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Flight Simulations of the Stratos III Parachute Recovery System

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Stratos III is a rocketry project led by students from Delft University of Technology. The goal of this project is to reclaim the European student altitude record for a sounding rocket, which is currently set at 32.3 km. The flight data of this rocket has to be retrieved to definitively prove the altitude at apogee. As not all data is sent down and the risk of losing contact with the rocket is sufficiently high, a parachute recovery system is required. To predict the performance of this system, the team developed two simulation tools: ParSim, for the conceptual design of the recovery system and TumSim for detailed design. The input parameters for both simulations are the aerodynamic coefficients, masses, moments of inertia, and initial conditions. These are gathered from literature and experimental research.

The first tool, ParSim, has been designed as a conceptual design tool to analyse the free-fall velocities and parachute inflation effects during the mission. The drag of the parachute is superimposed onto the body drag and the altitude-velocity profile is taken into account. The second tool, TumSim, has been developed to predict the dynamics of the payload during descent. This tool simulates the coupled transitional and rotational motion of the nose cone during the free fall. TumSim is therefore capable of determining the aerodynamic stability necessary for understanding the behaviour of the body during descent. The article will give insight in the assumptions and equations used in both tools.
These tools have been verified using several tools, like DRAMA, and several missions, such as SuperMax and ASPIRE. Furthermore, the data has been validated against the DARE Stratos II+ mission. The verification and validation results will be further discussed in the article.

These tools have been used to predict the Stratos III nose cone flight profile and the team is confident that these results are representative of the actual flight. The article will give the flight simulations of the Stratos III flight and compare these simulations to the actual flight data from July 2018 . After the Stratos III flight, the simulations can be further modified and used for future DARE missions. The nature of these tools allow them to serve as a baseline model for future entry, descent and landing systems.

Nomenclature

Variable	Description	Unit
α	Angle of attack	Rad
α_t	Total angle of attack	Rad
φ	Aerodynamic roll angle	Rad
CG	Centre of Gravity	m
A	Reference area	m^2
C_D	Drag coefficient	−
C_L	Lift coefficient	−
C_l	Roll moment coefficient	−
C_{lp}	Derivative of roll damping moment coefficient	−
$C_{m\alpha}$	Derivative of pitching moment coefficient	−
C_{mq}	Derivative of pitch damping moment coefficient	−
C_X	Axial force coefficient	−
C_{X_0}	Axial force coefficient at zero angle of attack	−
$C_{X_{\alpha_t 2}}$	Derivative of axial force coefficient	−
$C_{Y_{p\alpha}}$	Derivative of Magnus force coefficient	−
$C_{Y_{p\alpha_t}}$, $C_{Y_{p\alpha_t 3}}$	First and cubic order Magnus force coefficient	−
$C_{Z\alpha}$	Derivative of Normal force coefficient	−
$C_{Z\alpha_t}$, $C_{Z\alpha_t 3}$	First and cubic order Normal force coefficient	−
DOF	Degrees of Freedom	−
D	Drag	N
d	Body diameter	m
F	Force	N
G	Gravitational constant	$m^3kg^{-1}s^{-2}$
g	Gravitational acceleration	m/s^2
H	Altitude	m
l_{aero}, m_{aero}, n_{aero}	Roll, Pitch and Yaw moments	N
L	Lift	N
l_{par}	Parachute Line length	m
$\boldsymbol{I}$	Inertia matrix	kgm^{-2}
M	Mach number	−
m	Mass	kg
q	Dynamic pressure	Pa
R	Distance of body from centre of Earth	m
r_n	Nose radius	m
t	Time	s
V	Total velocity	m/s
u, v, w	Components of velocity in body frame	m/s
W	Weight	N
x, y, z	Distance	m
X, Y, Z	Force components in Axial, transverse and normal direction	N
X_a, Y_a, Z_a	Aerodynamic force components in Axial, transverse and normal direction	N
X_B, Y_B, Z_B	Components of body reference frame	N
X_V, Y_V, Z_V	Components of vertical reference frame	N
γ	Flight path angle	rad
χ	Heading	rad
τ	Longitude	rad
δ	Latitude	rad
ω_{cb}	Angular velocity of Earth	rad/s

I. Introduction

Stratos III is a student built sounding rocket designed to break the current European Altitude Record for Amateur rockets. In October 2015, Stratos II+ set the record at 21.5 km.[1] However, it was broken again in November 2016 by the German HyEnD team and set to an altitude of 32.3km.[2] Stratos III flew in July 2018 from INTA's El Arenosillo launch site in Spain. Unfortunately, the rocket broke up after approximately 20 s of flight and no flight data was obtained.

During the design phases, it was important to ensure the recovery system remained within the set requirements. To predict the performance of the recovery system, tools were required. During conceptual design commercial tools were not available to the team. The decision was therefore made to develop them in-house. This article gives an overview of the logic behind the tools that were developed including the verification and validation. Finally, it gives the predictions of the Stratos III flight.

Two tools were developed for the Stratos III project. These were named ParSim and TumSim. ParSim is a 3DOF conceptual design tool capable of quickly running many cases with different inputs to determine the most suitable design for the mission. Later in the project, ParSim can be used to perform a sensitivity analysis. The second tool, TumSim, is a 6DOF tool designed to determine the free fall trajectory of an aerodynamically unstable body.

The recovery system that the tools have been designed for is a two-stage system using a drogue parachute to stabilise the body and a main parachute to decelerate it to landing velocity. The object to be recovered was the upper section of the rocket consisting of a recovery bay and conical section which are rigidly attached to each other and will henceforth be referred to as nose cone. A more detailed description of the system including the design choices can be found in the article "Systematic Design for a Parachute Recovery System for the Stratos III Student Build Sounding Rocket".[3]

II. Simulation tool 1 - ParSim

ParSim is a tool developed for the Stratos III recovery system in order to calculate the load generated by the parachute to help generate a conceptual design. The tool was expanded to allow it to model more than just Stratos but also multiple other recovery systems. Furthermore ParSim also has the capability to do Grid Searches and Monte Carlo Analysis for a given system.

As ParSim is a tool meant for the conceptual design of Entry, Descent and Landing (EDL) systems a 10 % mass contingency is accepted. This is in line with the AIAA recommendations on uncertainty for critical design phase for a class 1 mission *.[4]

It was designed to be able to compute multiple flight cases quickly, as such assumptions had to be made in order to reduce computation time. These assumptions are listed below:

- 2D-Trajectory
- COESA as atmosphere model

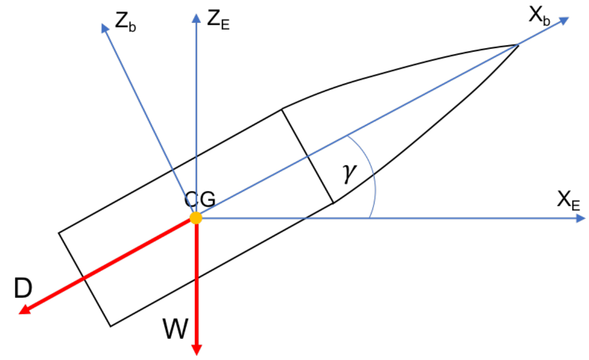

Fig. 1: Free body diagram of ParSim for $\alpha = 0$

- Homogeneous spherical earth
- Constant α
- Non rotating earth
- Parachute forces always act parallel to the free stream
- Linear Parachute inflation model (linear increase of parachute area over time)
- No wind
- Constant C_D with parachute inflation†
- C_D is only a function of α and Mach number

ParSim is a modular tool with different modules for the calculation of different results. These modules work sequentially and are dependent on the outputs of each other. A flowchart indicating the functioning of the ParSim Code can be seen in Appendix A.

