



ASTOS Model Setup – Sub-Orbital Rocket Trajectory Modelling

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High Level Overview

Planet model (Earth)

Atmospheric model (US 76)

Wind model (custom or generic)

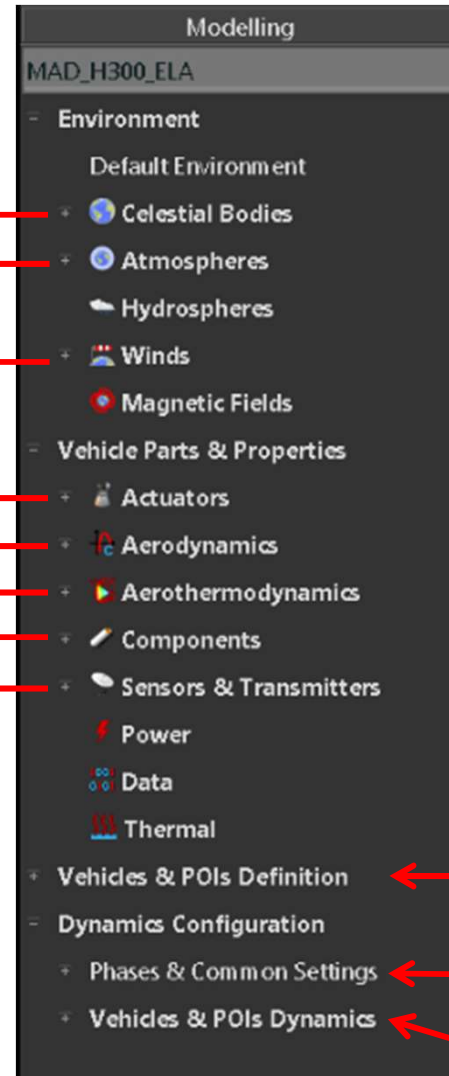
Thrust curve

Aerodynamic tables

Aerothermal data (not required for now)

Masses and dimensional data

Sensors (IMU etc.) (not required for now)



Modular

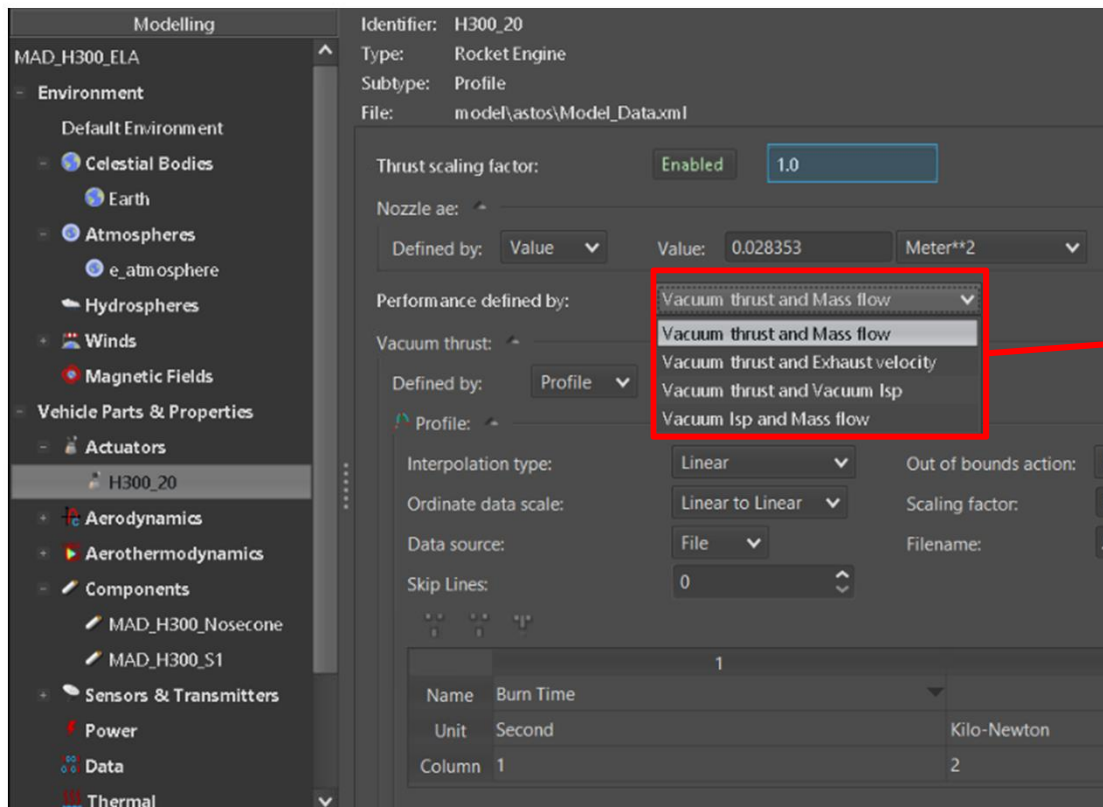
Component Integration

Trajectory Phase Settings

Model Integration



Thrust Model



Performance definition variations

- Typically vacuum thrust and mass flow is selected
- For simplification, mass flow is usually set as constant value



