the maximum admissible load is expressed in pounds per squared foot.



Data from MIL-T-87130, Reference 273

TYPE	CLASS	WIDTH (Inches)	MAX. WEIGHT (oz/yd)	MIN. BREAKING STRENGTH (lb)	WARP			FILL			WEAVE
					DENIER	PLY	TOTAL ENDS	DENIER	PLY	PICKS (per in)	
VI	2	1	.12	525	200	1	90	200	1	50	Plain
	3	1	.11	750	200	1	108	200	1	35	Plain
	4	1	.23	1,400	400	1	102	400	1	31	Plain
	5	1	.22	1,500	400	1	108	400	1	26	Plain
	6	1	.36	2,400	1500	2	24	1500	1	14	Plain
	7	1	.44	3,200	1000	2	48	1000	1	15	Plain
	8	1	.55	3,000	1500	2	30	1000	1	12	Plain
	9	1	1.00	6,000	1500	3	44	1500	1	10	Plain
	10	1	1.50	9,500	1500	3	76	1500	1	8	2/2 HBT - Center Reversal
	11	1	1.65	12,500	1500	3	89	1500	1	9	Plain
VII	1	1-⅛	.23	1,100	400	1	96	400	1	34	
	2	1-⅛	.45	2,750	1000	2	45	1000	2	12	Plain
	6	1-⅛	2.00	13,500	1500	2	140	1500	2	14	5/1 HBT - Center Reversal
VIII	1	1-¼	.23	800	400	1	60	1000	1	26	Plain
IX	1	1-½	.12	500	200	1	82	200	1	48	Plain
	2	1-½		1,100	200	1	172	200	1	36	Plain
	5	1-½		3,000	1000	1	96	1000	1	18	Plain
X	1	1-¾	.17	1,000	200	1	156	200	1	34	Plain
	2	1-¾	.35	1,200	400	1	103	1000	1	23	Plain
	3	1-¾	.45	2,500	1000	1	84	1000	1	16	Plain
	5	1-¾	.60	4,000	1000	2	55	1000	1	15	Plain
	6	1-¾	.80	4,500	1500	2	50	1500	1	17	Plain

Figure 20: Materials table example

4 Preliminary sizing and trajectory program

4.1 Input

- Initial and final dynamic pressure value
- Selected parachute type
- Maximum load factor
- Material type
- Entry point altitude
- Planet selection

4.2 Output

- Number of stages
- Parachute dynamic pressure cutting conditions
- Parachute construction parameters:
  - Number of gores
  - Number of lines
  - Number of ribbons if a ribbon type
  - Number of slots for slotted kinds
  - Porosity
  - Vent diameter
- Loads on parachute elements
- Parachutes masses
- Parachutes diameters
- Trajectory graphs:
  - Displacement vs altitude
  - Altitude vs time
  - Load factor vs time
  - Dynamic pressure vs time
  - Mach number vs time
  - Parachute drag area vs time

4.3 Program general description

The tool was developed in order to give a preliminary sizing of a possible parachute system. Giving the input described above the program first of all finds a possible staging strategy, including an estimation of number and diameter of the selected type of parachute and end conditions. Once done the strategy definition, starting from the found forces, stresses on main components of parachutes are calculeted. Knowing the selected material property and margin of safety required is possible calculating the numeber of layers of the selected materials necessary. At this point parachutes mass can be calculated.
The sizing part of the tool is almost finished, the individuated strategy can be simulated and verified using the developed 2 DOF simulator. It must be noted that differently from the sizing case, in which the entire study was made in terms of dynamic pressure, for the simulator entry point altitude and atmospheric model are necessary. The simulator can describe three kind of conditions:

- Free fall/lines stretching: this situation is presented at the very beginning of the simulation when the first parachute is not still open or among two stages, when one has been jettisoned and the other is not open. In this phase the only drag comes from the vehicle. This pahse is considered end when the vehicle has run across a certain distance, espressed as a vehicle diameter multiple.
- Parachute inflation: the next phase is the inflation. During inflation the drag area of the parachute evolution is described with an esponetial law, growing the drag area the drag of the parachute becomes more and more important compared to the vehicle one. In this phase the possibility of reefing is foreseen, in this case the growing of the drag area stops for a certain period, which can be specified, then starts growing again. At the end of this phase the parachute reaches its nominal diameter.
- The last phase is the nominal diameter of parachute decelerated one. It's possible selecting three kinds of end conditions for this phase based on dynamic pressure, time or altitude. In case of altitude or time is quite easy understanding that when that time or altitude is reached the parachute is jettisoned. Speaking in terms of dynamic pressure alone is not possible, in fact in supersonic condition dynamic pressure trend is not costant and the condition can be ambiguous, so an other condtion on Mach is insert.

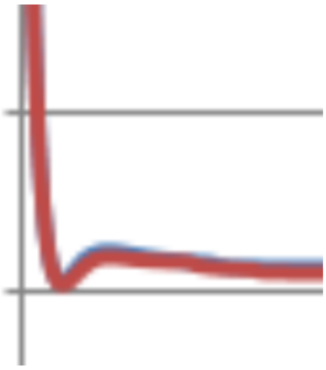


Figure 21: detail of dynamic pressure in supersonic

The tool was developed in Matlab code, dividing the sizing and simulating parts in two main scripts. The simulating script can be used for the three different end stage conditions described before, a dedicated version of the script is present for all of them. Both the mains can recall function for particular duties.

Sizing sub-functions

- Stress evaluator:takes in input opening force, margin of safety and material skills, calculates the number of required layers.
- Mass calculator: there is one mass calculator function for each kind of parachute, actually ringsail and ringslot masses are calculated with the same one. Selecting the desired parachute type the related function is selected.

Simulator sub-functions

- Atmospheric model: for the Earth case a Matlab model was used, for the Mars one a dedicated function was built, interpolating data. In particular the model must provide air density and sound speed in function of the altitude.
- Vehicle drag correction: a medium drag coefficient for the vehicle must be set as input, anyway the Cd is not costant considering high Mach number variation. For this reason a correction model was built, also in this case interpolating data. Data came from an Earth application, so the correction is more relaiable if applied on Earth simulation, anyway it works pretty well also on Mars simulation. In general it is possible to say that the Cd of the vehicle is increased by correction when Mach is high.
- Parachute drag correction: this function works almost in the same way of the last one, considering the Mach number provides a drag correction. Also in this case the correction was found interpolating data. The trend is opposite to the veichle one, in fact the correction decreases the parachute Cd if Mach is high. Considering the two different trend the veihicle contribution is preponderant in the first period and becomes always less important when Mach decreases.

4.4 Cd variation effects simulation

From the standard time based version of the simulator a modified one was developed. In this version the medium Cd provided by user in input it is made to vary from 50% to 150% , in order to study the variation and uncertainties effects on the descend. This kind of study can be easly made on parachute and vehicle Cd, the correction in fucntion of Mach number is still used. This simulation was simply implemented inserting the entire simulat in a "for" cicle and plotting result curves in the same graph.

5 Staging definition, sizing and trajectory simulation

In this section the first part of the tool will be examined in detail. First of all a flow chart of the staging strategy definition will be shown, then subfunctions will be described.

5.1 Staging definition and diameter estimation

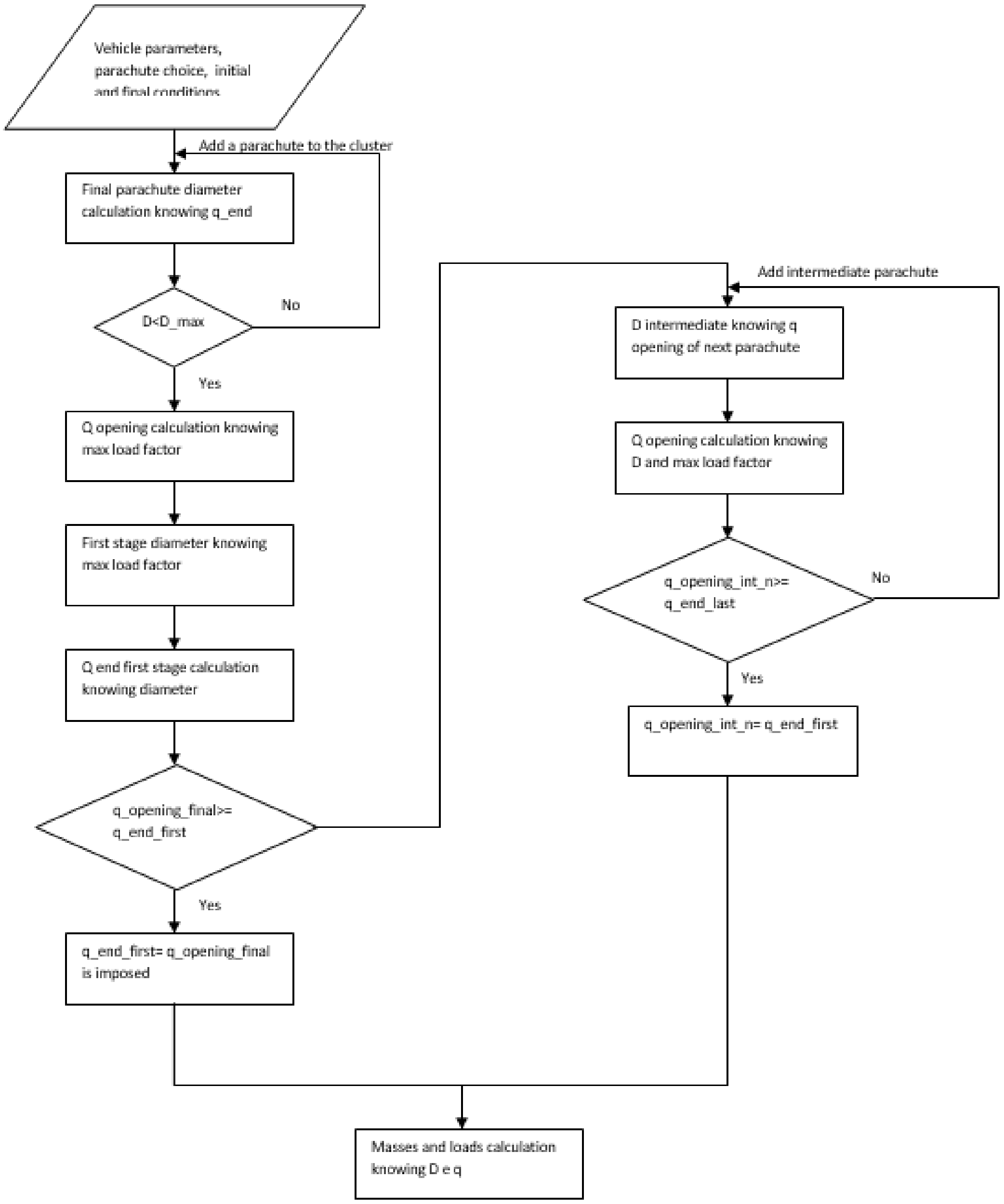


Figure 22: Staging strategy and sizing tool flow chart

As it can be seen in the flow chart parachutes type, vehicle parameters, conditions at entry and exit point and load factor are required as input. The first thing calculated is the diameter of the final parachute, knowing the weight of the payload and the final dynamic pressure. If the calculated diameter is bigger than the maximum desired a parachute is added in the cluster, considering a loss of performance. Once the final parachute diameter is calculated the dynamic pressure at which this stage starts can be found imposing that it happens at the maximum possible load factor.

At this point if only one parachute is not sufficient, considering the imposed minimum reefing value, a second stage is added. This stage diameter can be found considering that at the inflation the maximum load factor is reached, the dynamic pressure of end stage can be found imposing that at this point drag must be equal to the weight of the vehicle.

Now if dynamic pressure of first stage end is lower than final stage start one two stages are sufficient and the dynamic pressure of second stage inflation is set equal to first end condition. Else if this is not true intermediate stages are required, they are added until the dynamic pressure gap is completely filled. It must be noted that all the intermediate stages, not knowing a priori the number of intermediate stages are treated using the same parachute type. The intermediate stages diameters and dynamic pressure are calculated just like the other stages, knowing the vehicle weight and maximum load factor.
Main data from the staging strategy part of the tool are:

- Number of stages: it is the first thing that can be calculated, making also possible to know if a single stage configuration is possible or not.
- Dynamic pressure conditions: they can be used in the simulator, associated with the Mach number in order to distinguish the parachute cut condition.
- Opening force: it is calculated using the Cx typical for every parachute type, it is necessary for the stress components calculation.
- Diameter: this data is necessary for the mass estimation and also obviously for the descent simulation.

5.2 Sizing

Using data obtained from the staging strategy it is possible to size the parachutes. In particular knowing the inflation force it is possible to calculate the stress on the materials of the canopy, lines, vent and skirt reinforcements. Once calculated the stress, in order to satisfy the requested safe margin a certain number of layers of material is calculated for each part of the parachute. For all the parachute kinds the same function is used, with a different canopy stress calculation for ribbon type. The calculation details will be discussed in the next part.