The governing equation in ParSim can be found in equation 1. These equations are given in the local horizon frame as can be seen in Fig. 1. For ParSim it is assumed that the aerodynamic forces work in the direction of the body. The forces calculated here are translated to accelerations using Newtons second law. These accelerations are integrated to generate the altitude and velocity profiles.

$$\begin{bmatrix} F_{x_E} \\ F_{z_E} \end{bmatrix} = \begin{bmatrix} -(D_b + D_{par})\cos\gamma \\ -m_b \frac{m_{earth} G}{R^2} - (D_b + D_{par})\sin\gamma \end{bmatrix} \quad [1]$$

The differential equation solver used is the ODE45 function integrated in MATLAB which is based on the DormandPrince method.[5] For the parachute inflation phases ParSim uses the ODE15s function which uses a variable step, variable order integrator.[5] The relative tolerance is set at $5 \cdot 10^{-5}$ and the absolute tolerance $5 \cdot 10^{-8}$. Also the maximum step-size is

*Class 1 is defined as a new, one of a kind, or first generation spacecraft

†The C_D does not depend on the shape during inflation, only the area changes

altered to obtain a better solution. For the inflation moments the maximum step-size is set at 1 % of the given inflation time and for the free fall the maximum step-size is 1 s. These values are chosen because of the steadiness of the free-fall and the sudden behaviour of the inflation. Since the differential equation solver does not store the forces, only the accelerations, the forces have to be re-calculated afterwards. The shock load coefficient (C_k) is taken into account by multiplying the forces during inflation with a symmetric triangular function. The peak of the triangle equals the shock load coefficient in height and inflation time respectively.[6] ParSim requires the following inputs from the user:

- Initial flight conditions
  - Apogee altitude, H, [km]
  - Initial range, R, [km]
  - Velocity, V, [m/s]
  - Flight path angle, fl [deg]
- Body:
  - Body diameter, d, [m]
  - Mass, m [kg]
  - Nose tip radius, r_n [mm]
  - Drag coefficient, C_D over Mach
- Parachute
  - Area, A, [m^2]
  - Drag coefficient, C_{D0} (M=0) [-]
  - Deployment altitude, H_d, [m]
  - Time until deployment, t_1, [s]
  - Deployment time, t_d, [s]
  - Line length, l_{par}, [m]
  - Shock load factor, c_k, [-]
- Envelope
  - Maximum force allowed, F_{max}, [kN]
  - Dynamic pressure range of the parachute, Pa_{max}, [Pa]
  - Mach range of parachute, M_{max}, [-]

III. Simulation tool 2 - TumSim

TumSim is the tool developed to analyse the tumbling behaviour of aerodynamically unstable bodies. Quaternions are used to simplify the calculation of Euler angles. It was observed in Stratos II+ and several DLR flights that a tumbling body generates more drag than a stable body. Understanding this tumbling behaviour and its impact on the vehicle velocity is critical to guarantee the successful deployment of the parachute systems.[7] As, TumSim focuses on predicting the free fall behaviour it does not determine the parachute forces. TumSim uses the following assumptions:

- Rigid body without any elastic behaviour.
- US 1976 Atmosphere model is used
- Earth is assumed to be ellipsoidal, rotating and gravitational acceleration is considered as a function of latitude and altitude (WGS 84)
- Wind effects are not included
- Magnus effect forces are not taken into account
- Aerodynamic coefficients are a function of total angle of attack and Mach number.

In TumSim, the body reference frame is fixed to the vehicle. The X_B axis is along the plane of symmetry and is positive in forward direction. The Z_B axis is also along the plane of symmetry and is positive in downward direction. The Y_B axis completes the right-handed system. The vertical reference frame is assumed such that the Z_V axis is pointed towards the Earth, along the radial component of gravitational acceleration. The X_V is along the meridian plane. X_V axis is perpendicular to Z_V axis and is pointed towards north. The Y_V completes the right-handed system.

The initial conditions required by TumSim are:

1. Body parameters - Mass (m), diameter/dimensions, moment of inertia matrix I, center of gravity definition
2. Entry location - Range, longitude, latitude (R, τ, δ).
3. Entry velocity of the body (u, v, w) referenced in body frame.
4. Euler angle orientation (θ, ϕ, ψ) and rotation rate (p, q, r) referenced in body frame.

The following set of equations have been implemented in TumSim.[8] To determine the aerodynamic forces and moments acting on the body, the angular position of the body with respect to airflow (V) has to be determined. Conventionally, pitch angle of attack (α) and sideslip angle (β) are used for this purpose. For axially symmetric body subjected to high orientation changes, it is rather convenient to use total angle of attack (α_t) and ballistic roll angle (φ), since these angles are independent of body spin. α_t and φ can be computed as follows:

$$\alpha_t = \arctan\left(\frac{\sqrt{(w)^2 + (v)^2}}{u}\right) \qquad [2]$$

$$\varphi = \arctan\left(\frac{v}{w}\right) \qquad [3]$$

The aero-body transformation matrix containing α_t and φ is:

$$T_{AB} = \begin{bmatrix} \cos\alpha_t & \sin\alpha_t \sin\varphi & \sin\alpha_t \cos\varphi \\ 0 & \cos\varphi & -\sin\varphi \\ -\sin\alpha_t & \cos\alpha_t \sin\varphi & \cos\alpha_t \cos\varphi \end{bmatrix}$$

To determine the position of the body in geodetic coordinates (altitude, longitude, latitude) following kinematic position equations are implemented:

$$\dot{R} = V \sin\gamma \qquad [4]$$

$$\dot{\tau} = \frac{V \sin\chi \cos\gamma}{R\cos\delta} \qquad [5]$$

$$\dot{\delta} = \frac{V \cos\chi \cos\gamma}{R} \qquad [6]$$

Dynamic equation of translational motion consist of velocity of body (V), flight path angle (γ) and heading (χ).