Thrust Model

General Thrust Equation

$$F = \dot{m} V_e + (P_e - P_0)A_e$$

For vacuum thrust,

$$P_0 = 0 ,$$
$$F_{vac} = \dot{m} V_e + P_e A_e$$

For sea level thrust,

$$P_0 = P_{SL} = 100 \text{ kPa}$$
$$F_{SL} = \dot{m} V_e + (P_e - P_{SL})A_e$$

Conversion of SL thrust to vacuum thrust:

$$F_{vac} = F_{SL} + P_{SL} A_e$$

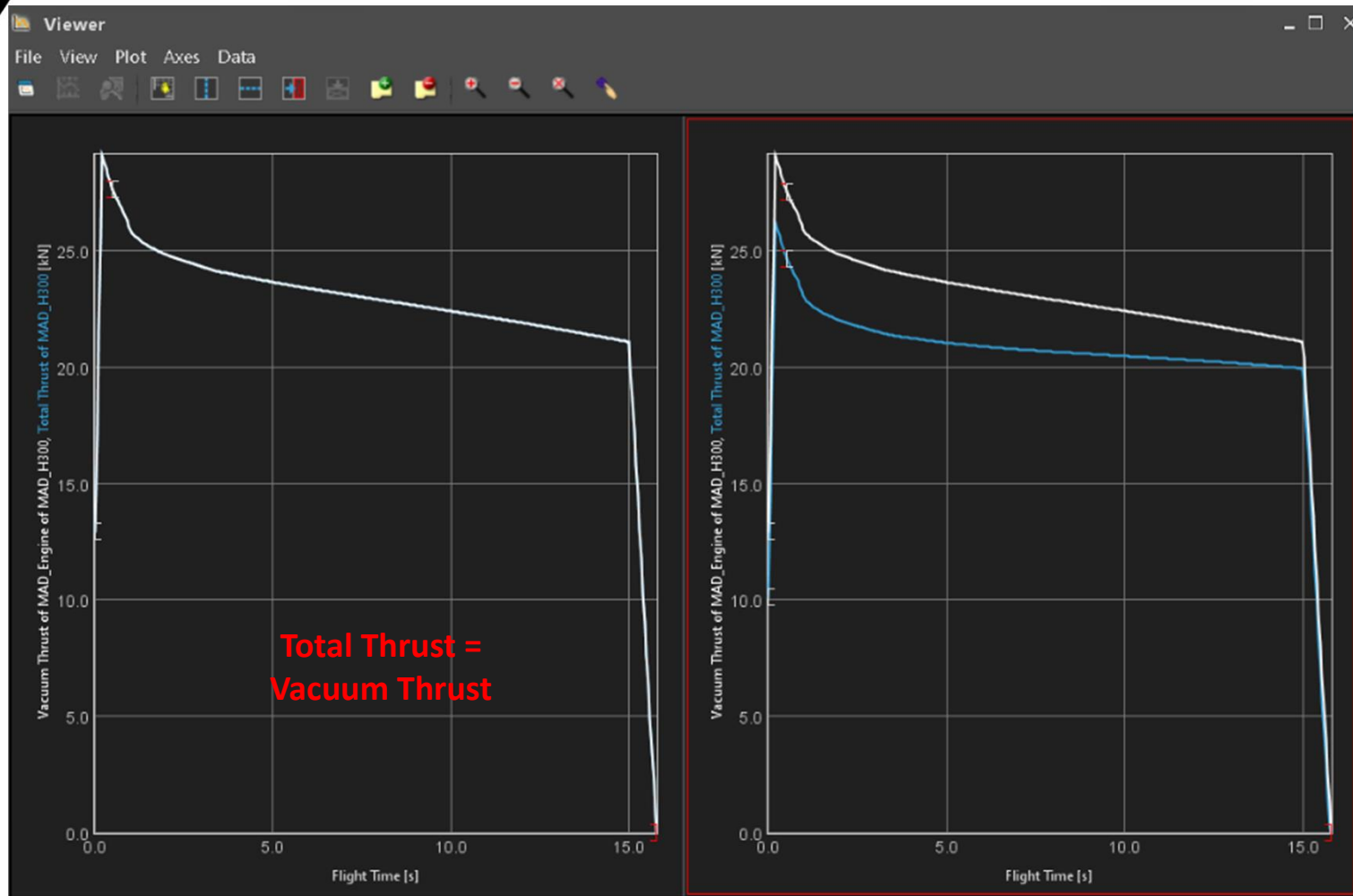
Vacuum thrust
curve data as
Astos input

Propulsion thrust
curve data

Nozzle exhaust
area as input



Thrust Model

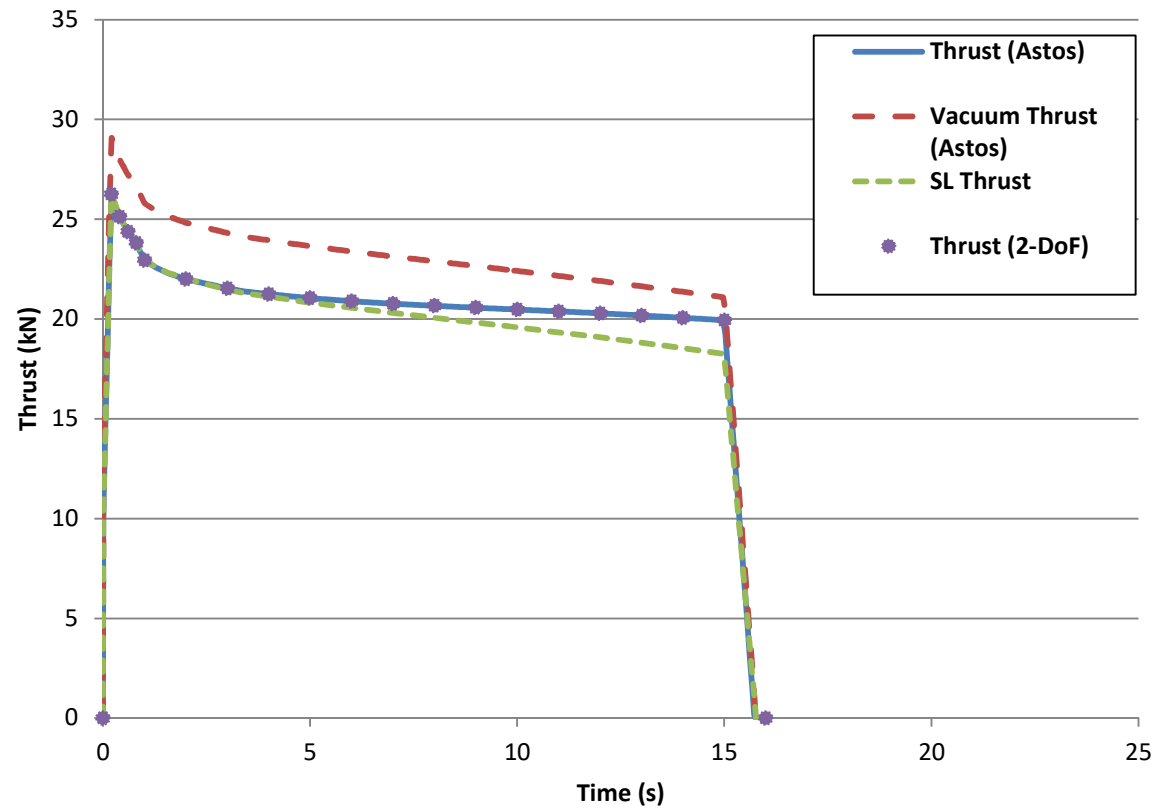


Nozzle exhaust
area = 0

Nozzle exhaust
area $\neq 0$



Thrust Model





Aerodynamics Model

Force and moment equations in body-fixed coordinates

$$\vec{F}_{\text{aero},B} = qA_{\text{ref}} \begin{bmatrix} -C_A(x) \\ C_Y(x) + \left(\frac{dC_Y}{d\beta}(x) \right) \beta \\ -C_N(x) - \left(\frac{dC_N}{d\alpha}(x) \right) \alpha \end{bmatrix}_B$$

$$\vec{M}_{\text{aero}} = \begin{bmatrix} l \\ m \\ n \end{bmatrix}_B = qA_{\text{ref}}L_{\text{ref}} \begin{bmatrix} C_{LL_t}(x) \\ C_{M_t}(x) \\ C_{LN_t}(x) \end{bmatrix}_B \begin{bmatrix} +F_Z\Delta y + F_Y\Delta z \\ +F_Z\Delta x - F_X\Delta z \\ -F_Y\Delta x - F_X\Delta y \end{bmatrix}$$



Aerodynamics Model

Moment Coefficients Computation (Astos Model Reference)

$$C_{LL_t}(x) = C_{LL}(x) + \beta \left(\frac{dC_{LL}}{d\beta}(x) \right) + P \left(\frac{dC_{LL}}{dP}(x) \right) + R \left(\frac{dC_{LL}}{dR}(x) \right) + \Delta_{fin} \left(\frac{dC_{LL}}{d\Delta_{fin}}(x) \right)$$

$$C_{M_t}(x) = C_M(x) + \beta \left(\frac{dC_M}{d\beta}(x) \right) + Q \left(\frac{dC_M}{dQ}(x) \right) + \alpha \left(\frac{dC_M}{d\alpha}(x) \right) + \alpha_t \left(\frac{dC_M}{d\alpha_t}(x) \right) + \dot{\alpha}_t \left(\frac{dC_M}{d\dot{\alpha}_t}(x) \right)$$