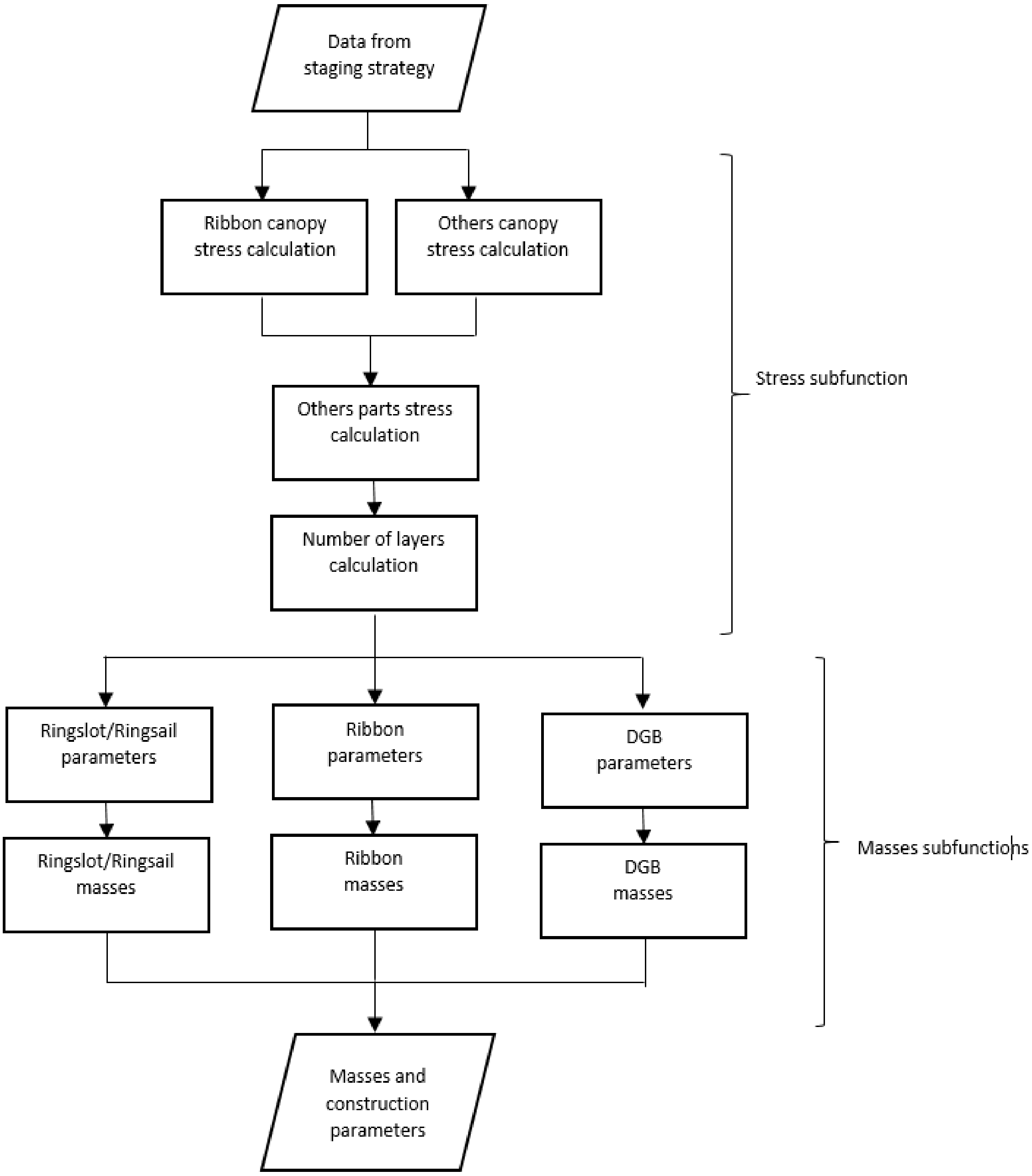


Figure 23: Sizing flow chart

Once the number of layers are calculated, the mass of each part of the parachute can be calculated, just like the stress estimation also the mass is calculated using dedicated subfunctions. In order to calculate the mass, first construction parameters are calculated, these parameters typical for a certain kind of parachute are calculated in the same dedicated subfunctions. Since ringsail and ringlot type parachute are really similar the mass estimation of both is made with the same subfunction.

5.2.1 Stress estimation

As said before the stress estimation is made using a dedicated subfunction. The subfunction calculates stress of four main components, canopy, lines, reinforcements of skirt and vents. The stress values are compared to the resistance of the selected materials and to the required safe margin, calculating the number of layers necessary.

- Canopy: for the fabric made canopy parachutes it can be calculated as the force at inflation divided by the surface of the canopy. In a ribbon type parachute this is not possible and the stress must be calculated in the same way used for the reinforcements, made just like the ribbon bands.
- Skirt and vent reinforcements: in this case the stress is calculated using a series of geometrical relations, in order to find the area enclosed by a gore, so pressure acting on that area can be calculated. This value is corrected with a certain factor, then projected finding the acting force on the reinforcement.

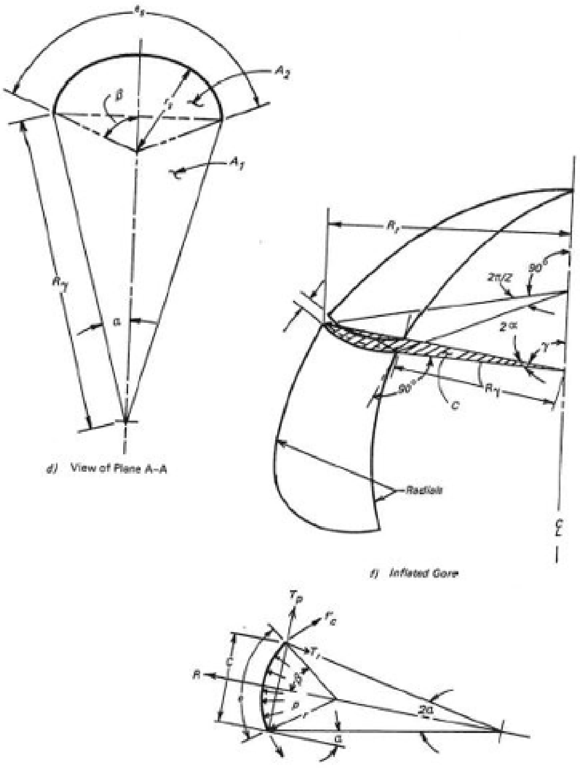


Figure 24: Reinforcement stress calculation scheme

- Lines: lines stress can be easly calculated, as P=Finflation/(number_of_lines*cos(alfa)). Where alfa is the angle between the lines and the longitudinal axis of the parachute. It can be calculated as alfa=arcsin(D/2/Llines).

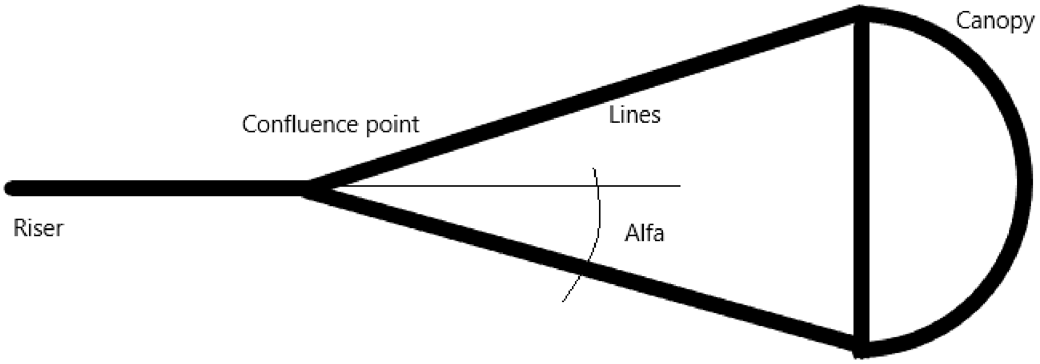


Figure 25: Lines stress calculation scheme

5.2.2 Costruction parameters

As shown before some parameters are necessary in order to determinate the geometry of the parachute and so calculating the mass of the parachute itself. First of all is necessary finding some ratios, useful for scaling the parachute geometry in function of the nominal diameter, these ratio have been cited also in the parachutes description:

- LL/D0: lenght of the lines ratio.
- NL/D0: number of gores or lines ratio.
- DV/D0: vent diameter.
- NH/D0: number of horizontal ribbons, in case of ribbon type parachutes.
- NS/D0: number of slots in case of ribbon, ringslot or ringsail type parachutes (can be used the number of rings also).
- GH/D0: gore height.
- GW/D0: gore width at vent or at skirt.
- RH/D0: ring height for ringslot and ringsail type parachutes.
- DH/D0: disk height for DGB type parachutes.

Starting from these ratios the geometry of the parachute can be scaled from similar ones. It's also possible finding the porosity of a parachute, knowing the geometry, calculated as open area to total canopy area ratio.

5.2.3 Mass estimation

Once the number of layer and the geometrical parameters have been calculated it is possible to proceed to the mass estimation. Also in this case the mass of reinforcements, lines and canopy are calculated. The first three components can be easly calculated in the same way for all kind of parachutes, it is sufficient knowing the lenght and number of layer for each components, band density is given as mass for lenght unit.
What is different for each kind of parachute is the canopy mass (and also porosity) determination:

- Ribbon: in this case the canopy is made of bands just like the other components. With geometrical relations it is possible calculating the lenght of every band, and so calculating the mass.
- Ringslot/Ringsail: for these two kinds of parachutes the canopy mass calculation is pretty similar and can be used the same subfunction. It is possible dividing the canopy calculating the mass of one gore, multiplying for the number of gore. Using this method the gore can be seen made of a number of trapezes, it is possible finding their area, calculating the total closed area of the canopy. For the fabric the density is given as mass for surface unit.
- DGB: the disk-gap-band canopy can be treated in a simalr way of the ringslot one. In this case looking at the gore it can be divided in a trapeze for the disk and a rectangle for the band. Also in this case is necessary the calculation of the total area, the same kind of materials of the ringslot case are used.

5.3 Trajectory

In this section the descent trajectory simulator will be described. First of all the required data for the simulation will be shown, then the stages phases will be analized. Finally also the output data will be discussed.

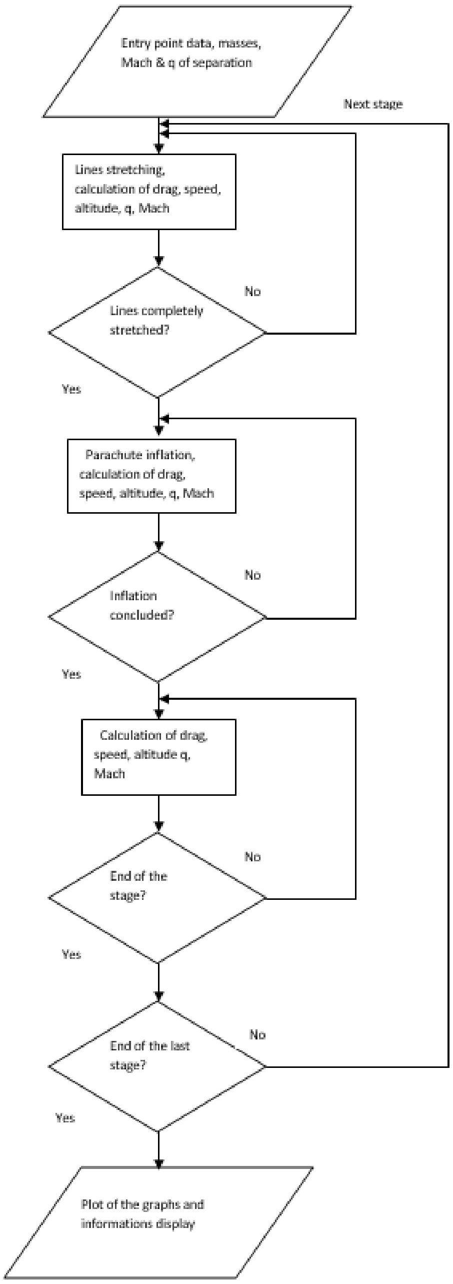


Figure 26: Trajectory simulator flow chart

5.3.1 Data from sizing and other input

Some data calculated with the sizing part of the tool, or used yet before as input, are strictly necessary for the simulation:

- Number of stages: obviously the first thing to know is how many parachutes are necessary.
- Type of parachute: the selected kind of parachute is necessary in order to select the associated Cd and Cx.
- Parachute diameter: the diameter togheter with the Cd is necessary in order to calculate the drag area.
- Vehicle diameter and Cd: also in this case are necessary for calculating the vehicle drag area.
- Vehicle mass: rapresents the biggest part of the descent system mass.
- Parachutes masses: during the sizing phase are considered negligible. In this phase the calculated masses are added to the vehicle mass, giving the total starting mass, when a stage is cutted its mass is subtracted from the total one.
- Dynamic pressure: if dynamic pressure is selected as end stage condition the calculated one is used in the simulator, using also the Mach required as input.
- Planet: the planet selection is necessary in order to know the gravity acceleration.
- Reefing value: imposed in case of multi-stage configuration or calculated in a single stage one.