$$\dot{V} = -\frac{D}{m} - g\sin\gamma + \omega_{cb}^2 R\cos\delta(\sin\gamma\cos\delta - \cos\gamma\sin\delta\cos\chi) \qquad [7]$$

$$\dot{\gamma} = \frac{1}{V}\Bigg(\frac{V^2}{R}\cos\gamma - g\cos\gamma + 2\omega_{cb}V\cos\delta\sin\chi + ((\omega_{cb}^2)Rcos(\delta))(\cos\delta)cos(\gamma) + sin(\gamma)sin(\delta)cos(\chi))) \qquad [8]$$

$$\dot{\chi} = \frac{L\sin\sigma}{m} + 2\omega_{cb}V(\sin\delta\cos\gamma - \cos\delta\sin\gamma\cos\chi) + \frac{V^2}{R}\cos^2\gamma\tan\delta\sin\chi + \omega_{cb}^2 R\cos\delta\sin\delta\sin\chi \qquad [9]$$

The total force acting on the body (X, Y, Z) are aerodynamic forces (X_a, Y_a, Z_a) and weight force. Aerodynamic moments are represented by $l_{aero}, m_{aero}, n_{aero}$. In order to compute the aerodynamic forces and moments, aerodynamic coefficients are required. The aerodynamic coefficients C_X, C_Y, C_Z are expanded as function of Mach number (M), sine of total angle of attack (ϵ) and roll angle (φ). Depending on the availability of the coefficients and derivatives, additional terms can be included. The following equations represent forces acting on an axisymmetric body:

$$X_a = -q_\infty A C_X \qquad [10]$$

$$Y_a = q_\infty A\Bigg[-C_{Z\alpha}\frac{v}{V} + C_{Y_{p\alpha}}\frac{pd}{2V}\frac{w}{V} + \cdots\Bigg] \qquad [11]$$

$$Z_a = q_\infty A\Bigg[-C_{Z\alpha}\frac{w}{V} - C_{Y_{p\alpha}}\frac{pd}{2V}\frac{v}{V} + \cdots\Bigg] \qquad [12]$$

where $C_X, C_{Y_{p\alpha}}, C_{Z\alpha}$ are

$$C_X = C_{X_0} + C_{X_{\alpha_t 2}}\epsilon^2 + \cdots \qquad [13]$$

$$C_{Y_{p\alpha}} = C_{Y_{p\alpha_t}} + C_{Y_{p\alpha_t 3}}\epsilon^2 \qquad [14]$$

$$C_{Z\alpha} = C_{Z\alpha_t} + C_{Z\alpha_t 3}\epsilon^2 + \cdots \qquad [15]$$

Following equations represent the aerodynamic moments:

$$l_{aero} = q_\infty Ad\Bigg[C_l + C_{lp}\frac{pd}{2V}\Bigg] \qquad [16]$$

$$m_{aero} = q_\infty Ad\Bigg[C_{m\alpha}\frac{w}{V} + C_{mq}\frac{qd}{2V} + \cdots\Bigg] \qquad [17]$$

$$n_{aero} = q_\infty Ad\Bigg[-C_{m\alpha}\frac{v}{V} + C_{mq}\frac{rd}{2V} + \cdots\Bigg] \qquad [18]$$

The body moments are transformed to the centre of gravity of the tumbling body. These are then used to solve the dynamic equations of rotational motion.

$$\boldsymbol{\dot{\omega} = I^{-1}(M_{cg} - \omega \times I\omega)} \qquad [19]$$

where

- $\boldsymbol{\dot{\omega}} = [p, q, r]^T$ is the rotation vector of body frame w.r.t inertial frame.
- I $= \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}$ is inertia matrix of the body (assuming body has a plane of mass symmetry along XY body plane i.e. $I_{xy} = I_{yz} = 0$
- $\boldsymbol{M_{cg}} = [M_x, M_y, M_z]^T$ is the total moments acting about the centre of gravity on the body

In order to determine the rotation history of the body, the Euler angles - pitch (θ), yaw (ψ) and roll(ϕ) are integrated in the form of quaternions. The integrator used in TumSim is the ODE15s. Collecting the dynamic and kinematic set of equations and integrating, the TumSim provides the velocity, rotation, rotation rate in body axis and location of body in geodetic coordinate.

IV. Validation

The validation of the tools has been done using comparable commercial tools and external and internal flight data. The following data sets have been used:

Table 1: Comparing a free falling sphere in DRAMA and ParSim

Parameter	**DRAMA**	**ParSim**	[%]
Distance	2202.19 km	2119 km	-3.78
Impact velocity	159.2 m/s	154.8 m/s	-2.76
Flight time	462.1 s	450.93 s	-2.42

- HTG - DRAMA/SESAM
- DARE - Stratos II+ mission
- Vorticity - SuperMax mission
- NASA - ASPIRE mission
- NASA - 6DOF validation set

IV.i DRAMA

DRAMA, or Debris Risk Assessment and Mitigation Analysis, is a tool to assist in making risk assessments for orbital and end of life operations of a satellite. One of the applications in the DRAMA tool is SESAM, which is responsible for assessing the reentry survival. This tool determines the mechanical and thermal stresses on an entering object to determine whether it, or parts of it, can survive atmospheric entry. By creating an indestructible sphere with a diameter of one meter, one can compare the data between DRAMA and ParSim. Furthermore, the sphere has an assumed drag coefficient of 0.5.[9] The following initial conditions were assumed:

- Initial altitude = 71.86 km
- Initial horizontal velocity = 7.39 km/s
- Initial vertical velocity = 0 km/s

The whole flight can be compared in Fig. 2 and 3. From the figures, it can be seen that at the beginning of the flight ParSim gives a higher velocity than DRAMA. After about 250 s the velocities are equal and stay close to each other. The landing velocities of ParSim and DRAMA are 154.8 and 159.2 m/s respectively. Due to the error in velocity, an error in altitude occurs. At about 200 s this error is largest. Here it is about 1 km difference which is about 2 %.

As can be seen, in Table 1 ParSim approaches the DRAMA data within 10 %. This is sufficient for the conceptual phase of the Stratos project. It can also be seen that TumSim predicts the DRAMA data set to a much higher accuracy. The differences between DRAMA and ParSim are most likely caused by the following:

- ParSim assumes a spherical gravitational field, DRAMA assumes two harmonics gravity model[10]
- ParSim assumes a constant C_D-Mach for this case where DRAMA varied the C_D according to the Mach number
- Parsim and DRAMA assume different atmospheres