$$C_{LN_t}(x) = C_{LN}(x) + \beta \left(\frac{dC_{LN}}{d\beta}(x) \right) + P \left(\frac{dC_{LN}}{dP}(x) \right) + R \left(\frac{dC_{LN}}{dR}(x) \right)$$

Currently Used

~~$$C_{LL_t}(x) = C_{LL}(x) + \beta \left(\frac{dC_{LL}}{d\beta}(x) \right) + P \left(\frac{dC_{LL}}{dP}(x) \right) + R \left(\frac{dC_{LL}}{dR}(x) \right) + \Delta_{fin} \left(\frac{dC_{LL}}{d\Delta_{fin}}(x) \right)$$~~

~~$$C_{M_t}(x) = C_M(x) + \beta \left(\frac{dC_M}{d\beta}(x) \right) + Q \left(\frac{dC_M}{dQ}(x) \right) + \alpha \left(\frac{dC_M}{d\alpha}(x) \right) + \alpha_t \left(\frac{dC_M}{d\alpha_t}(x) \right) + \dot{\alpha}_t \left(\frac{dC_M}{d\dot{\alpha}_t}(x) \right)$$~~

~~$$C_{LN_t}(x) = C_{LN}(x) + \beta \left(\frac{dC_{LN}}{d\beta}(x) \right) + P \left(\frac{dC_{LN}}{dP}(x) \right) + R \left(\frac{dC_{LN}}{dR}(x) \right)$$~~



Aerodynamics Model

For rotational symmetry, we assume:

$$\frac{dC_Y}{d\beta} (X) = - \frac{dC_N}{d\alpha} (X)$$

$$\frac{dC_M}{dQ} (X) = \frac{dC_{LN}}{dR} (X)$$

Equivalent notations when compared to other literature:

$$\frac{dC_N}{d\alpha} (X) \quad - \quad C_{N_A} \qquad \frac{dC_M}{dQ} (X) \quad - \quad C_{M_Q}$$

$$\frac{dC_Y}{d\beta} (X) \quad - \quad C_{Y_\beta} \qquad \frac{dC_{LN}}{dR} (X) \quad - \quad C_{N_R}$$

$$\frac{dC_{LL}}{dP} (X) \quad - \quad C_{L_P}$$

$$\frac{dC_{LL}}{d\Delta_{fin}} (X) \quad - \quad C_{L_\delta}$$



Aerodynamics Model

Definition of Reference Quantities

Identifier: MAD_H300_JetOff_0km
Type: Tabular
File: model\astos\Model_Data.xml

Aerodynamic moments definition: Centre of Pressure Position

Reference area: -
Defined by: Area
Area: -
Defined by: Value
Reference area: 0.0754 Meter**2

Reference Length: 0.31 Meter

Center of pressure: -
The offset is specified with respect to the global node!