Other input are required, which are not calculated in the sizing part:

- End conditions of a stage: the end conditions can be of three different kinds:
  - Dynamic pressure and Mach
  - Time
  - Altitude
- Altitudes: altitude at entry point is necessary for the starting position and velocity determination; the final altitude is used in order to have a condition at which the simulation ends.
- Free fall distance: before the parachute could start to inflate the vehicle must run across a certain distance, expressed as a ratio of the vehicle diameter.
- Inflation time: the time required from the parachute for reaching its maximum area.
- MES: mortar ejection speed, the speed at which the first parachute bag is shot, the others are extracted by the stage before.
- FPA entry point: flight path angle at the entry point.
- Disreef time: time at which disreef starts and ends.

5.3.2 Free fall and line stretching

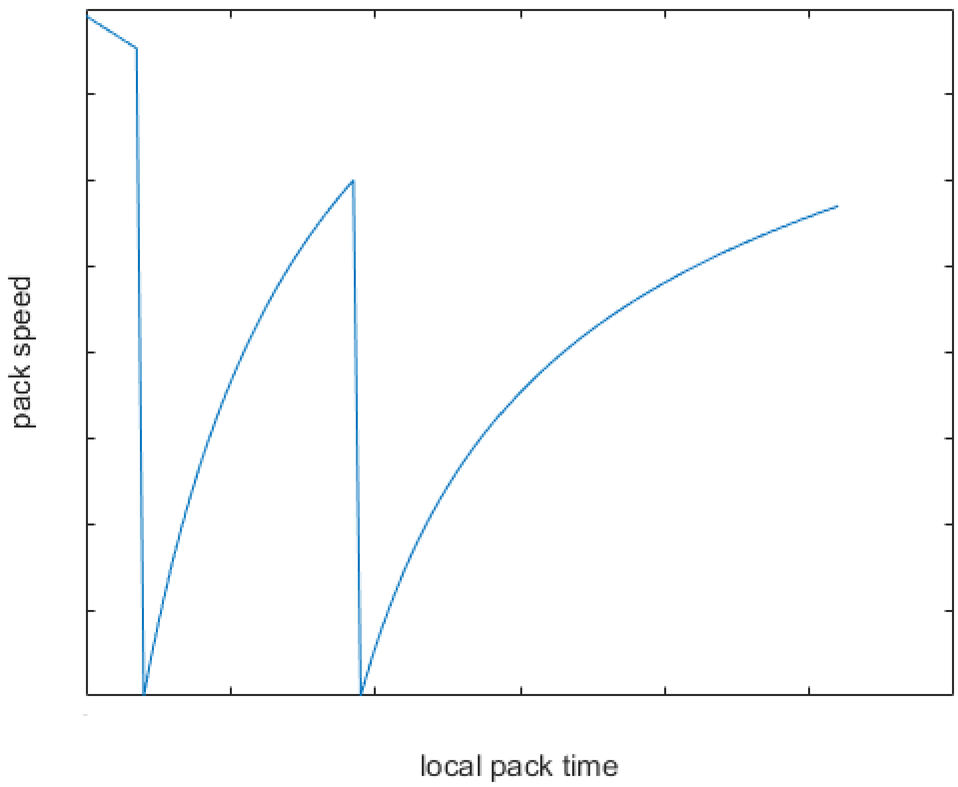


Figure 27: Bag speed graph

The first phase of each stage is the free-fall phase. During this phase lines are stretching and vehicle has to run across a certain distance given as input, must be noted that this distance is relative to the bag-vehicle bag system not to the absolute altitude of the vehicle. As you can see in the image above the speed trend of the bags are reported in the same graph.

The first stage bag has the initial velocity given by the mortar, then the separation speed decreases because of the gravity acting on the bag and also because the vehicle is slowing down.

The other two stages bags of this example have a different speed variation, this is because they are starting with a null separation speed, extracted by the stage before, the vehicle without a parachute dragging starts to accelerate to the planet direction ,increasing the separation speed. The lines stretching lasts fractions of seconds.

5.3.3 Parachute opening

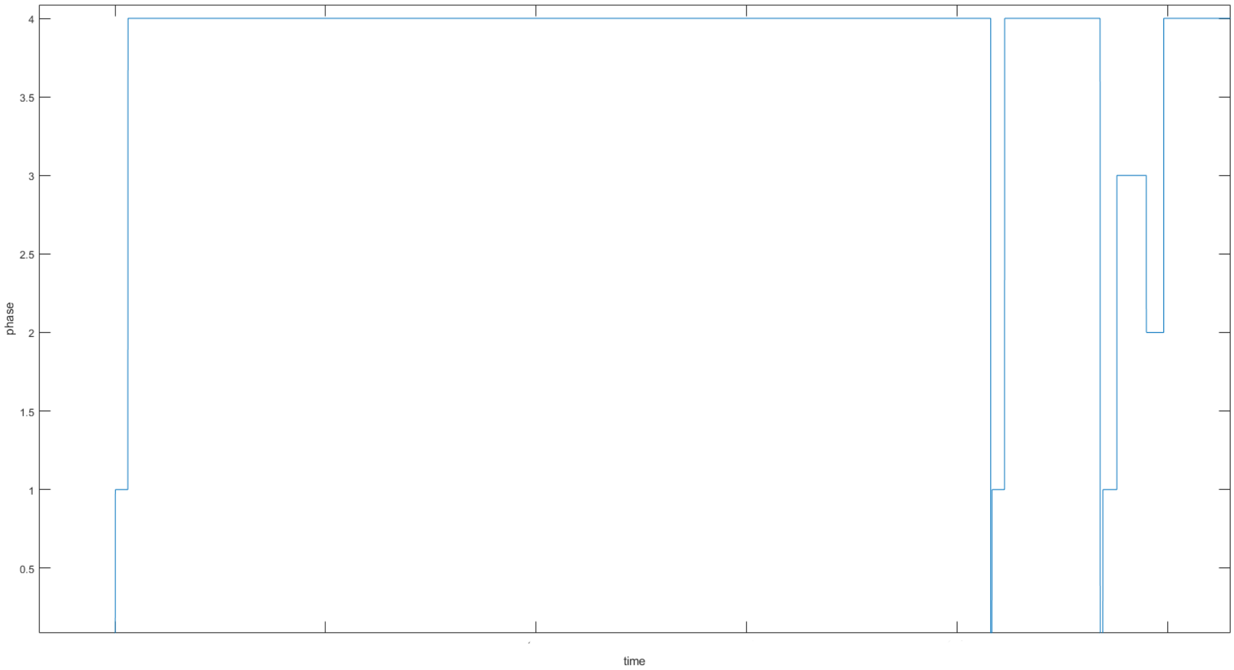


Figure 28: Opening phases

In this first image the sequence of the IXV example is reported, the final part has been cutted being constant at the final value.
Five different phases are present in this example, the maximum possible in this model. The next three are always present:

- Phase 0: there is no parachute opening, lines are still stretching.
- Phase 1: lines stretching is finished, the parachute is inflating.
- Phase 4: parachute is fully inflated and no reefing is present anymore.

The next two phases are present only if a reefing of the parachute is used:

- Phase 3: the first inflation is finished, there is a pause moment before the disreef starts
- Phase 2: disreefing is happening.

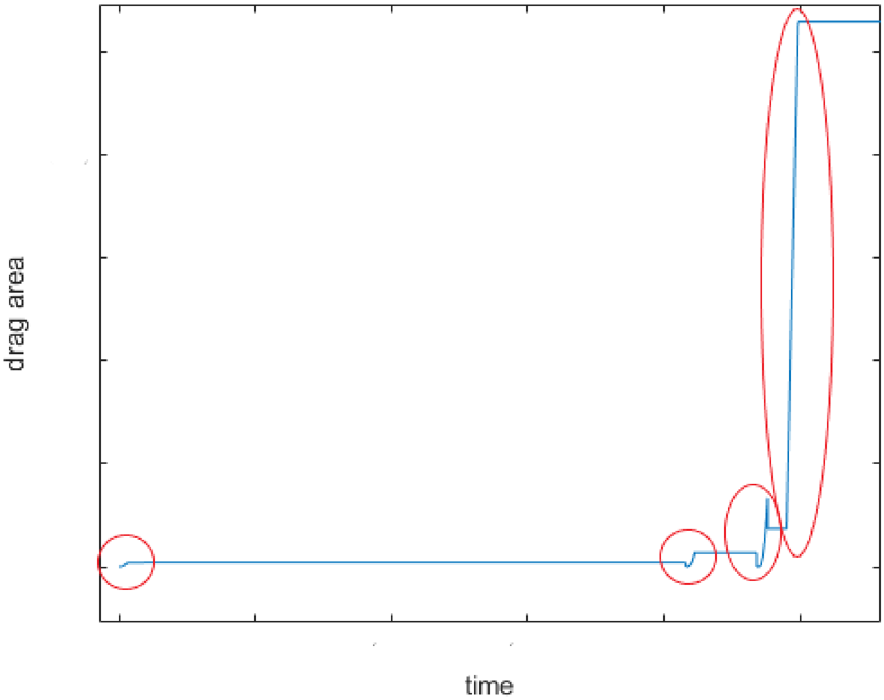


Figure 29: Drag area evolution

In the grap is reported the evolution of the drag area of the stages. Obviously it is zero when there is no parachute. In red are circled the inflation phases.
the inflation transitory is described with an exponential law.

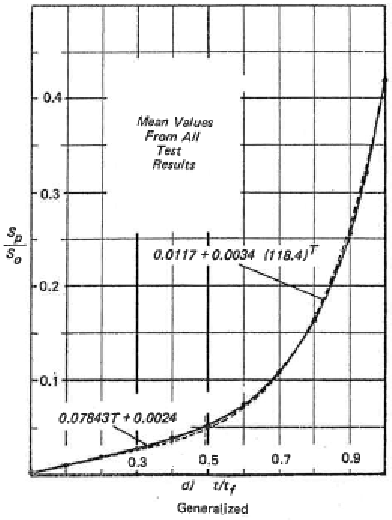


Figure 30: Drag area evolution

5.3.4 Descent with parachute

Once the parachute is inflated the load factor reaches quickly the steady state value. The drag areas of both parachute and vehicle stay almost constant, only small changes happens because of the Mach corrections. These corrections are present also during the transients, but their influence is not easly appreciable.

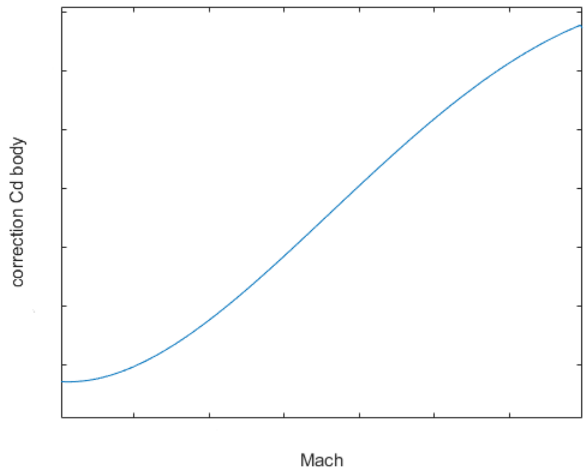


Figure 31: Vehicle Cd correction

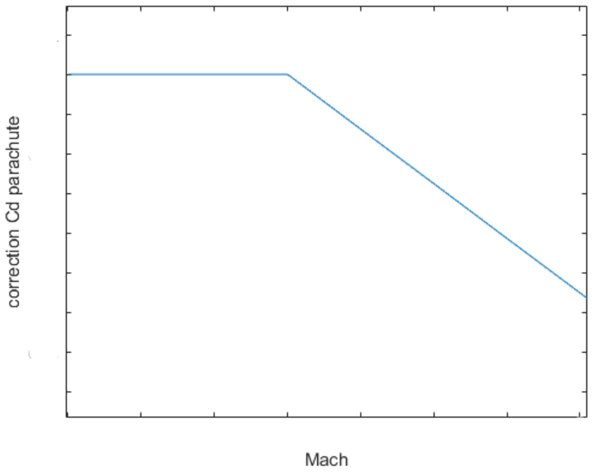


Figure 32: Parachute Cd correction

The two graphs rapresent the Cd variation of parachute and vehicle. The parachute one decreases with mach, keeping to decrease with the same trend. The vehicle one increases with Mach. then remains constant at a certain value.

5.3.5 Graphs and data obtanained

The tool can give as output many different graphs and data. Even if in GUI the graphs are just four in the matlab model there is the possibility to obtain many others (were not specified the graph is in function of the time):

- Horizontal and vertical coordinates of the descent.
- Accelaration and speed during the descent.
- Trajectory angle.
- Dynamic pressure.
- Altitude.
- Dragging force.
- Mach number.
- Global load factor.
- Parachutes load factor.
- Bag speed during lines stretching.
- Stage phase.
- Drag area variation.

For each parachute stage also the following data are calculated:

- Final altitude.
- Final speed.
- Final dynamic pressure.
- Maximum load factor of the stage.

Thanks to these data it is possible to verify if the descent trajactory is as espected and if the load factor requirements are respected. Also a separated model was elaborated in which the descent is repeated changing the Cd in order to investigate the effects of the variation.