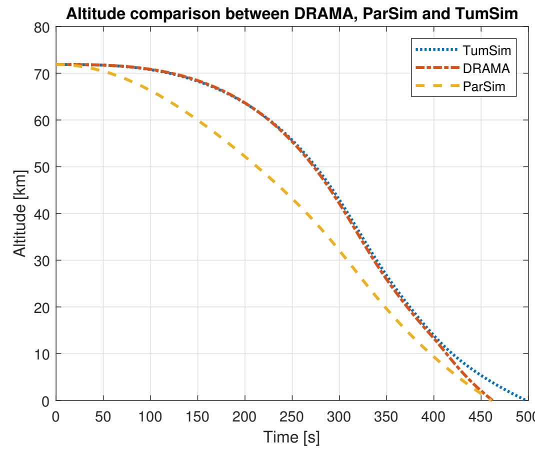

Fig. 2: Altitude Time profile of the sphere

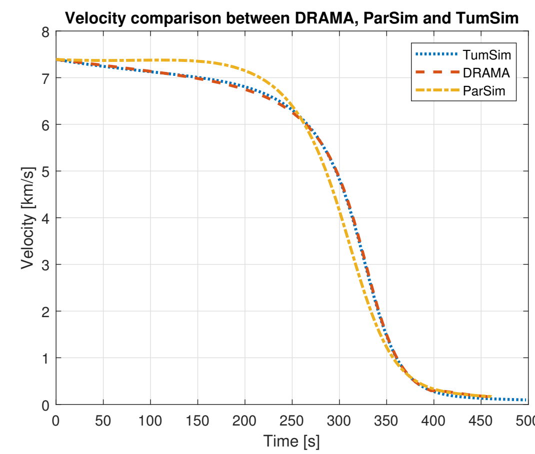

Fig. 3: Velocity - Time profile of the sphere

IV.ii Stratos II+

The Stratos II+ rocket was launched in October 2015 from the El Arenosillo range in Spain. The rocket flew to an apogee of 21.5 km where the drogue parachute was to be deployed. Unfortunately, the drogue parachute snapped off and the nose cone went into a free fall. In this free fall, the nose cone entered a tumbling motion of about 2 Hz causing it to bleed off energy and thus velocity. The tumbling motion can be seen in the onboard video data.[11] At first

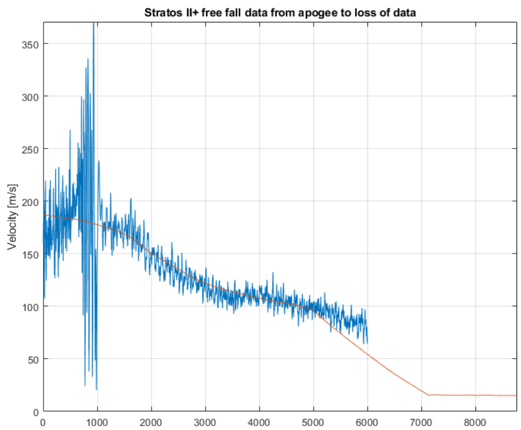

Fig. 4: Velocity plot of Stratos II+ from apogee until loss of data

the capsule accelerates in a ballistic manner, however when the flat spin occurs, after some time the deceleration decreases and the capsule reaches an equilibrium velocity. At about 2.5 km the 6 m^2 cruciform main parachute was deployed allowing the nose cone to land safely in the Atlantic ocean.

For simulating the flight in ParSim and TumSim the aerodynamic coefficients have been used that were determined for the flight. These coefficients have also been used in the actual Stratos II+ flight simulations and are the most accurate coefficients available. However, as several unplanned events happened during the free fall the aerodynamic data might be inaccurate. Therefore, it is assumed that errors will show up when comparing the flight data with the simulation data. As ParSim cannot simulate the flat spin, it is assumed that the nose cone has a constant angle of attack of 90 deg which changes to 0 deg once the parachute is deployed. From the tracking radar the initial conditions, conditions at apogee, can be derived. These are as follows:

- $V_{apogee} = 160$ m/s
- $H_{apogee} = 21.5$ km

As can be seen in Table 2, the impact velocity is negligibly different as it is only dependent on the input conditions of the main parachute such as drag coefficient and surface area. The difference in flight conditions can be attributed to differences in body drag coefficients. As the rocket entered a flat spit, the apparent drag coefficient was higher than in the stable 90 deg case.

TumSim has only been run until 20 s from apogee. Up to this point, the data matches the flight data nicely. However, at about 20 s, there is an anomaly in the data set which causes a deviation between the simulated data and the flight data. It is unclear where this anomaly comes from.

Table 2: Comparing the Stratos II+ nose cone to ParSim

Parameter	**Stratos II+**	**ParSim**	[%]
Impact velocity	6.2 m/s	6.2 m/s	0
Flight time	586 s	656 s	11.95

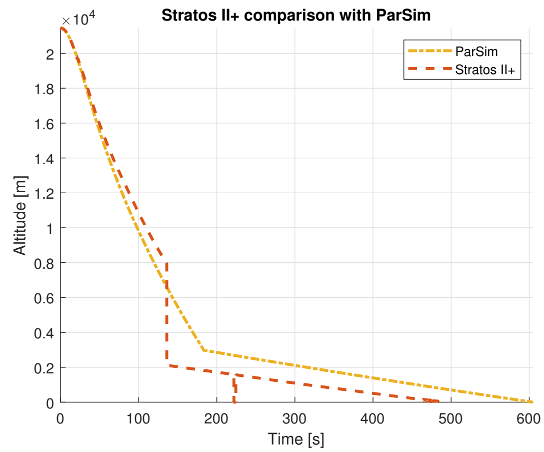

Fig. 5: Stratos II+ flight data compared to ParSim results

IV.iii SuperMax

SuperMax was a mission from Vorticity Inc designed to test parachutes in representative flight conditions. The mission piggy-backed on Maxus-9 reaching an apogee of about 679 km. The parachute was deployed at 19.1 km at a Mach number of 1.70. The following assumptions have been made:[12]

- ff = 0 deg
- $C_{D_{body}} = 1.3$
- $C_{D_{parachute}} = 0.5$
- $\gamma = 85.37$ deg (upward from horizon)
- $H_0 = 163$ km
- $V_0 = 3$ km/s

Table 3 shows that ParSim is well within the 10 % requirement when predicting the flight of SuperMax. The discrepancies can partially be explained by the drag data of the body. The drag coefficients have been assumed and have not been given in the

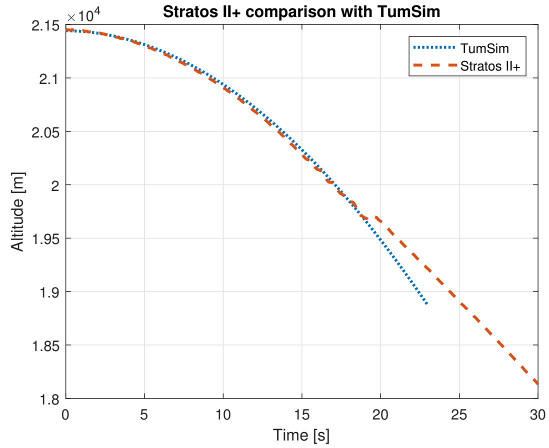

Fig. 6: Stratos II+ flight data compared to TumSim results

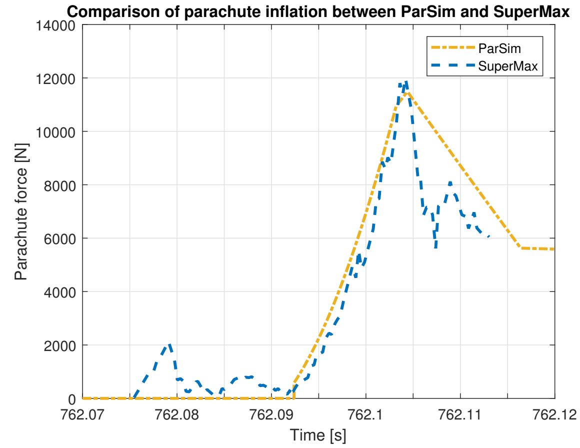

Fig. 7: Comparison of parachute inflation between SuperMax and ParSim

Table 3: Comparing SuperMax and ParSim

Parameter	SuperMax[12]	ParSim	[%]
Apogee	679 km	680.3 km	0.19
$M_{deployment}$	1.7	1.66	-2.35
$V_{Deployment}$	495 m/s	488.80 m/s	-1.25
Inflation load	12 kN	11.51 kN	-4.08

SuperMax article.