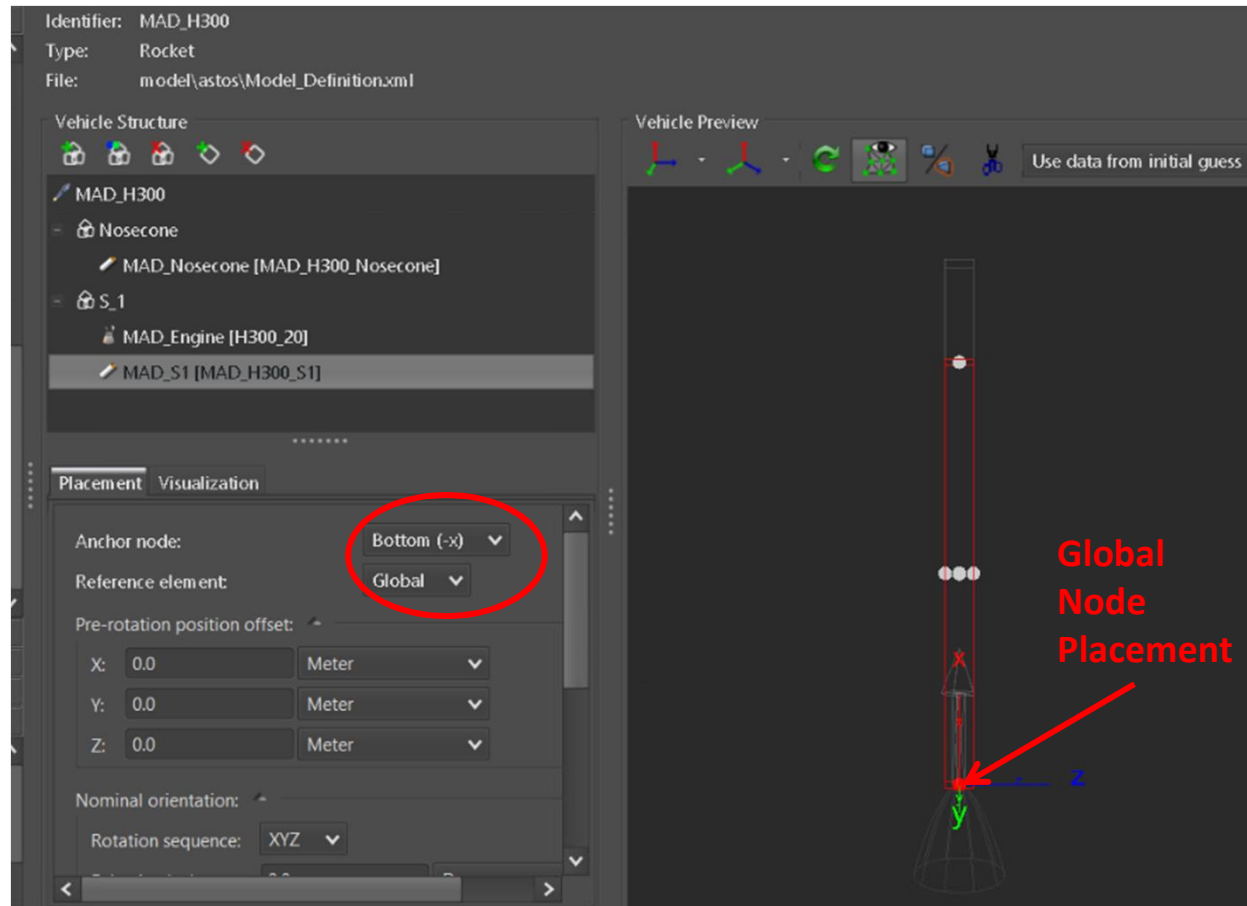
X Offset: -
Defined by: Profile
Profile: -
Interpolation type: Linear
Ordinate data scale: Linear to Linear
Data source: File
Skip Lines: 0
Out of bounds action: Nearest Value
Scaling factor: 1.0
Filename: .\data\Xcp.txt

Length and
area

XCP point is relative to where global node is positioned.



Aerodynamics Model



In this case, XCP is defined +ve since global node is at the bottom. In the case where global node is placed at tip of nose, XCP should be defined -ve.



Aerodynamics Model

1D Interpolation

Identifier: MAD_H300_JetOff_0km
Type: Tabular
File: model\astos\Model_Data.xml

Center of pressure:
The offset is specified with respect to the global node!

X Offset:
Defined by: Profile

Profile:
Interpolation type: Linear
Ordinate data scale: Linear to Linear
Data source: File
Skip Lines: 0

Out of bounds action: Nearest Value
Scaling factor: 1.0
Filename: .\data\Xcp.txt

Name	Unit	Column
Mach	None	1
	Meter	2

Xcp.txt - Notepad

File	Edit	Format	View	Help
Mach	Xcp			
0	0.90434			
0.3	0.89132			
0.5	0.88264			
0.8	0.84823			
0.99	0.82994			
1.01	0.81785			
1.2	0.76143			
1.5	0.9			
1.8	1.10026			
2	1.15854			
3	1.49489			
4	1.70848			

2nd column: Xcp

1st column : Mach (Values must be monotonically increasing)



Aerodynamics Model

2D Interpolation (according to Astos)

Example 1: 4 x 5 data matrix

The tabular data

$\begin{matrix} x \\ y \end{matrix}$	0	0.50	1.00	1.30	1.50
1.00	0.11	0.12	0.13	0.14	0.15
2.00	0.21	0.22	0.23	0.24	0.25
3.00	0.31	0.32	0.33	0.34	0.35
4.00	0.41	0.42	0.43	0.44	0.45

Fig. 10.2: A 4x5 matrix.

should be formatted in a file as follows:

```

0.00 0.50 1.00 1.30 1.50      - 1st indep. variable x
1.00 2.00 3.00 4.00          - 2nd indep. variable y
0.11 0.12 0.13 0.14 0.15      \
0.21 0.22 0.23 0.24 0.25      | x-y matrix
0.31 0.32 0.33 0.34 0.35      |
0.41 0.42 0.43 0.44 0.45      /

```

Fig. 10.3: A 4x5 matrix format in a file ready to be imported



Aerodynamics Model

Coefficients

Coefficients:

Type	Frame	Axis	Character
Force	Body-fixed (B)	Axial direction (-...	Absolute value
Force	Body-fixed (B)	Lateral direction ...	Sideslip slope
Force	Body-fixed (B)	Normal direction...	Angle of attack s...
Moment	Body-fixed (B)	Roll moment (+X)	Aerodynamic sur...
Moment	Body-fixed (B)	Roll moment (+X)	Body roll rate slo...
Moment	Body-fixed (B)	Pitch moment (+...	Body pitch rate s...
Moment	Body-fixed (B)	Yaw moment (+Z)	Body yaw rate sl...