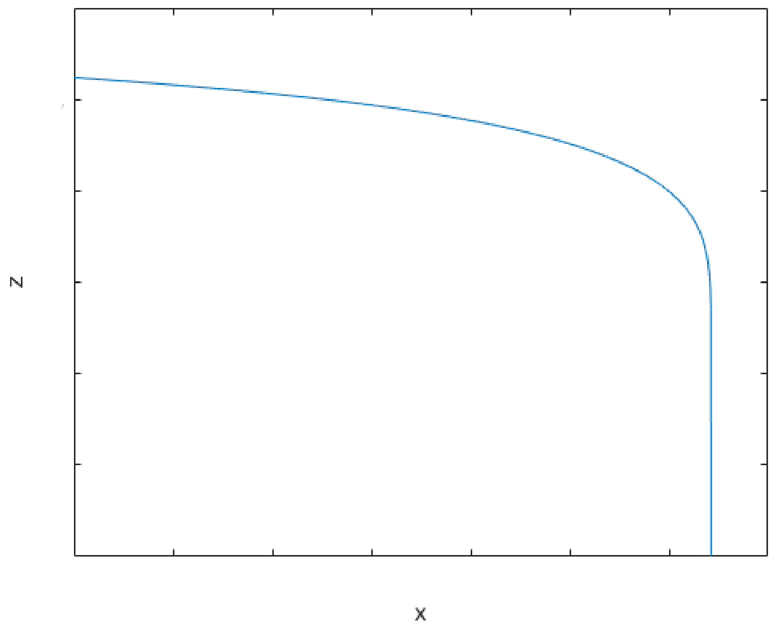


Figure 33: Descent trajectory

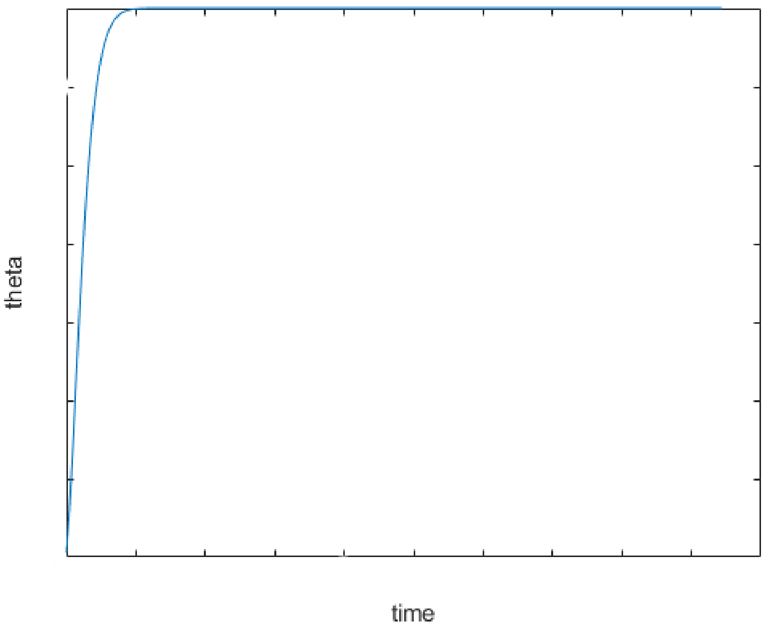


Figure 34: Flight path angle variation

The two graphs above rapresent the trajectory in x and z coordinates and the evoultion of the flight path angle. They are reported here because in no other section of this work are shown. The important thing to notice is that very quickly the horizontal component of the speed becomes null and the vehicle starts to descent in vertical.

6 Model evaluation

In this section main advantages of the tool and some limitations will be discussed in order to give the idea of how the tool could be helpful and in which conditions could give troubles.

6.1 Utility of the model

The model has some important advantages for a preliminary sizing study and descent validation:

- The sizing tool, working on dynamic pressure is not dependant on altitude.
- The tool is really quick to learn and run, the user can try many different configurations not loosing much time.
- Even if the simulator has just two DOF it can describe in a reliable way the descent.
- The tool can quickly give an idea of the masses, diameters and parameters of the parachutes, without a deep and long study.
- The user can also load data of existant parachutes systems and verify the descent phase.

6.2 Application limits

The developed tool has the important advantage of giving an easy and quick tool for a preliminary study of a parachute system. On the other hand has some limitation, due to the trying to make it as general as possible. This does not mean that this tool is not reliable, but some attenctions must be taken, in particular:

- The first limitation of the tool has been exposed before, in fact the estimation of the mass for a ribbon type parachute is not accurate. It should be better in future a better description of canopy loads. Anyway usually ribbons have small diamaters and so low mass velues, the error shouldn't be very significant, specially in multistage systems.
- A second limitaion of the tool is being strictly linked to Cd and Cx parameters. The program uses at the moment medium values found in litterature.
- At the moment Mars atmosphere model could be not very accurate, a better study is suggested in future. Also drag correction on Mars could be a little bit different, expecially for parachutes.
- Inflation time cannot be calculated in the sizing section, at the moment the user must provide it.
- Obviously being a 2 DOF kind the simulator cannot describe the effects of rotations around the axys.

7 Validation

The tool needed to be validated, so results from the part of the tool itself were compared with existing missions data. The most important results to validate were stress distribution on parachute components, sizing results as diameter, mass, end conditions and descent trjectory parameters.

7.1 Stress model validation

The stress model was validated considering the Exomars missions data and other parachutes found in literature. An excellent matching was found for lines, canopy in particular for fabric made ones, and skirt reinforcement. Some important differences were found in the vent reinforcement estimation, which is a particular critical part, difficult to study. In some cases the results were good in others significant differences were found, probably in some conditions such a preliminary study is not sufficient. Anyway the stress estimation of the vent, used for the mass estimation of this part is almost negligible on the total mass of the parachute.

7.2 Strategy and sizing model validation

7.2.1 Earth: IXV

The first sizing validation was made starting from dynamic pressure and maximum load factor of IXV. Obtained results were then compared with the mission ones. Numerical data cannot be reported so results are shown in terms of relative error from the real ones. As said before this mission had a three stages configuration. The most important data from sizing are diameter, mass and final dynamic pressure of that stage. The last one has no dynamic pressure data because is imposed as an input.

- Number of stages: 3, correct
- Firts stage:
    - Diameter error: -13%
    - Mass error: -43%
    - Final q error: -18.5%
- Second stage:
    - Diameter error: -14%
    - Mass error: +8%
    - Final q error: -4%
- Final stage:
    - Diameter error: +3%
    - Mass error: -21%

Results of the study are reported above. The first and most important thing to notice is that the estimated number of parachutes is correct, so the staging strategy matches. Diameter and dynamic pressure of the end of the stage have in all the three cases an error lower then 20%. For these data the error can be due to different Cd and Cx used.
Looking at the estimated mass error of the second and third stage the matching is pretty good as before, only the first stage mass shows an important difference. The first stage in fact is a ribbon type parachute, in this case load on canopy cannot be found as force/surface, but is more difficult. Also the diameter error contributes in the mass error. Even if the percentage error is important the first stage is lower in dimension compared to the others, expecially to the third, so its contribution is limited in the total mass.

7.2.2 Mars

For the sizing validation in Mars condition data from ExoMars 2020 were compared with the tool results. In this case load factor value were not really precise, so it should not be surprising having bigger error.

- Number of stages: 2, correct
- Firts stage:
  - Diameter error: +4%
  - Mass error: -30%
  - Final q error: 27%
- Final stage:
  - Diameter error: +10%
  - Mass error: +17%

Also in this case the right staging strategy was found, bigger error on dynamic pressure end condition can be found, anyway as said before a precise load factor was not available and also the Cd and Cx of the parachute are nor exactly the same. For the same reason the 30 % error on mass of the first stage can be explained, also different kind of material can help to explain that error.
On the other hand also a sizing with single stage reefed parachute was tried, giving almost the same results as real data.

7.3 Trajectory model validation

For the trajactory simulator validation data from the two missions were compared with the results of the simulator itself. Graphs of altitude, dynamic pressure, Mach number and load factor in function of the time of flight are reported above (load factor data were not available for ExoMars).
Both results from the simulator and data are reported without numerical values in order not to disclose sensitive information. In both cases result are really reliable, being concident in the Earth simulation and very close to real data in Mars case.

7.3.1 Earth

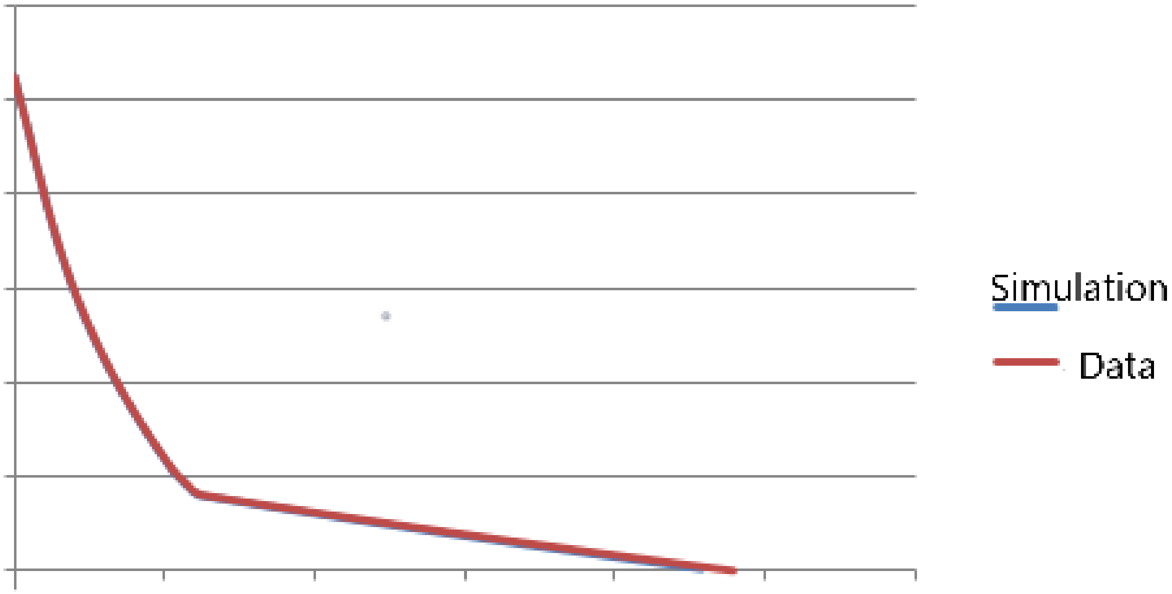


Figure 35: Altitude vs time, Earth case

For what concerns the trajectory simulation results and data are almost coincident in every moment, just a little difference of time can be found. In fact simulation with the tool ends some seconds before, anyway not an appreciable difference.

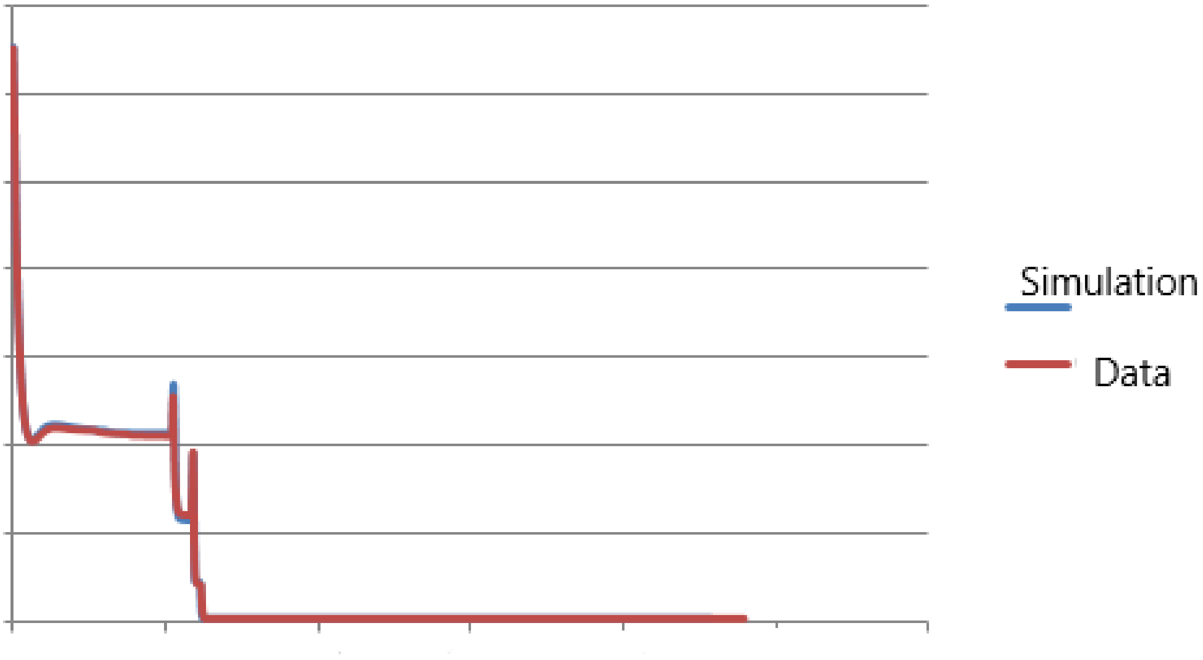


Figure 36: Dynamic pressure vs time, Earth case

In the graph above dynamic pressure in function of time is rapresented. Also in this case results of the simulator and data are almost coincident, just a little difference in the second dynamic pressure pick can be found, which means that in that transitory probably the simulation has a velocity a little bit higher than the one in data. Anyway the difference is about one hundred Pascal for few seconds.
The stages can be easly distinguished, in fact the second and the third pick are the free fall phases between the first and second and the second and the third stage.It can be noted that once the parachute is inflated the dynamic pressure tends quickly to assume a value almost costant. The little step during the final stage rapresents momentary state of equilibrium before the last parachute is disreefed. As said before during the supersonic descent the dynamic pressure has a trend change, in fact while speed is decreasing the density is rising.