Not only has the trajectory been simulated, also the parachute inflation has been predicted using ParSim. In Fig. 7 the measured data can be seen as a dotted line and the simulated data as the solid line. Several discrepancies can be identified. The line peak due to line stretch is ignored by ParSim and therefore does not show in the plot. Furthermore, the oscillating behaviour after peak loading is not taken into account in ParSim. It is assumed that this oscillating behaviour is the breathing of the parachute.

IV.iv ASPIRE

The Advanced Supersonic Parachute Inflation Research Experiment, ASPIRE, was a mission by NASA to validate the MARS 2020 parachute performance. The mission flew on a Black Brand rocket to an altitude of 51 km. The objective was to deploy the parachute at Mach 1.8 high in the atmosphere to replicate the conditions of a Mars mission.[13,14]

- $A_{par} = 363.04$ m^2
- $t_{deploy} = 42.3$ s
- $C_D = 0.75$
- $t_{inflation} = 0.5$ s
- $C_k = 1.3$
- $H_{Apogee} = 51000$ m
- $V_{apogee} = 395.76$ m/s
- $m_b = 1200$ kg
- $d_b = 720$ mm

Table 4: Comparing the ASPIRE to ParSim

Parameter	ASPIRE	ParSim	[%]
$M_{deployment}$	1.77	1.763	-0.39
$F_{inflation}$	144.07 kN	146.59 kN	1.74
H_{deploy}	42430 m	42332 m	-0.23

The comparison between ParSim and the ASPIRE mission can be found in table 4. As can be seen ParSim gives an estimate that is very close to the actual ASPIRE flight.

IV.v NASA validation case

The final validation of TumSim is done using the NASA validation case for 6DOF tools.[15] The chosen case is "Check-case 2 - dragless tumbling brick". The chosen simulation routine for comparison is JEOD/Trick (JSC) which stands for Johnson Space Center (JSC) Engineering Orbital Dynamics (JEOD). Fig. 8, 9 and 10 indicate the error of TumSim compared to the results obtained by NASA. As it can be seen, the errors are very small for the test case. It can be seen that while the errors in latitude, longitude and altitude do increase over time they dif-

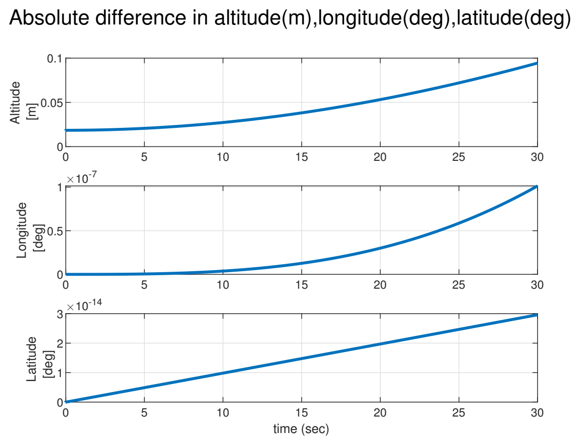

Fig. 8: Comparison of Latitude, Longitude and Altitude

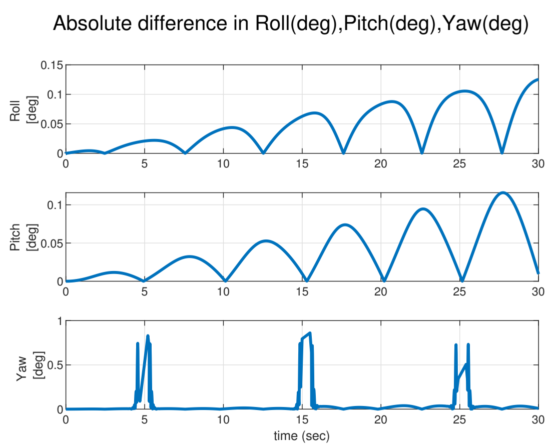

Fig. 9: Comparison of Roll, Pitch and Yaw

fer by less than one meter.

The errors in angles are quite small. When determining the total error in latitude, longitude and altitude in the end one finds a total error of 0.095 m. It can be seen that the error increases over time, this is most likely due to an integration error. The integrator in JEOD is Runge-Kutta fourth-order integrator with a 1 s time step. In TumSim, a variable step, variable order integrator is used.

The errors in pitch, yaw and roll can be attributed to interpolation errors. As the data sets were sampled at different rates, interpolation was required to compare them. In the yaw, the interpolation failed to capture the sharp changes and the failure points have been removed. This has been plotted in the yaw subplot of Fig 9. The attitude rates match the results

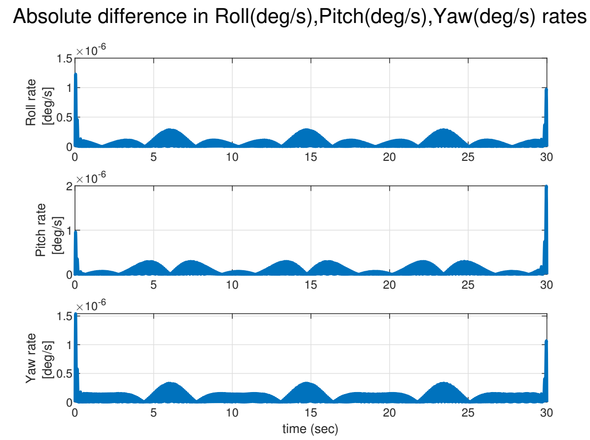

Fig. 10: Comparison of Roll, Pitch and Yaw Rates

from the validation set. From the errors in position, attitude and attitude rates, it can be concluded that they are sufficiently low and therefore TumSim can be considered validated for this case.

V. Flight Predictions

The ParSim and TumSim tools have been used to predict the final Stratos III flight. The inputs for both tools can be found in Table 5.

V.i ParSim - 0 degrees angle of attack

For ParSim the following results are obtained which can be seen in Fig. 11, 12 and 13. In these results the angle of attack was fixed at $\alpha = 0$ deg. In Fig. 11 it can be seen that the nose cone fall ballistically until about 150 s. After which the following 100 s are spent under the parachute descending the final 4 km.

Fig. 12 shows that that after apogee the velocity increases steadily to a maximum value of approximately 1190 m/s at approximately 140 s. After this point the body begins to decelerate rapidly as it reaches the thicker parts of the atmosphere. At 156 s the drogue it deployed ultimately slowing the body to a velocity of 58 m/s. At approximately 193 s after apogee the main parachute is deployed slowing the body to a final landing velocity of approximately 14 m/s.