C_D

$C_{Y\beta}$

C_{N_A}

C_{L_P}

C_{L_δ}

C_{M_Q}

C_{N_R}



Aerodynamics Model

Fin Cant

Aerodynamic surfaces:

ID
Surface_1

Selected surface:

Identifier: Surface_1

Deflection:

Defined by: Value

Deflection: 0.5 Degree

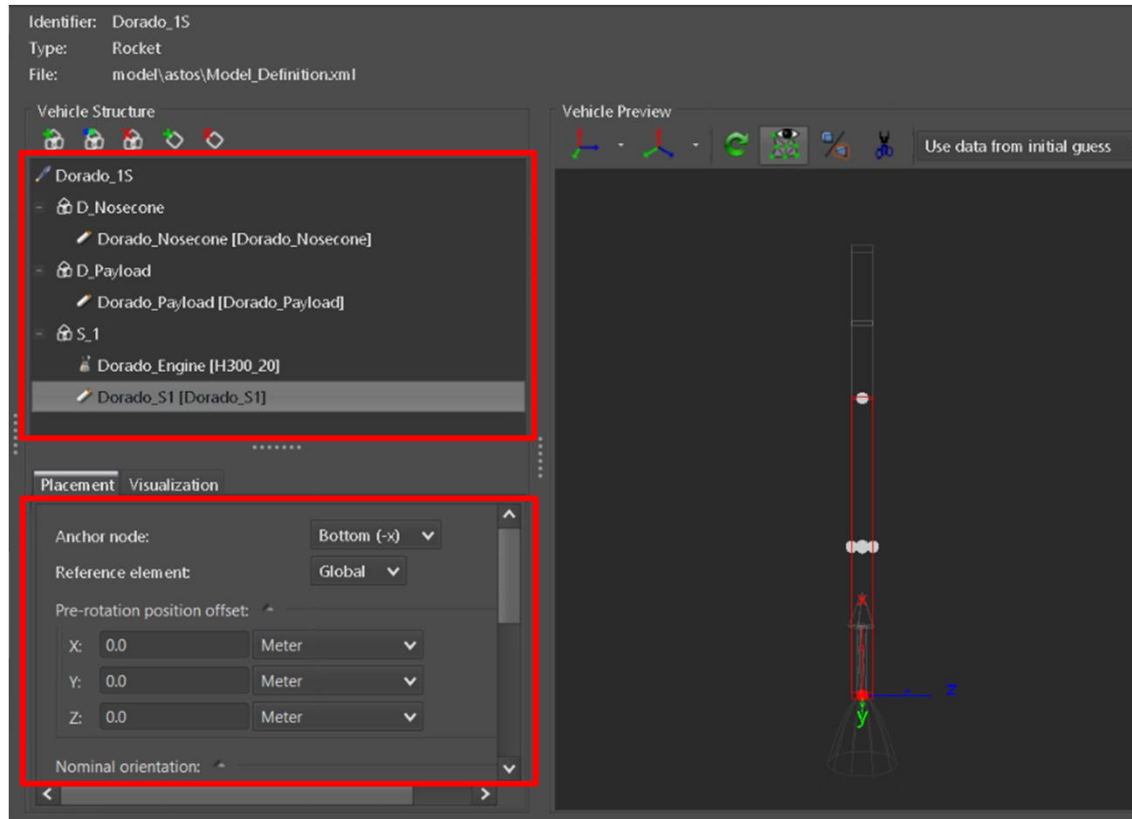
Define fin cant
angle



Vehicle Definition

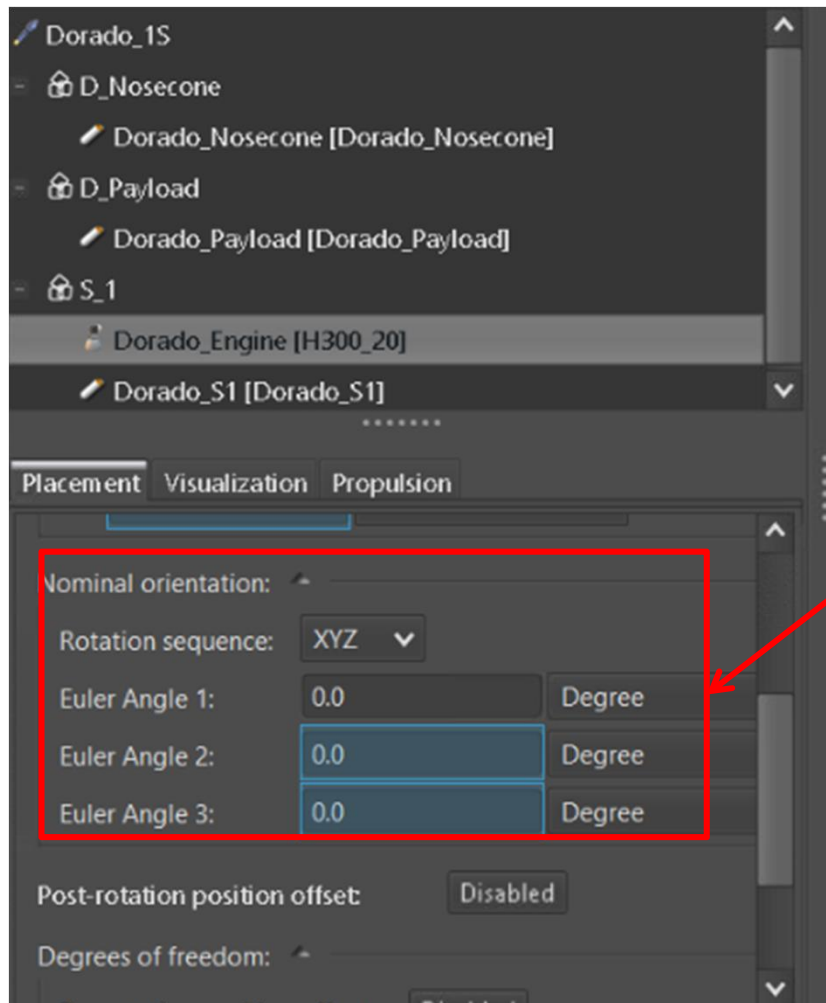
Specify components in use

Define component position using anchor node placement, and position/rotation offsets

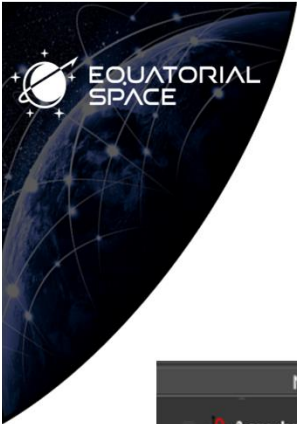




Vehicle Definition



For specifying thrust misalignments
during Monte Carlo simulations



Phase Definition

Overall

Modelling

- Aerodynamics
 - MAD_H300_JetOff_0km
 - MAD_H300_JetOff_30km
 - MAD_H300_JetOn
- + Aerothermodynamics
- + Components
- + Sensors & Transmitters
- + Power
- + Data
- + Thermal
- Vehicles & POIs Definition
 - MAD_H300
 - KTR
- Dynamics Configuration
 - Phases & Common Settings
 - Vehicles & POIs Dynamics
- Analyses
- Variables
- Optimization
- Results

Results

- Curve Plots
- Surface Plots
- Condition Plots
- Result Summary

Mission start date:

Time standard: **TT** Date format: **Calendar Date**

Calendar date:

Year: **2000** Month: **1** Day: **1** Hour: **0** Minute: **0** Second: **0.0**

Offset: **Disabled**

Independent variable: **Time (t)**

Default simulation settings:

Integration:

Integration method: **Dormand-Prince 4/5** Integration error: **1.0E-8**

Normalized step size: **Enabled** Minimum step size: **1.0E-10** Maximum step size: **Disabled**

Ignore the minimum step size and just print a warning if the step size becomes smaller than the minimum: **Enabled**

Output spacing:

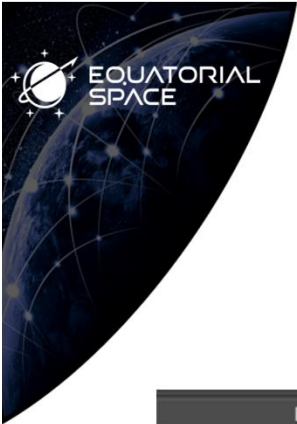
Specified by: **Interval length**

Interval length: **0.05** [Second] **Timestep**

Phases:

Use	Index	Phase ID
<input checked="" type="checkbox"/>	1	Ignition
<input checked="" type="checkbox"/>	2	Rail
<input checked="" type="checkbox"/>	3	Thrust
<input checked="" type="checkbox"/>	4	Coast
<input checked="" type="checkbox"/>	5	Coast_Above30km