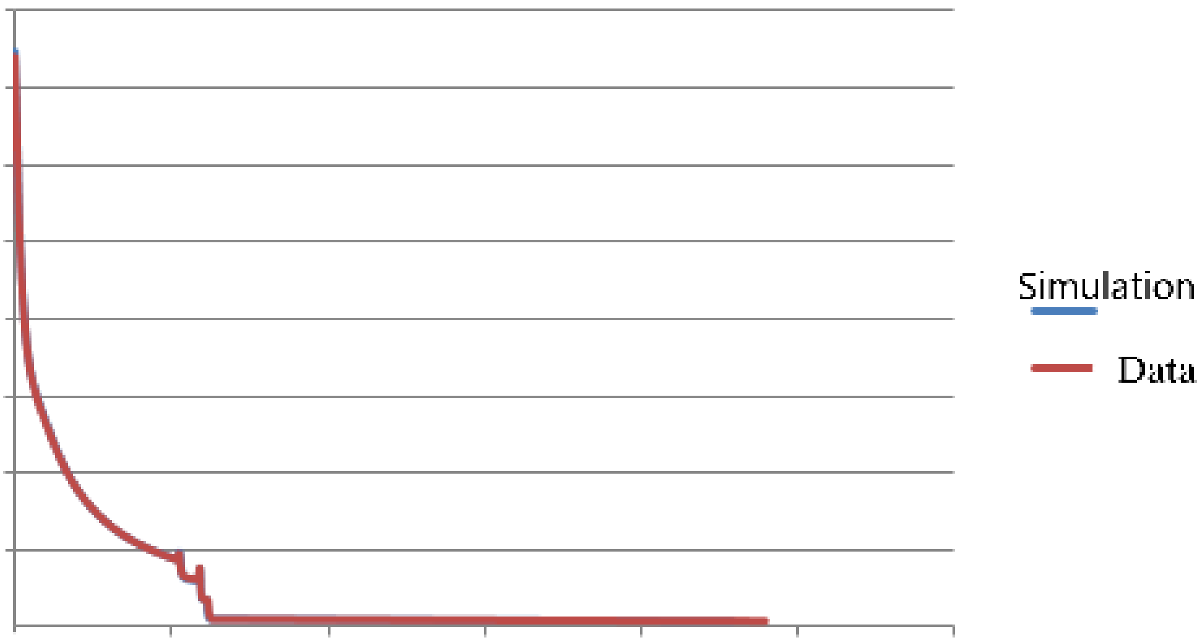


Figure 37: Mach vs time, Earth case

Also Mach number in function of time was calculated, negligible differences can be found between the two curves. Can be noted that the first parachute has the biggest Mach drop. Second and third parachutes have little drop, concentrated in the immediate seconds after inflation. The third parachute has a long descent phase with almost constant Mach number. Also in this graph can be seen a little step when the last parachute is disreefed. Just like in the dynamic pressure graph free fall phases show a pick in the curves, which means that speed is rising, not having a parachute drag contribution.

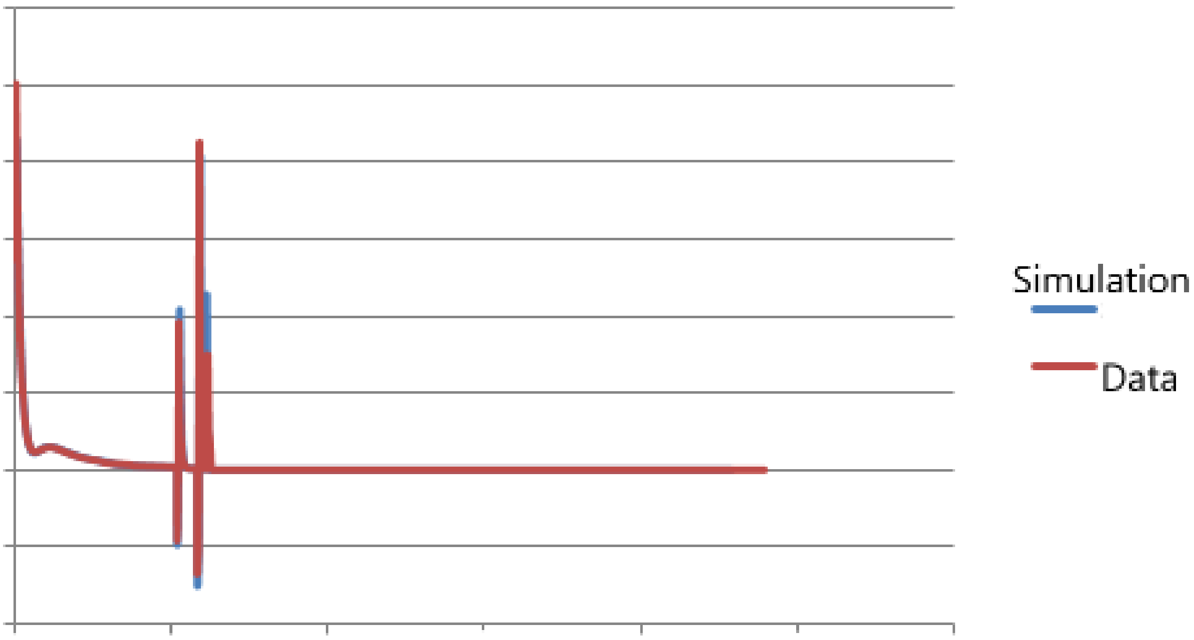


Figure 38: Load factor vs time, Earth case

The last graph reported for the Earth case validation is the load factor one. Little differences between tool simulation and data can be noted during the inflation picks of acceleration, anyway also in this case differences are very low and last for few seconds.These little inconsistencies can be explained knowing that probably not the same Cx are used in the two simulation.

The first pick of inflation load is so high because even if the parachute is the smallest dynamic pressure is maximum. The third parachute on the other hand has lower dynamic pressure but a very high drag area. The disreef load is rapresented by the last pick.

The first parachute load has a trend quite similar to the dynamic pressure, in fact drag and so accelaration is proportional to it. When inflation transitory are concluded load factor tends to one, which means that weight is balanced by drag of parachute and vehicle. When a parachutes is cutted the veichle is slowed down only by its drag, which is lower than its weight, so pick under 1 g happens, the second one is higher in module because Mach number is lower and so vehicle drag.

7.3.2 Mars

The simulator was also validated comparing results with Exomars 2020 data. In this case some differences are more visible, this happens because both vehicle and parachutes drag correction, in function of Mach number, were written interpolating data from IXV. This means that for that kind of vehicle and specially for Earth case correction are almost perfect, in Mars atmosphere some errors are present. Anyway differences are limited and accettable, with about ten seconds of flight time error.

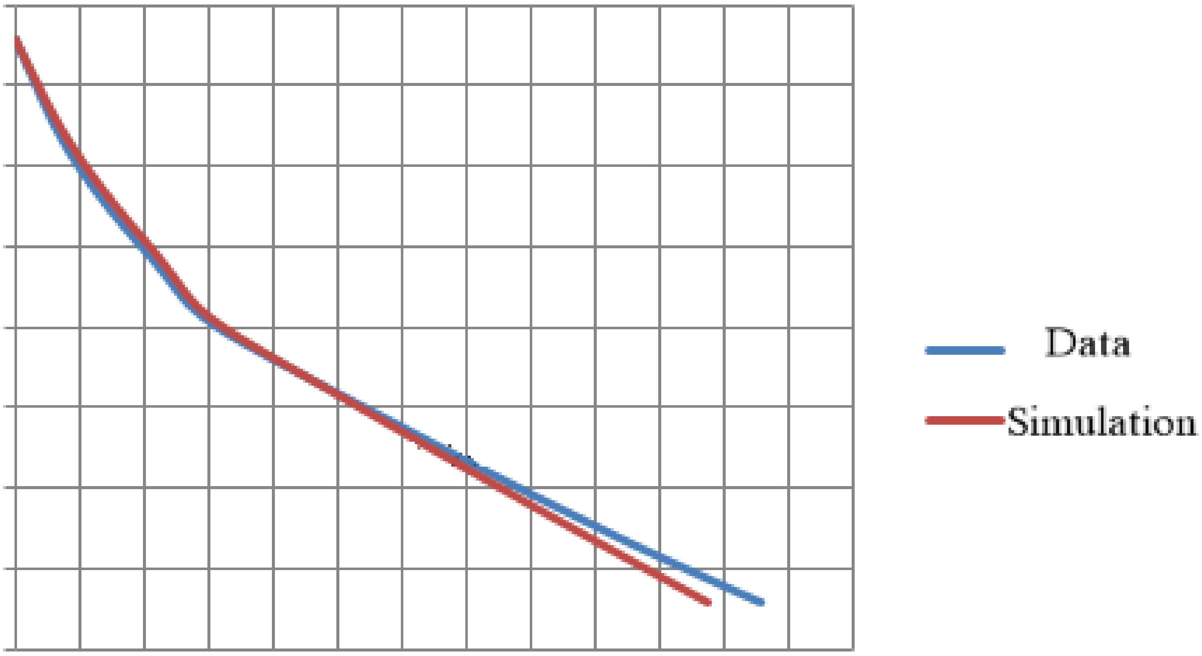


Figure 39: Altitude vs time, Mars case

This first graphs of ExoMars comparison rapresents the altitude in fucntion of time. It can be noted that during the first moment of first parachute phase the tool simulator calculates that the vehicle is a little bit higher with a velocity a little bit lower and so dynamic pressure. During the last seconds of first parachute stage the trend changes and the vehicle starts to lose altitude faster. This trend becomes more strong during the second parachute stage. This can be explained with little imprecisions in the drag-mach correction function and also with little differences in Cd.

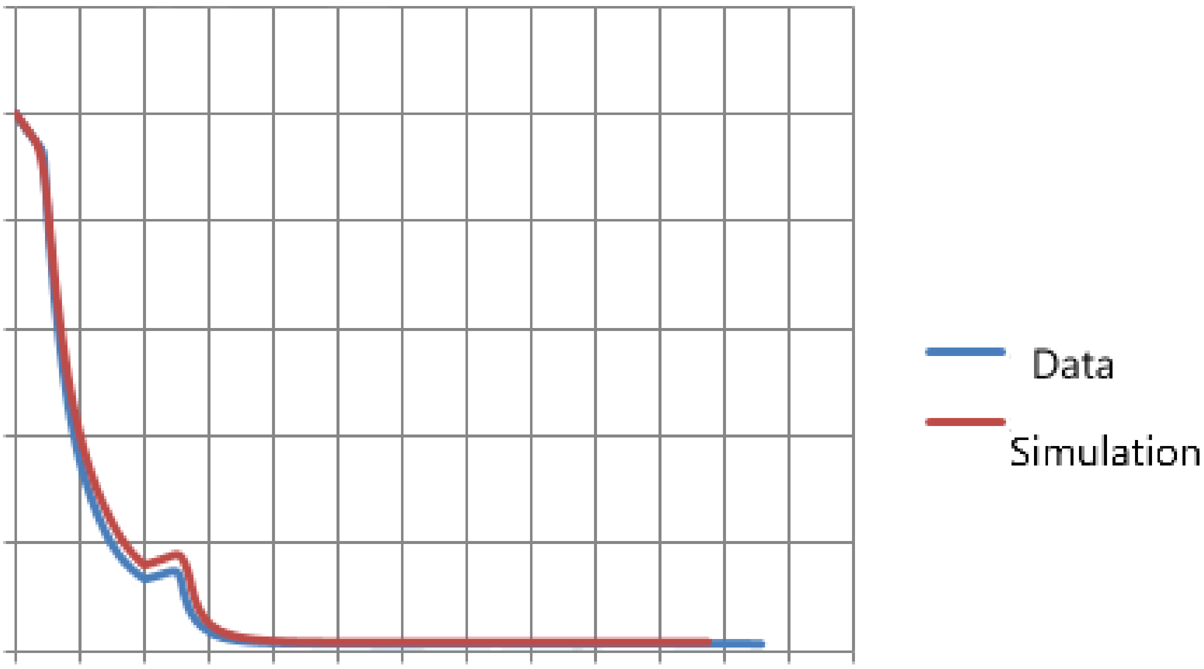


Figure 40: Dynamic pressure vs time, Mars case

In this graph dynamic pressure variation in function of the flight time is reported. As suggested for the altitude graph, it's clear that from about the half of first stage the dynamic pressure starts to become bigger in the simulator calculation, compared with data.
Unlike the Earth case there is no trend change in supersonic descent. An other thing to notice is that the dynamic pressure decreasing is not as fast as on Earth, but slower. This is probably due to the less dense Mars atmosphere.
Also the free-fall phase has significant differences from Earth simulation, in fact no dynamic pressure pick happens but a gradual increase. During the free-fall simulation and data curves are almost parallel.