As was decided for the deployment logic of the nose cone the drogue would deploy after the drag peak of the body in order to reduce the shock loading of the drogue on the system. Although this could not totally be achieved the deployment is at about 25 % of the maximum body drag. The maximum force from the

Table 5: Inputs for both simulations

Input		Value
Apogee	[km]	100
Initial range	[km]	0
V horizontal	[m/s]	340
Flight path angle	[deg]	0
Body diameter	[mm]	278
Mass	[kg]	16
Nose tip radius	[mm]	15
Drogue area	[m^2]	0.2
Drogue C_{D_0} (M = 0)	[-]	0.2943
Drogue deployment altitude	[m]	4000
Drogue deployment time	[s]	0.2
Drogue line length	[m]	3
Drogue shock load factor	[-]	2
Drogue force limit	[kN]	10
Drogue dynamic pressure range	[Pa]	65 - 314000
Drogue mach range	[-]	0.015 - 3
Main area	[m^2]	2
Main C_{D_0} (M = 0)	[-]	0.65
Main deployment altitude	[m]	1000
Main deployment time	[s]	0.2
Main line length	[m]	3.5
Main shock load factor	[-]	2
Main force limit	[kN]	4
Main dynamic pressure range	[Pa]	15 - 34000
Main mach range	[-]	0.014 - 0.4

parachute itself is 2.5 kN on top of the 1 kN which is still generated by the body. The maximum force from the main parachute is 3.3 kN. Both the forces are well below the set requirement of 10 kN for the drogue and 4 kN for the main respectively. A figure of the forces can be seen in Fig. 13.

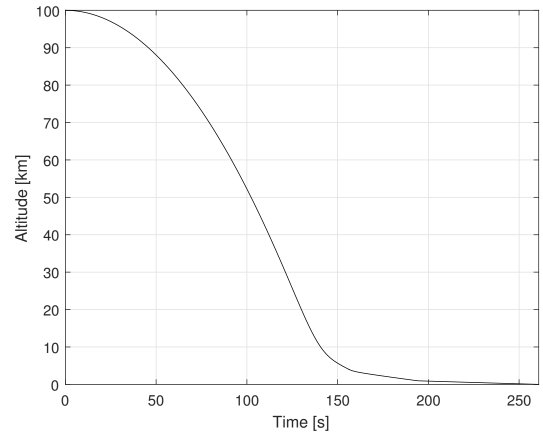

Fig. 11: ParSim prediction for the altitude with an α of 0 deg

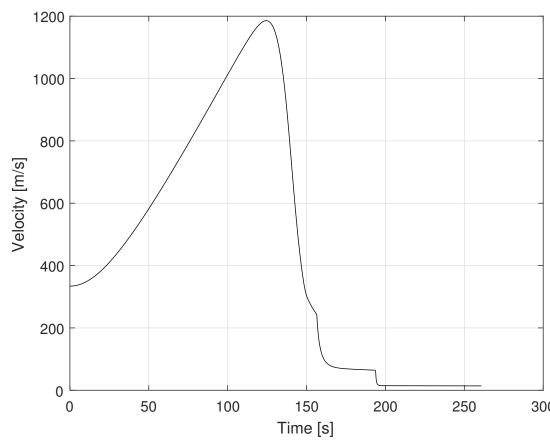

Fig. 12: ParSim prediction for the velocity with an α of 0 deg

V.ii ParSim - 90 degrees angle of attack

Since it was assumed that the nose cone could also go in a flat spin, this was also run in ParSim. It was assumed that the α before deployment was fixed at 90 deg. The results of this can be seen in Fig. 14, 15 and 16.

What can be observed immediately in Fig. 14, is that the time from apogee to splashdown doubled to 530 s. This is caused by the increase in the body drag resulting in the line levelling off at 150 s. Besides that the general behaviour of the graph is the same.

In the 90 deg case the velocity increases to 958 m/s at approximately 100 s. The velocity then decreases to 50 m/s at 415 s at which point the drogue is deployed. The velocity then increases to 59 m/s. This is because once the drogue is deployed the body goes from a 90 deg angle of attack to a nose down configuration which actually reduces the overall drag coefficient. At 460 s the main parachute is deployed decelerating the body to the landing velocity of approximately 14 m/s.

Fig. 16 differs a lot from its 0 deg ff counterparts. All the forces are reduced drastically until the drogue is fully deployed. The main parachute force is the same as for the 0 deg case. This is because it is assumed that after the drogue is deployed the nose cone is again in the 0 deg orientation. This also shows that the drogue reaches its steady-state load during