Phase selection for trajectory simulation



Phase Definition

Ignition Phase

The image shows a software interface for defining simulation phases. On the left is a sidebar with a tree view under the 'Modelling' section. The tree includes 'MAD_H300_ELA', 'Environment', 'Vehicle Parts & Properties', 'Vehicles & POIs Definition' (with sub-items 'MAD_H300' and 'KTR'), 'Dynamics Configuration', 'Phases & Common Settings', 'Ignition' (highlighted), 'Rail', 'Thrust', 'Coast', 'Coast_Above30km', 'Vehicles & POIs Dynamics', and 'MAD_H300'. At the bottom of the sidebar are buttons for 'Analyses', 'Variables', 'Optimization', and 'Results'. The main panel on the right is titled 'Description:' and contains three settings: 'Phase span defined by:' set to 'Mission Time' with a value of '0.01' (circled in red) and unit 'Second'; 'Additional phase end conditions:' set to 'Disabled'; and 'Simulation settings:' set to 'Default'. A red arrow points from the '0.01' value to the text 'Ignition start time on thrust curve'.

Modelling

MAD_H300_ELA

- + Environment
- + Vehicle Parts & Properties
- Vehicles & POIs Definition
 - MAD_H300
 - KTR
- Dynamics Configuration
 - Phases & Common Settings
 - Ignition
 - Rail
 - Thrust
 - Coast
 - Coast_Above30km
 - Vehicles & POIs Dynamics
 - MAD_H300

Analyses

Variables

Optimization

Results

Description:

Phase span defined by: Mission Time 0.01 Second

Additional phase end conditions: Disabled

Simulation settings: Default

Ignition start time on thrust curve



Phase Definition

Rail Phase

Modelling

- MAD_H300_ELA
- Environment
- Vehicle Parts & Properties
- Vehicles & POIs Definition
 - MAD_H300
 - KTR
- Dynamics Configuration
 - Phases & Common Settings
 - Ignition
 - Rail**
 - Thrust
 - Coast
 - Coast_Above30km
 - Vehicles & POIs Dynamics
 - MAD_H300
- Analyses
- Variables
- Optimization
- Results

Description:

Phase span defined by: Mission Time 2.0 Second

Additional phase end conditions: **Enabled** "Enabled" for boolean condition to work