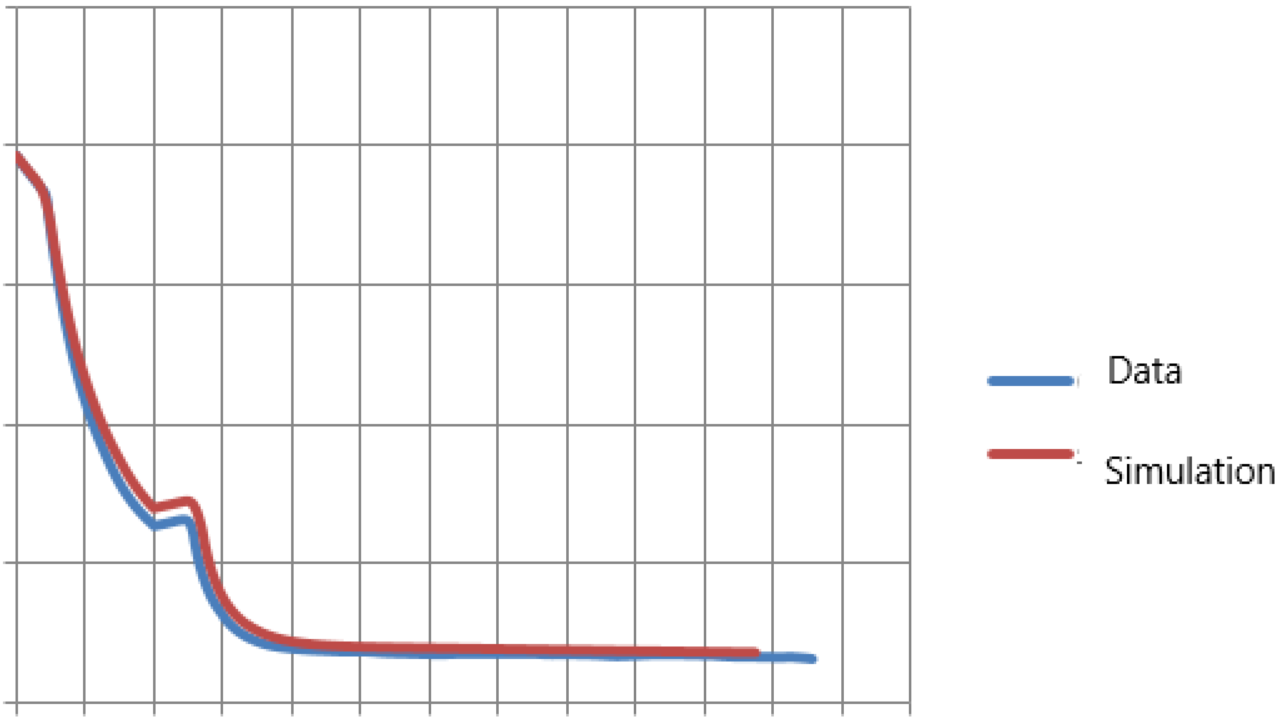


Figure 41: Mach vs time, Earth case

The last graph of comparison is Mach in function of time of flight. Unlike the Earth case Mach and dyanmic pressure curves have the same trend, obviously with different values. The same consideration made for dynamic pressure are valid.

7.4 Cd variation effects in Mars simulation

Even if it is written in the validation section, these graphs are a study on the effects of uncertainties and variations of parachute medium drag coefficient. The simulation has been made inserting the code into a for cicle, whose purpose is to provide the ith element of the Cd variation vector at each step, not changing the code functioning. The Cd of parachute has been made change from 50% to 150%.

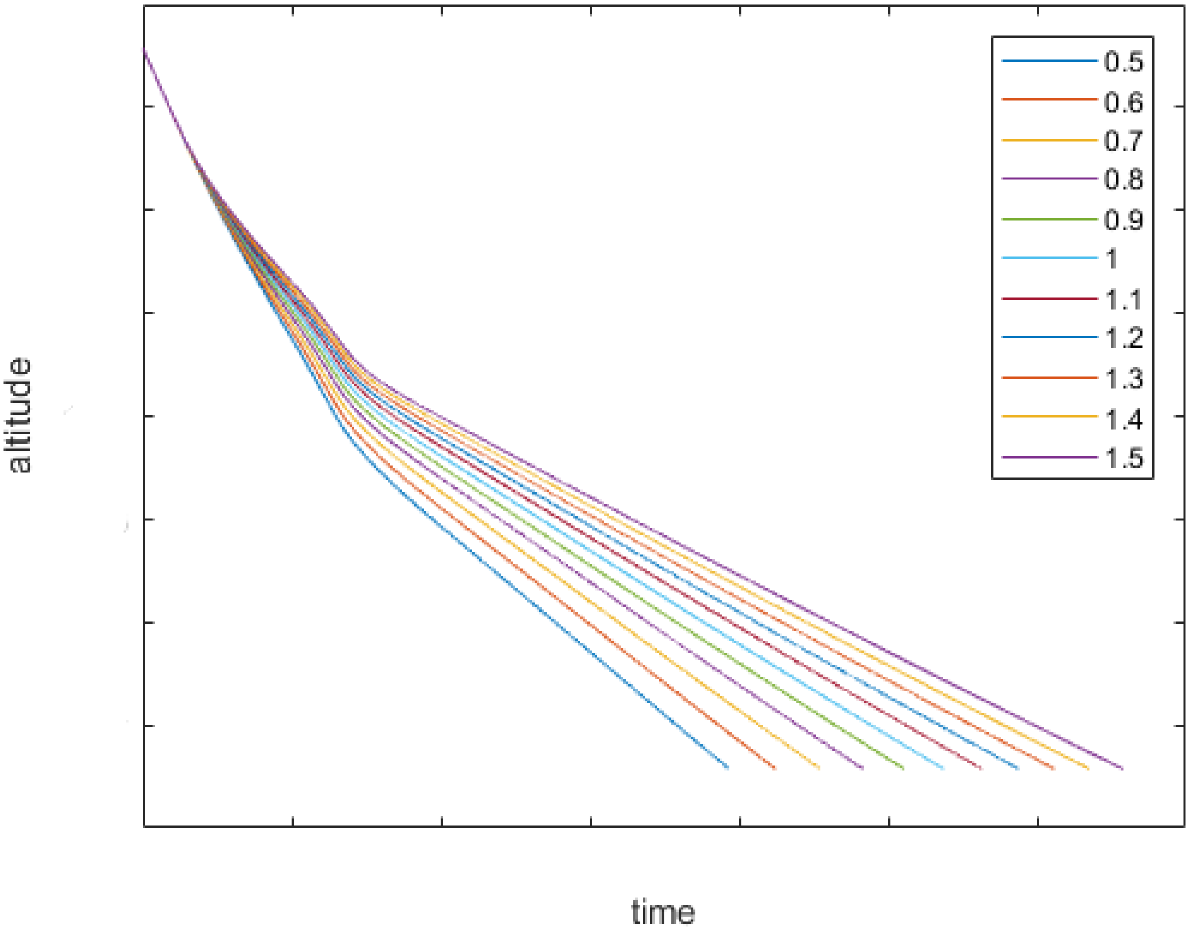


Figure 42: Altitude vs time, Mars case with Cd variation

The first graph reported is the altitude one. As it could be expected parachutes with lower Cd have a lower flight time. The first parts of the curves are coincident, in fact only vehicle drag is acting, starting from same altitude and speed.

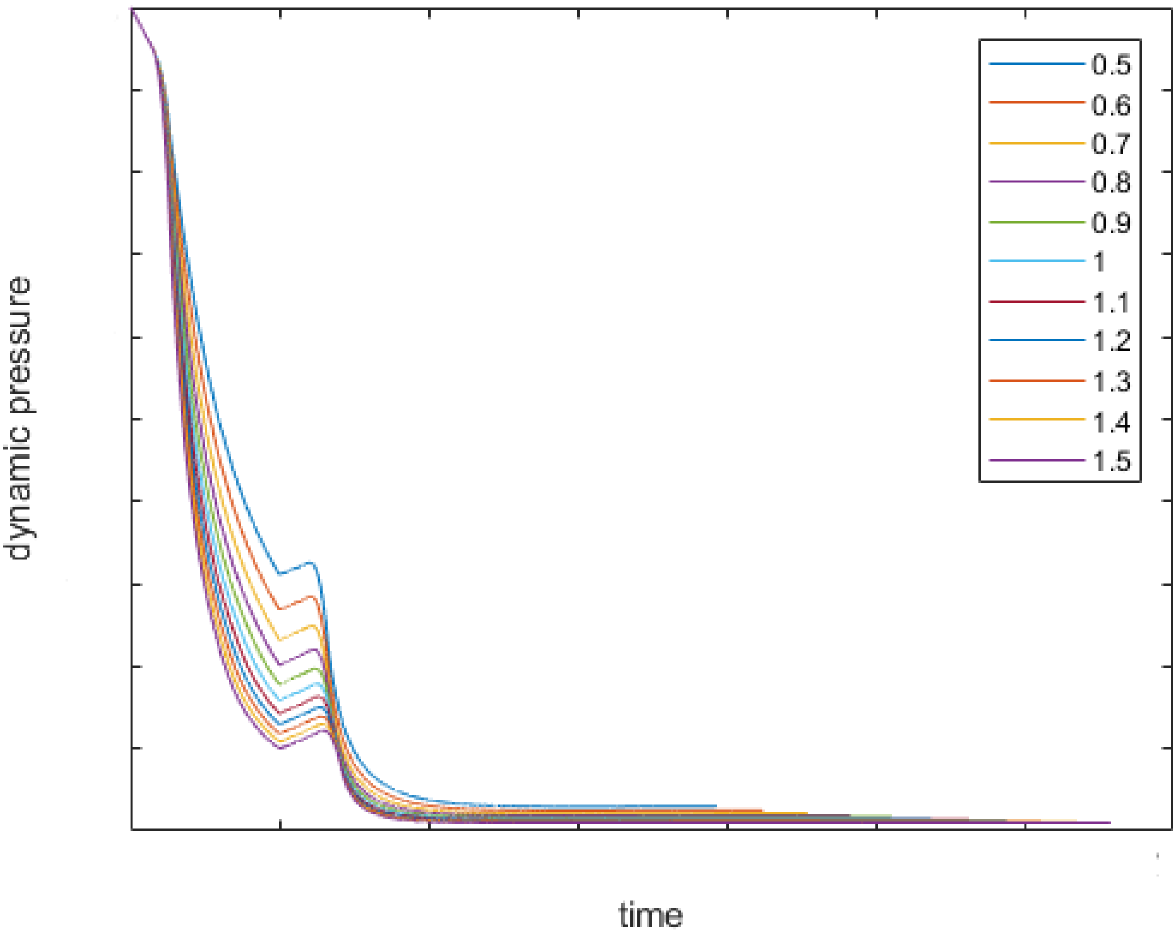


Figure 43: Dynamic pressure vs time, Mars case with Cd variation

In the second one dynamic pressure is reported. Also in this case the first free fall phase is identical in all the cases. In lower Cd cases having lower drag, speed is higher and so is dynamic pressure. During the second free fall phase curves are almost parallel (Mach has a certain effect on Cd of the vehicle but not so significant). After the second inflation configuration with lower Cd, having higher dynamic pressure have also an higher drag force and steeper curves. After the transitory all the configurations reache a balance state, lower Cd configuration obviously have higher equilibrium dynamic pressure.

8 User interface

In this section the user interface will be described in detail. First the sizing tool parts then the simulator ones.

8.1 Sizing tool

- Vehicle data and planet selection

Mass [redacted]

Diameter [redacted]

Drag coefficient [redacted]

● Mars

○ Earth

Figure 44: Vehicle and planet boxes

First of all the tool requires to select the planet, Earth or Mars (Mars is selected as default). Also vehicle data as Mass, diameter and medium drag coefficient. Obviously data must be accettable, no negative values.
Near the two boxes of planet seletion and vehicle data there is the sizing start button.
The labels are obscured in order to not release data.