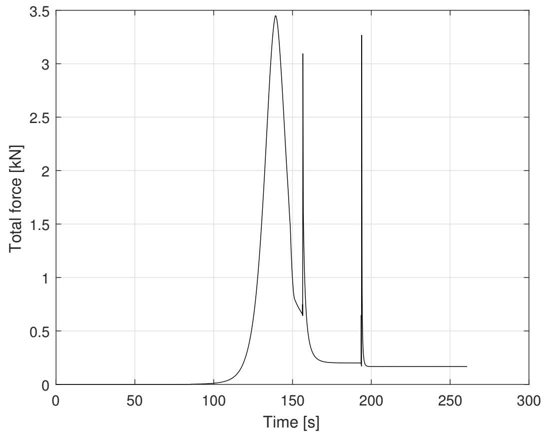

Fig. 13: ParSim prediction for the Forces with an α of 0 deg

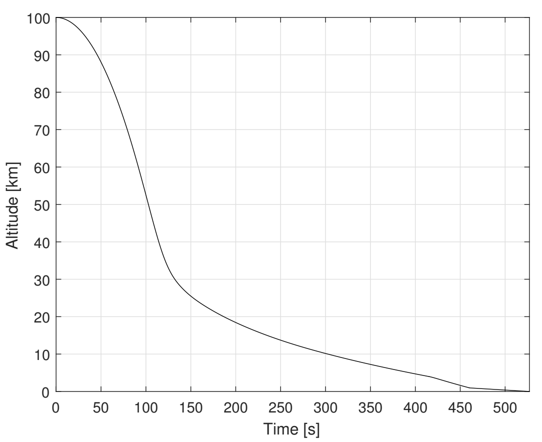

Fig. 14: ParSim prediction for the altitude with an α of 90 deg

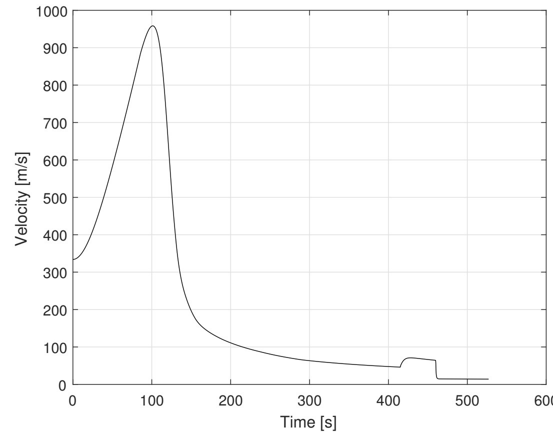

Fig. 15: ParSim prediction for the velocity with an α of 90 deg

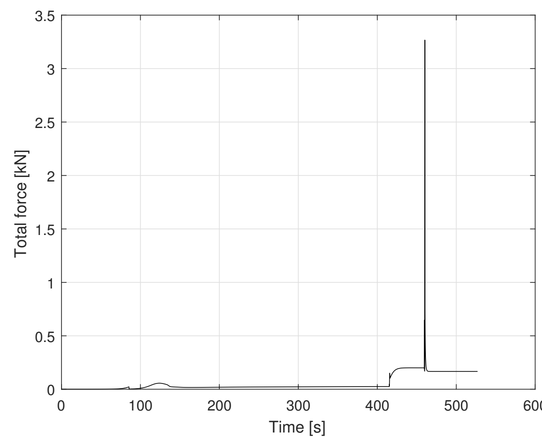

Fig. 16: ParSim prediction for the forces with an α of 90 deg

the descent.

V.iii TumSim - 0 degrees angle of attack

The predicted results of TumSim for the Stratos III nosecone body re-entering at zero angle of attack can be seen in Fig. 17, 18, 19 and 20. The initial conditions for body attitude have been assumed to be 0 degrees in all the body axes. As the attitude is propagated, it is seen that the pitch stabilises to -90 deg (nosetip down facing Earth) in an oscillatory manner which is expected since the center of gravity of nosecone is located far from the nosetip. Similarly an oscillatory behaviour is seen in the yaw motion, which damped out after passing the high dynamic pressure region (between 100 and 130 s) but they are insignificant unless some external force/wind disturbs this motion. For the parachute deployment the pitch orientation of nosecone is of great interest. This is because the nosecone has a parachute systems in the rear section and to ensure nominal deployment the parachute system must face away from the airflow. Thus, it can be inferred using TumSim whether a free fall of a nosecone would be favourable for the parachute system. The nosecone structure is also subjected to oscillations across all the axis. The maximum oscillation observed is in the range of 0.04 Hz occurring between 100 and 130s. This gives us a sense of loads that the nosecone might be subjected, which is essential for structural integrity testing.

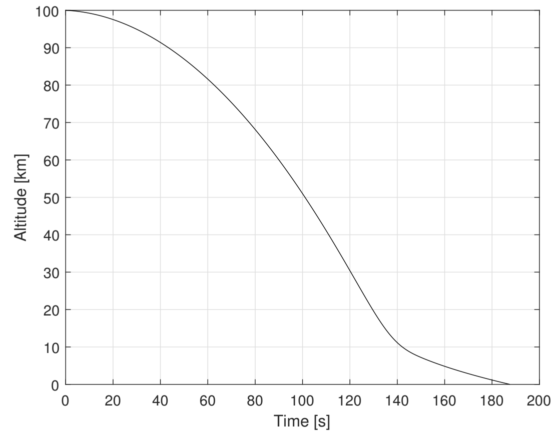

Fig. 17: TumSim prediction for the altitude with an α of 0 deg

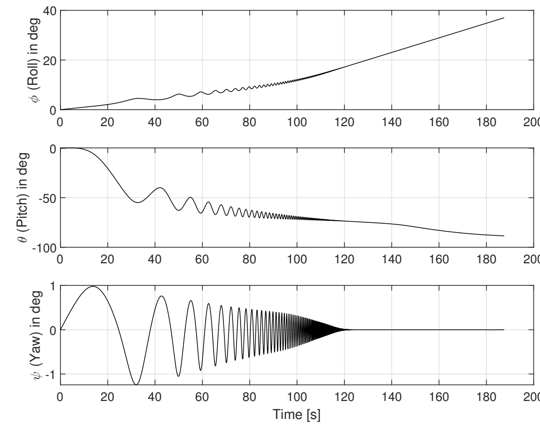

Fig. 19: TumSim prediction for the body rotation with an α of 0 deg

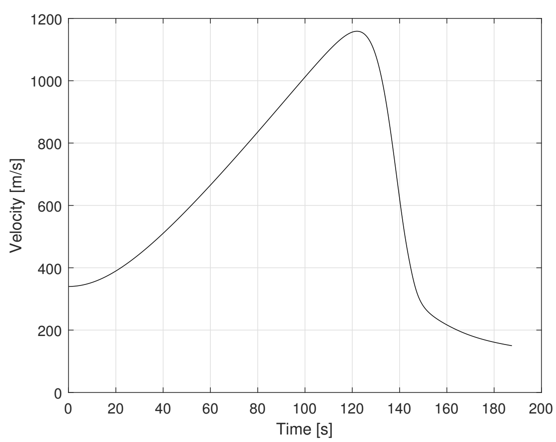

Fig. 18: TumSim prediction for the velocity with an α of 0 deg

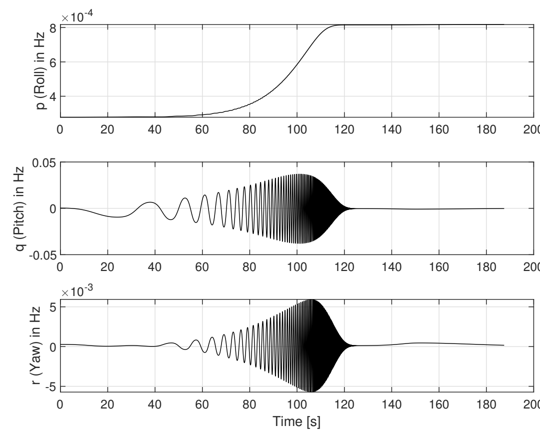

Fig. 20: TumSim prediction for the rotation rate with an α of 0 deg

V.iv Comparison

When overlaying the ParSim and TumSim data one can see that the results match quite closely. The most important difference comes from the fact that ParSim includes the parachute performance which TumSim ignores. This is most apparent in Fig. 21 where the velocity decrease can be seen after 156 s

Furthermore, the ParSim tool predicts a slightly higher maximum velocity. This is caused by the variable angle of attack of TumSim, which therefore has a higher drag coefficient. This can be confirmed by Fig. 21 where the velocity of ParSim and TumSim are equal until the nose cone enters the atmosphere.

VI. Conclusion

The tools that were not available to the team have successfully been created and validated. It proved to be needed to split the ParSim and TumSim tools as the requirements were different.