One condition or All conditions must be fulfilled

Position

Remove

Is active: **Enabled**

Vehicle ID: MAD_H300

Phase ends if: value equal or greater than reference Reference: 10.0 Meter

Constraint applies to:

Default configurations: Apply configuration

Frame: PCPF

Representation: Spherical

Coordinate: Altitude

Boolean condition: phase ends when altitude > launch rail height

Add

Simulation settings: Default

No. of phases vary from case to case, depends on dynamics of trajectory phases

Phase ends when

- Boolean condition is reached, OR
- Phase span reaches mission time or phase time defined



Phase Definition

Thrust Phase

Modelling

MAD_H300_ELA

- Environment
- Vehicle Parts & Properties
- Vehicles & POIs Definition
 - MAD_H300
 - KTR
- Dynamics Configuration
 - Phases & Common Settings
 - Ignition
 - Rail
 - Thrust**
 - Coast
 - Coast_Above30km
 - Vehicles & POIs Dynamics
 - MAD_H300
- Analyses
- Variables
- Optimization
- Results

Description:

Phase span defined by: Mission Time 15.77 Second

Additional phase end conditions: Disabled

Simulation settings: Default

End time on thrust curve



Phase Definition

Coast Phase

Modelling

MAD_H300_ELA

Environment

Vehicle Parts & Properties

Vehicles & POIs Definition

MAD_H300

KTR

Dynamics Configuration

Phases & Common Settings

Ignition

Rail

Thrust

Coast

Coast_Above30km

Vehicles & POIs Dynamics

MAD_H300

Analyses

Variables

Optimization

Results

Description:

Phase span defined by: Mission Time 200.0 Second

Additional phase end conditions: Enabled

One condition or All conditions must be fulfilled

Position

Remove

Is active: Enabled

Vehicle ID: MAD_H300

Phase ends if: value equal or greater than reference Reference: 30.0 Kilo-Meter

Constraint applies to:

Default configurations: Apply configuration

Frame: PCPF

Representation: Spherical

Coordinate: Altitude

Add

Simulation settings: Default

Boolean condition: phase ends when altitude > 30 km



Phase Definition

2nd Coast Phase

Modelling

MAD_H300_ELA

- + Environment
- + Vehicle Parts & Properties
- Vehicles & POIs Definition
 - MAD_H300
 - KTR
- Dynamics Configuration
 - Phases & Common Settings
 - Ignition
 - Rail
 - Thrust
 - Coast
 - Coast_Above30km**
 - Vehicles & POIs Dynamics
 - MAD_H300

Analyses

Variables

Optimization

Results

Description:

Phase span defined by: Mission Time 400.0 Second

Additional phase end conditions: Enabled

☒ One condition or ☐ All conditions must be fulfilled

Position

Remove

Is active: Enabled

Vehicle ID: MAD_H300

Phase ends if: value equal or smaller than reference Reference: 0.0 Kilo-Meter

Constraint applies to:

Default configurations: Apply configuration

Frame: PCPF

Representation: Spherical

Coordinate: Altitude

Add

Simulation settings: Default

Boolean condition: phase ends when altitude < 0 km



Trajectory Parameters

Initial State

Modelling

- MAD_H300_JetOff_0km
- MAD_H300_JetOff_30km
- MAD_H300_JetOn
- Aerothermodynamics
- Components
- Sensors & Transmitters
- Power
- Data
- Thermal
- Vehicles & POIs Definition
 - MAD_H300
 - KTR
- Dynamics Configuration
 - Phases & Common Settings
 - Vehicles & POIs Dynamics
 - MAD_H300
- Analyses
- Variables
- Optimization
- Results

Initial State | Default Settings | Ignition | Rail | Thrust | Coast | Coast_Above30km

State type: Position & Velocity

Position:

Frame: PCPF Representation: Polar

Altitude type: Altitude Latitude type: Latitude

Reference point: Global

Altitude: 0.0 Meter

Longitude: 136.796342 Degree

Latitude: -12.389436 Degree

Lat, long, alt

Velocity:

Reference frame: Relative PCPF Representation frame: L Representation: Polar

Speed: 0.0 Kilo-Meter/Seco...