- Parachute data

Parachutes data

Single parachute max reef [redacted]

Max diameter allowed [redacted]

Final stage
○ Ribbon
● Ringslot
○ Ringsail
○ DGB

Intermediate stages
○ Ribbon
○ Ringslot
○ Ringsail
● DGB

First stage
○ Ribbon
○ Ringslot
○ Ringsail
● DGB

	Final stage	Intermediate stages	First stage
Reefing	[redacted]	[redacted]	[redacted]
Max g	[redacted]	[redacted]	[redacted]

q entry point [redacted]

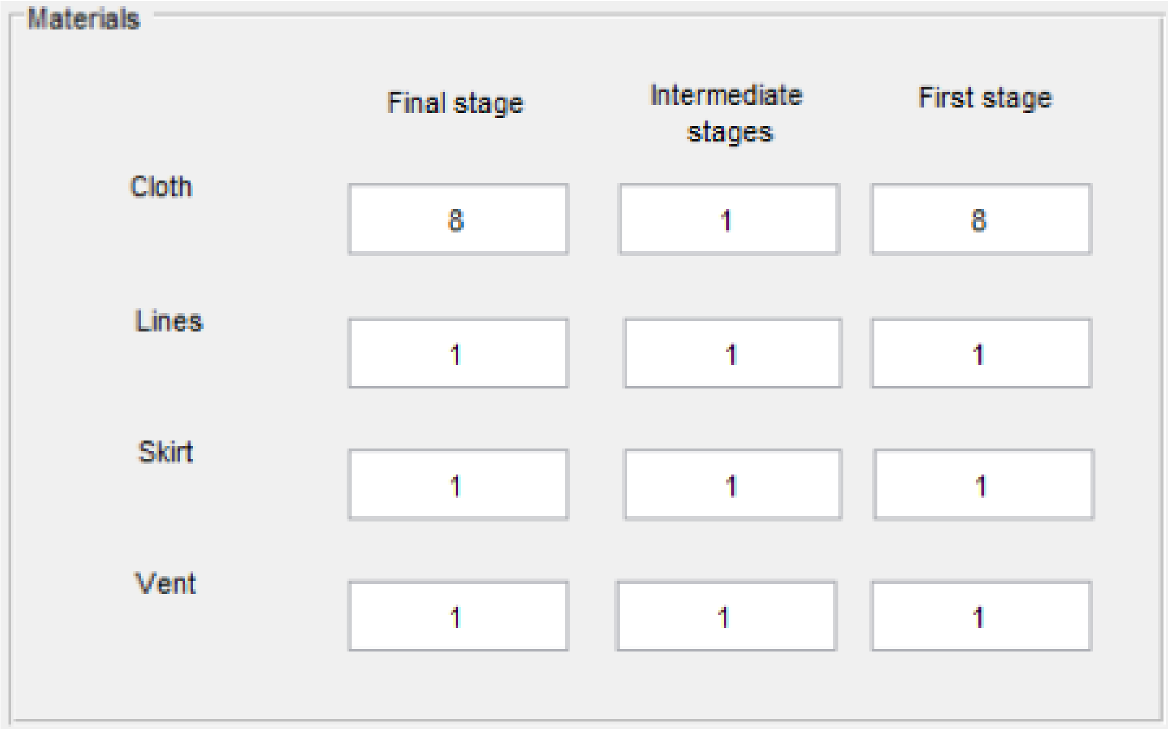
q final [redacted]

Safe margin [redacted]

Figure 45: Parachute box

The second data box concerns parachutes data. The intermadiate parachutes, maximum two stages, are treated using the same data. For each possible stage are required type selection, reefing and maximum load factor.
Also the maximum diameter for the final stage is required, if the calculated diameter is bigger an other parachute is added in the cluster. The minimum reefing value is necessary in order to determinate if a single stage is possible. Safe margin is required for the number of layer calculation in function of stress in the parachute parts. Dynamic pressure at entry point and final point is required for the staging determination .

- Materials data



	Final stage	Intermediate stages	First stage
Cloth	8	1	8
Lines	1	1	1
Skirt	1	1	1
Vent	1	1	1

Figure 46: Materials box

In this table material selection is required. The number insert in the labels is associeted to a certain material in the database. Each row of the table is a parachute part material, each column a stage. Must be noted that as said before intermediate stages as treated in the same way.
In this case labels are not obscured because number are associeted to the database, not showing the database itself is impossible to date back to data.

- Sizing results

Sizing results

Number of stages: 2

Single stage reefing: /

	First stage	Final stage	Intermediate stage (1)	Intermediate stage (2)	Single stage
Opening force	[redacted]	[redacted]	0	0	0
Parachutes in the cluster	[redacted]	[redacted]	0	0	0
Diameter	[redacted]	[redacted]	0	0	0
Mass	[redacted]	[redacted]	0	0	0
Opening dynamic pressure	[redacted]	[redacted]	0	0	0
Final dynamic pressure	[redacted]	[redacted]	0	0	0
Porosity	[redacted]	[redacted]	0	0	0

Errors: No errors found

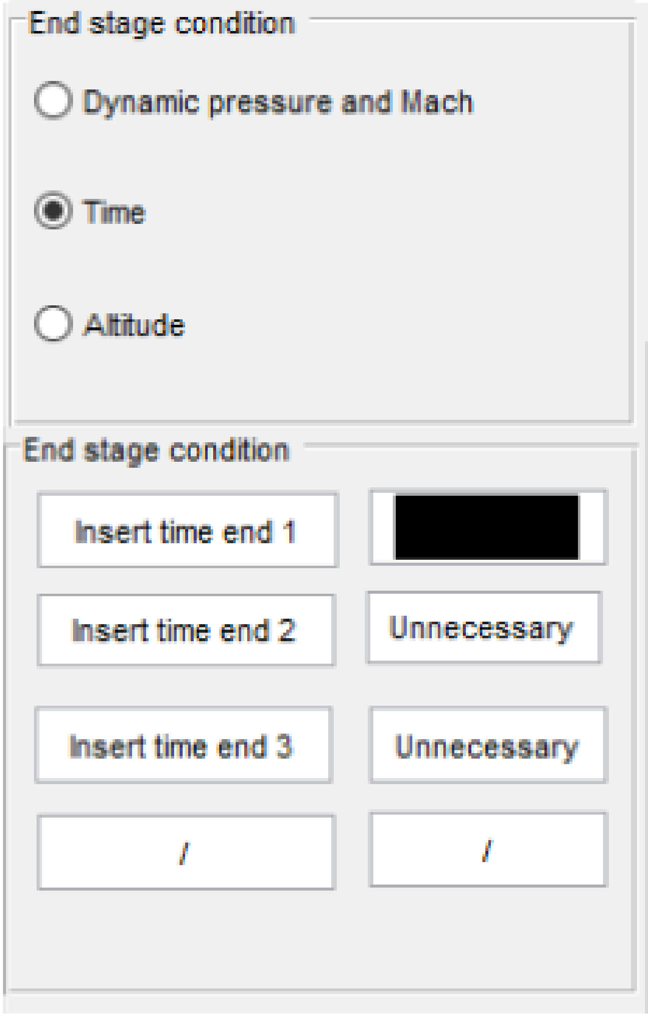
Figure 47: Sizing results box

The last box of the sizing part of the tool is the results table. The two labels in the upper part show the number of calculated stages and if possible the single stage configuration the reefing value.
In the lower part there is the error massages box, in this case no error were found, these labels anyway will be described in the next sections.
The most significant part is the table of results. In the rows are shown opening force, number of parachutes in the cluster, diameter, parachute mass, dynamic pressure at opening and cutting and porosity.
The columns are first stage, final stage, the two intermediate stages and the single stage. If some of the parachutes are not required by the staging strategy the column is filled with zeros.
Also in this case results are obscured.

8.2 Simulator

Once the sizing tool gives results it is possible to pass to the simulator, it is also possible to load data from an external data file.

- End stage conditions



End stage condition

○ Dynamic pressure and Mach

● Time

○ Altitude

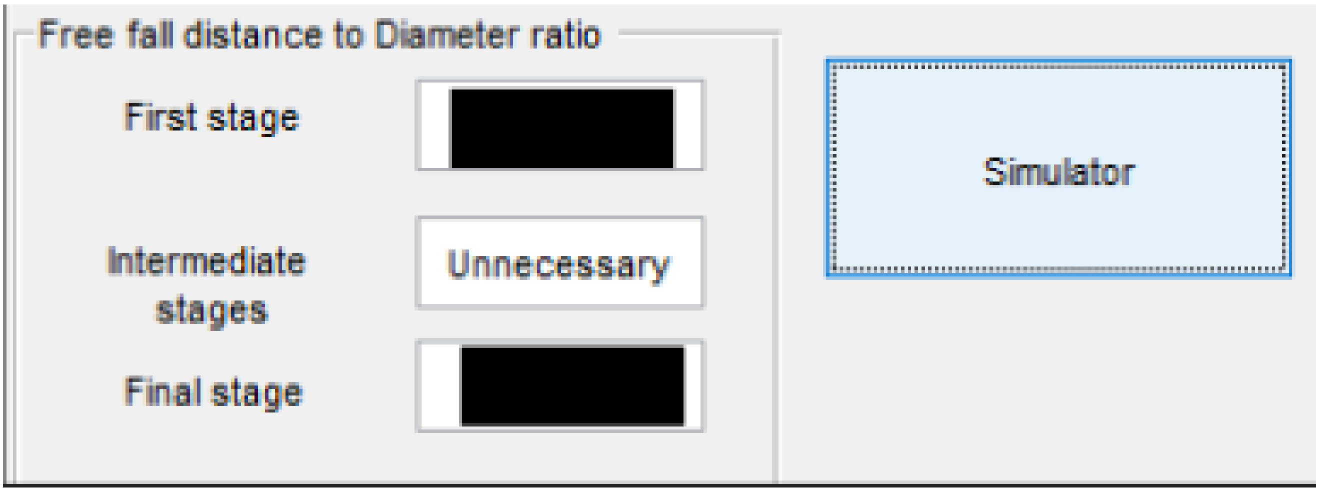
End stage condition

Insert time end 1	
Insert time end 2	Unnecessary
Insert time end 3	Unnecessary
/	/

Figure 48: End stage boxes

First of all the simulator requires the selection of the stage end conditions. It is possible to select dynamic pressure and Mach, time or altitude conditions.
In this case time was selected as end condition, having just two stages only the first one end condition is necessary, the second is the final altitude, required in the box that will be described in the next sections.
The last two labels with a "/" are associated with the dyanamic pressure tolerance as end condition, if q is selected as end condition. This is necessary because the dynamic pressure and Mach could be not exactly linked. Only if the first button is selected the last labels show the message "Insert tolerance on q".

- Free fall data



Free fall distance to Diameter ratio

First stage [redacted]

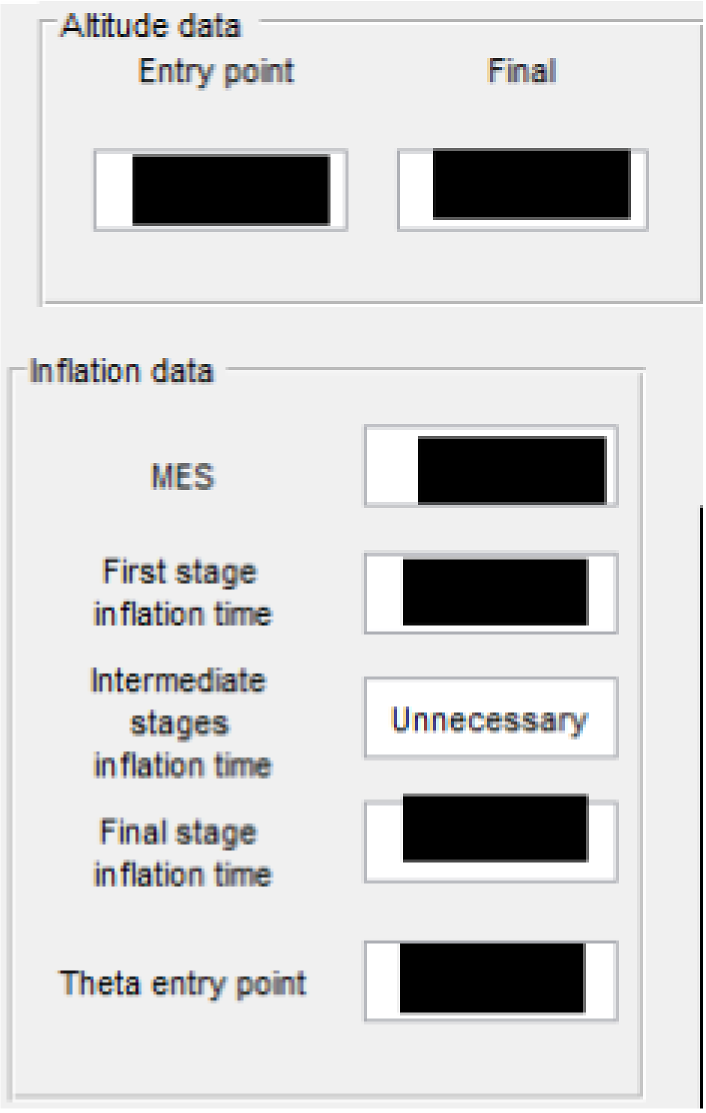
Intermediate stages Unnecessary

Final stage [redacted]

Figure 49: Free fall box

In this box the free fall distances are required. Close to this box there is also the simulator start button.
These data are necessary because before the parachutes can start its inflation the vehicle must run across a certain distance. This distance is expressed as a ratio to the vehicle diameter. In this case having just two stages the intermediate value is unnecessary.