For ParSim it was proven that all results were below 10 %. Or that it could be explained why the error was larger than 10 %. For ParSim it can be said that it consistently overestimates the outputs. It is recommended for users to keep the the 10 % margin into account when using ParSim. TumSim was proven to be an accurate 6DOF simulation tool that enables very accurate predictions for aerodynamically unstable objects. For any engineer using these tools to develop an EDL system it is advised to also run a

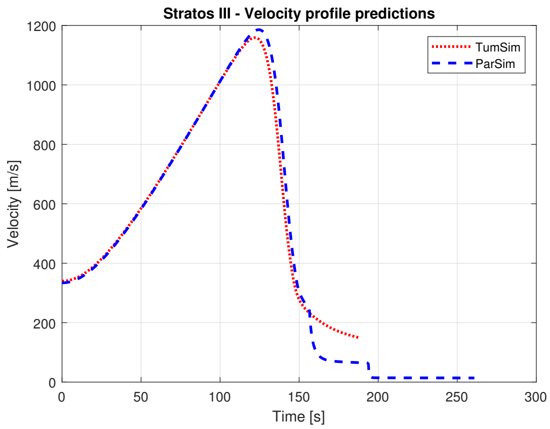

Fig. 21: Stratos III velocity profile comparisons between ParSim and TumSim

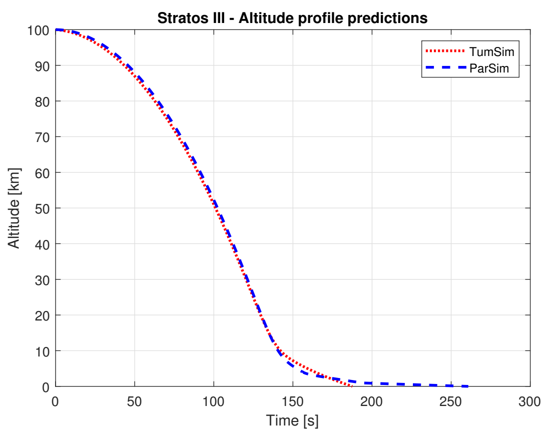

Fig. 22: Stratos III altitude profile comparisons between ParSim and TumSim

TumSim analysis when the data sets are known.

VII. Recommendations

Both ParSim and TumSim in their current state are not finished and several upgrades are recommended for future development. These are as follows:

- Include wind for a better analysis of drift and thus a better prediction of the landing location
- Include line stretch in the force model of ParSim
- Combine TumSim and ParSim in a single tool to make it more user friendly

Acknowledgements

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Appendix A: ParSim Flowchart

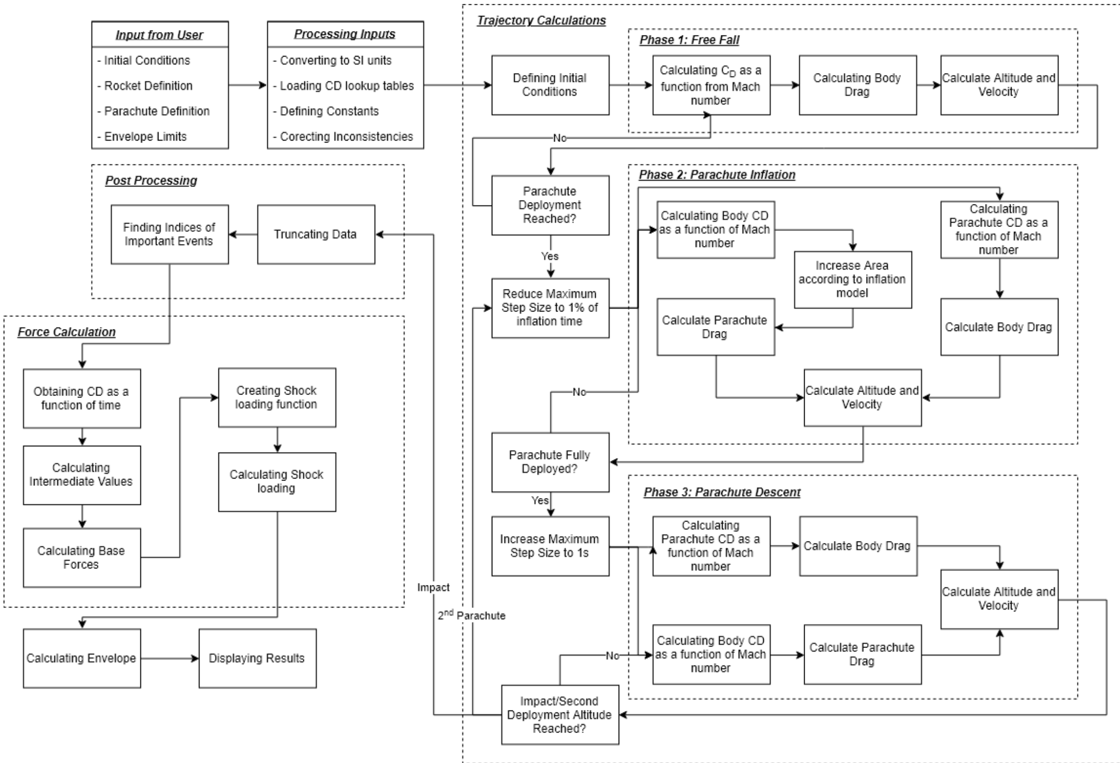

Fig. 23: ParSim Flowchart

Appendix B: TumSim Flowchart

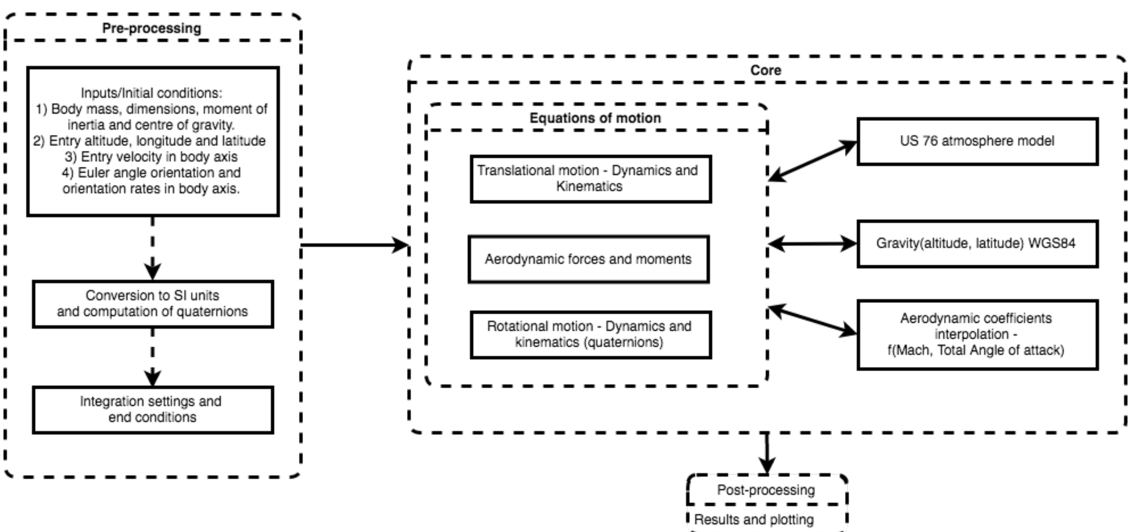

Fig. 24: TumSim Flowchart