- Altitude and inflation data



Altitude data

Entry point: [redacted]

Final: [redacted]

Inflation data

MES: [redacted]

First stage inflation time: [redacted]

Intermediate stages inflation time: Unnecessary

Final stage inflation time: [redacted]

Theta entry point: [redacted]

Figure 50: Altitude and inflation boxes

Altitude at entry point and at the end of parachute is required, in order to have the starting and end points. Also the angle of trajectory at the entry point is necessary. For the inflation of the first parachute mortar ejection speed is required, for the other stages is supposed that the parachute before extracts the next parachute. Also in this case obviously the intermediate stage is not present and no information is needed.

- Disreef time data

Figure 51: Disreef time boxes

The time of starting and end of the disreef, reported in function of the end of the inflation, are required. In this case no reef was present, so the message "unnecessary" is shown. Obviously also the second stage has the same message because there is no intermediate stage.
Near the disreef data box there is also the load button. If the user does not want to run the first part of the tool is possible to load data with this button from an excell file.

- Graphs

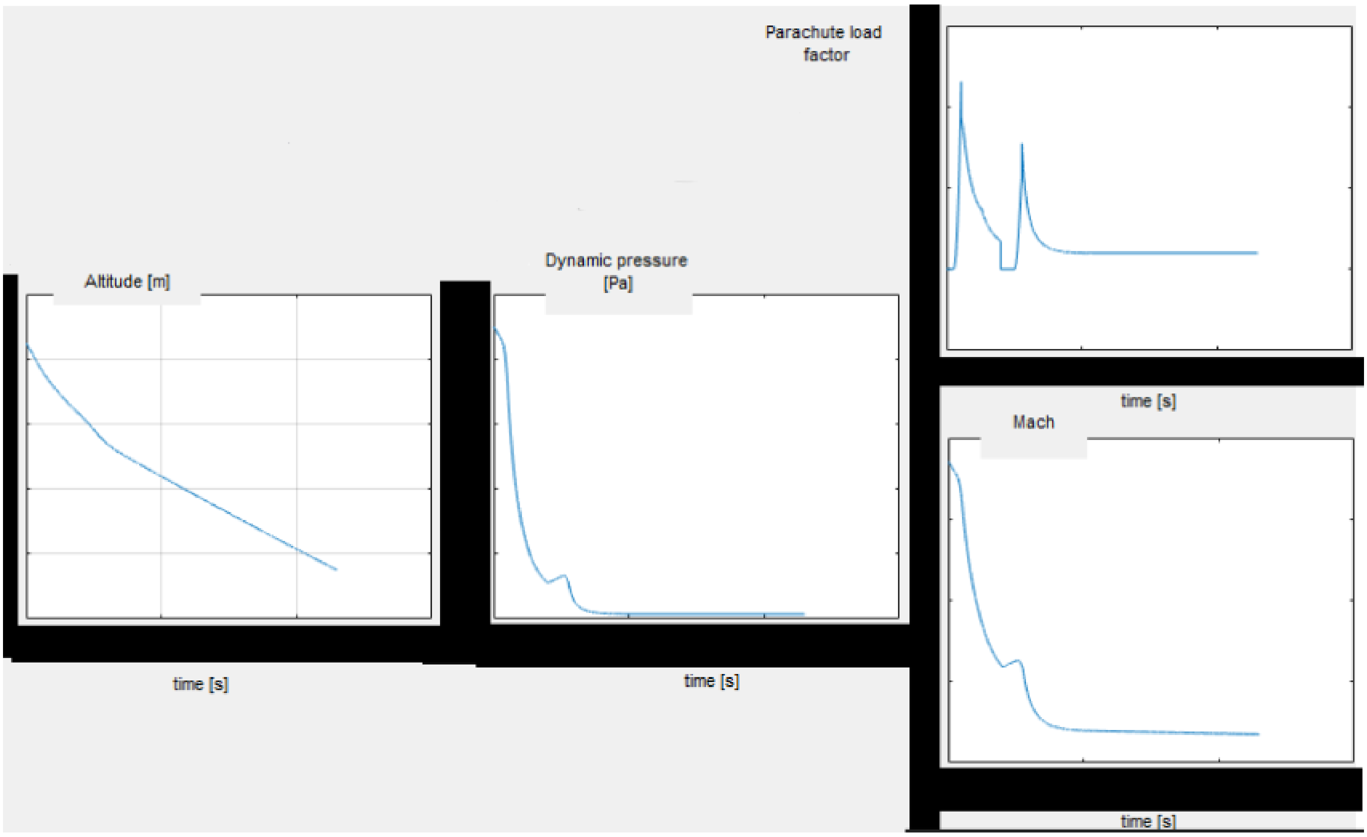


Figure 52: Graphs

Finally four graphs are shown, altitude, dynamic pressure, parachute load factor and Mach number. Also in this case the data of x and y axys are obscured. At the moment data of the graph are just shown, in future it would be quite easy adding the saving option in a separated file.

8.3 Errors and messages

- Not accetable value

Mass

errore

Figure 53: Error

If user tries to insert not accetable data like negative mass or reefing greater than one the program shows an error message. Also selecting a not existing material will generate an error message. With an error present the program will not proceed. Check if all data are accettable.

- Empty value window

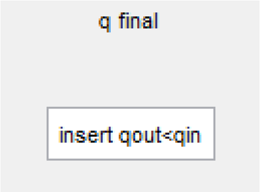
Mass

insert a value

Figure 54: Missing value

If all the input windows are not filled the program will not proceed, showing the message "insert a value". Check if all windows are filled.

- Inconsistent data



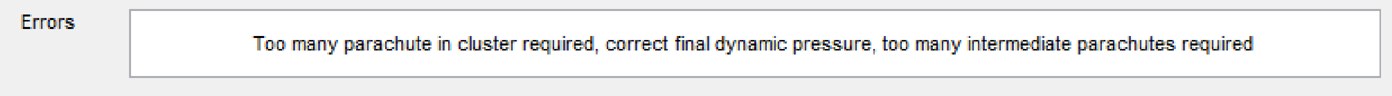
q final

insert qout<qin

Figure 55: Inconsistent data

Some input windows are linked with others, for example entry point and final dynamic pressure or the end stage conditions. Even if the single value is accettable could happen that putting together data would not be accettable. For example entry point dynamic pressure cannot be lower than final one. Check also if this kind of data make sense together.

- Too many parachute in cluster or too many intermediate stages

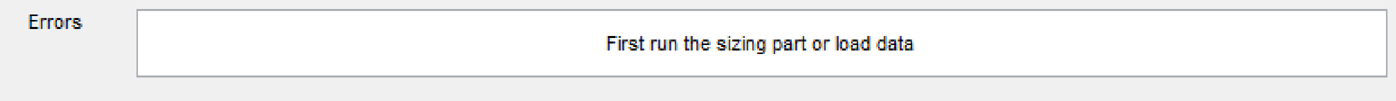


Too many parachute in cluster required, correct final dynamic pressure, too many intermediate parachutes required

Figure 56: Not accettable results

If final dynamic pressure is too low compared to the weight of the vehicle may happen that too many parachutes in the cluster are required. It could also happen that too many intermediate parachutes are required (two intermediate is set to be the maximum). Try to change the dynamic pressure values.

- Run of second part without data

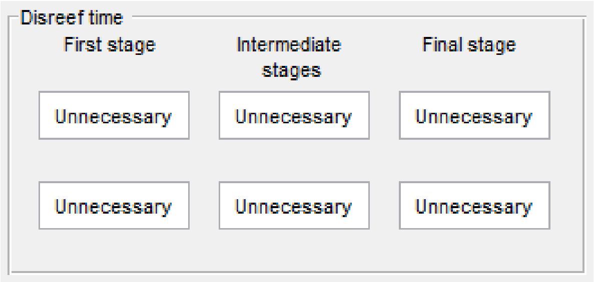


First run the sizing part or load data

Figure 57: Missing part run message

If user tries to start the trajectory simulation before running the sizing part or loading data the program will not proceed and will require one of the two actions.

- Unecessary data

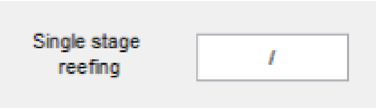


First stage	Intermediate stages	Final stage
Unnecessary	Unnecessary	Unnecessary
Unnecessary	Unnecessary	Unnecessary

Figure 58: Unnecessary data

The number of input windows for the trajectory simulation is the maximum, in case of a four stages configuration. A similar speach can be made for the input boxes for disreef timing. If some of these data are not required, for example reefing is one or the number of stages is lower, the message unnecessary is shown in the associated box.

- Reef single stage

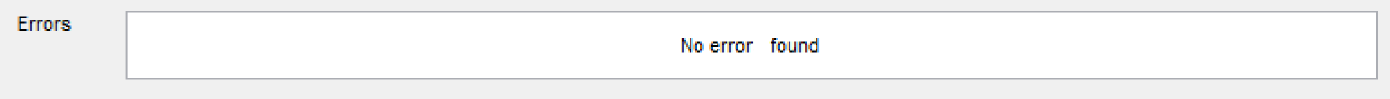


/

Figure 59: Reef single stage

If the single stage reef value satisfies the one imposed as minimum as input the single stage is possible. In this case the required reef is shown. If the requirement is not satisfied the single stage configuration is not possible and the box has a ”/”.

- No error found



No error found

Figure 60: No error found

If none of the errors above happens the sizing can proceed and data are shown in the parachute data table. In this case the error bar shows the message ”no error found”.

Vehicle data

Mass [redacted]

Diameter [redacted]

Drag coefficient [redacted]

Planet

● Mars

○ Earth

Materials

	Final stage	Intermediate stages	First stage
Cloth	8	1	8
Lines	1	1	1
Skirt	1	1	1
Vent	1	1	1

Sizing results

Number of stages: 2

Single stage reefing: /

	First stage	Final stage	Intermediate stage (1)	Intermediate stage (2)	Single stage
Opening force	[redacted]	[redacted]	0	0	0
Parachutes in the cluster	[redacted]	[redacted]	0	0	0
Diameter	[redacted]	[redacted]	0	0	0
Mass	[redacted]	[redacted]	0	0	0
Opening dynamic pressure	[redacted]	[redacted]	0	0	0
Final dynamic pressure	[redacted]	[redacted]	0	0	0
Porosity	[redacted]	[redacted]	0	0	0

Errors: No errors found

Parachutes data

Single parachute max reef [redacted]

Max diameter allowed [redacted]

Final stage

○ Ribbon

● Ringslot

○ Ringsail

○ DGB

Reefing [redacted]

Max g [redacted]

Intermediate stages

○ Ribbon

○ Ringslot

○ Ringsail

● DGB

Reefing [redacted]

Max g [redacted]

First stage

○ Ribbon

○ Ringslot

○ Ringsail

● DGB

Reefing [redacted]

Max g [redacted]

q entry point [redacted]

q final [redacted]

Safe margin [redacted]

End stage condition

○ Dynamic pressure and Mach

● Time

○ Altitude

End stage condition

Insert time end 1 [redacted]

Insert time end 2 Unnecessary

Insert time end 3 Unnecessary

/ /

Free fall distance to Diameter ratio

First stage [redacted]

Intermediate stages Unnecessary

Final stage [redacted]

Altitude data

Entry point [redacted]

Final [redacted]

Inflation data

MES [redacted]

First stage inflation time [redacted]

Intermediate stages inflation time Unnecessary

Final stage inflation time [redacted]

Theta entry point [redacted]

Disreef time

First stage	Intermediate stages	Final stage
Unnecessary	Unnecessary	Unnecessary
Unnecessary	Unnecessary	Unnecessary

Figure 61: User interface window

9 Bibliography

- Thomas Bennett, Jerry Rowan, Antonio Saluzzi, Stéphane Langlois, "Design, Development and Verification of the Intermediate eXperimental Vehicle Descent System", 21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar 23 - 26 May 2011, Dublin, Ireland
- Thomas W. Bennett, Jerry Rowan, Antonio Saluzzi, "Final Development and Verification of the Intermediate Experimental Vehicle Descent", 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, 2015, 10.2514/6.2015-2123
- John Lingard, John Underwood, Shane Glynn, Dominique Franqueville, Patrick Arfi, Olivier Bayle, Francesco Potenza, Stefano Portigliotti, "ExoMars Parachute System", 20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, 2009, 10.2514/6.2009-2975
- J. Stephen Lingard, John C. Underwood, Arrun Saunders, Matthew G. Darley, "ExoMars EDM Parachute System: Update on Design and Verification", AIAA Aerodynamic Decelerator Systems (ADS) Conference, 2013, 10.2514/6.2013-1278
- Juan Cruz, J. Lingard, "Aerodynamic Decelerators for Planetary Exploration: Past, Present, and Future", AIAA Guidance, Navigation, and Control Conference and Exhibit, 2006, 10.2514/6.2006-6792
- NASA CR 66587,"Final report 40 ft DGB parachute"
- NAS8-29144, Goodyear aerospace, engineering design manual of parachute decelerator characteristics for space shuttle solid rocket booster recovery
- NASA CR 66589, design report 65 foot diameter DGB parachute planetary entry parachute program
- E-0082-RT/1, Final technical report 55 ft Ringsail parachute planetary entry parachute program
- AGARD AG 319
- Irvin Recovery Systems Design Guide
- Parachute recovery system Knacke