Inclination: 85.0 Degree

Heading: 225.0 Degree

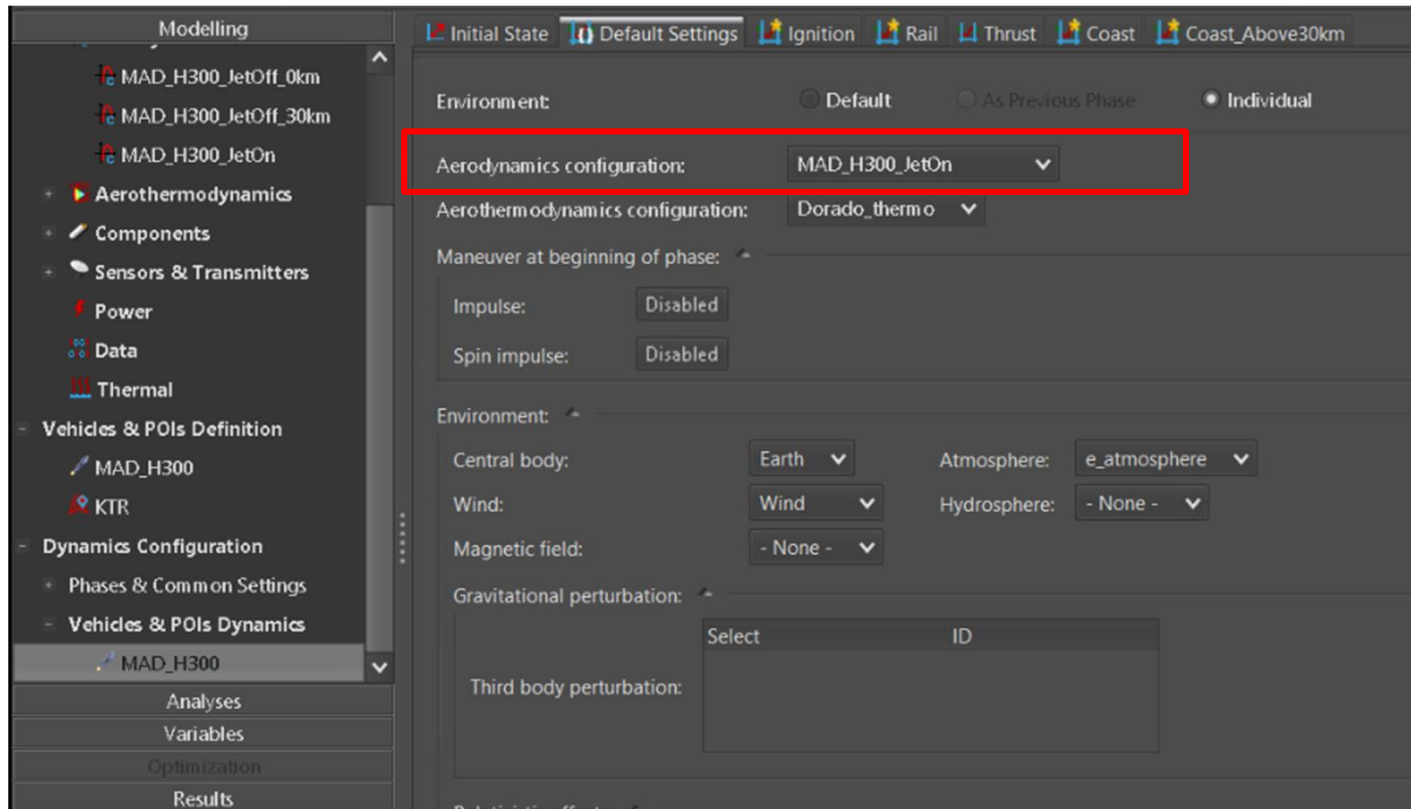
Speed, inclination, heading

Epoch differs from mission start date: Disabled



Trajectory Parameters

Default Settings



Default aerodynamics model: No base drag



Trajectory Parameters

Default Settings

The screenshot displays the 'Default Settings' tab of the Equatorial Space software. The interface includes several tabs: 'Initial State', 'Default Settings' (selected), 'Ignition', 'Rail', 'Thrust', 'Coast', and 'Coast_Above30km'. The 'Default Settings' section contains the following options:

- Celestial bodies:** A text input field.
- Formulation:** A dropdown menu set to 'General Relativity'.
- Solar radiation pressure:** A button labeled 'Disabled'.
- Solar radiation torque:** A button labeled 'Disabled'.
- Gravity gradient:** A button labeled 'Disabled'.
- Equations of motion:** A section highlighted by a red box, containing a dropdown menu set to 'Inertial Velocity'.
- Attitude:** A section highlighted by a red box, containing a dropdown menu set to 'Euler Angles', a 'Control/State' dropdown set to 'State', and a 'Coordinate frame' dropdown set to 'L'.

Default equation of motion and attitude control laws used



Trajectory Parameters

Equations of Motion: Inertial Velocity(Astos Model Reference)

Background

The states V_R , V_λ and V_δ specify the Cartesian components of the inertial velocity vector

$$\hat{V} \equiv \begin{bmatrix} V_R \\ V_\lambda \\ V_\delta \end{bmatrix}_L \quad (4.60)$$

The kinematic state equations represent the kinematic relationship established by the definition of the position and the velocity states

$$\frac{d}{dt} \begin{bmatrix} R \\ \lambda \\ \delta \end{bmatrix} = \begin{bmatrix} V_R \\ \frac{V_\lambda}{R \cos \delta} - \Omega_E \\ \frac{V_\delta}{R} \end{bmatrix} \quad (4.61)$$

and the dynamic state equations are

$$\frac{d}{dt} \begin{bmatrix} V_R \\ V_\lambda \\ V_\delta \end{bmatrix}_L = \begin{bmatrix} \frac{1}{R} \cdot (V_\lambda^2 + V_\delta^2) + \frac{F_R}{m} \\ \frac{1}{R} \cdot V_\lambda \cdot (V_\delta \cdot \tan \delta - V_R) + \frac{F_\lambda}{m} \\ -\frac{1}{R} \cdot (V_\lambda^2 \cdot \tan \delta + V_\delta \cdot V_R) + \frac{F_\delta}{m} \end{bmatrix} \quad (4.62)$$

Input to the system of Eq. 4.62 is the acceleration vector acting on the vehicle resulting from gravity, aerodynamic forces, thrust or other perturbations.



Trajectory Parameters

Default Settings

Initial State | **Default Settings** | Ignition | Rail | Thrust | Coast | Coast_Above30km

Mass Distribution:

Structure and consumables:

Combined:

Center of mass:

X Offset

Defined by:

Profile X_Offset:

Interpolation type: Out of bounds action:

Ordinate data scale: Scaling factor:

Data source:

1		Data
Name	Time	
Unit	Second	Meter
1	0.0	2.232
2	15.77	2.14

Default CoM



Trajectory Parameters

Default Settings

Initial State | **Default Settings** | Ignition | Rail | Thrust | Coast | Coast_Above30km

Gain: Disabled

YY

Defined by: Profile ▾

Profile YY: ▲

Interpolation type: Linear ▾ Out of bounds action: Nearest Value ▾

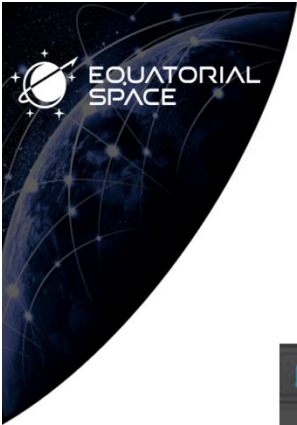
Ordinate data scale: Linear to Linear ▾ Scaling factor: 1.0

Data source: Local ▾

← → ↺ ↻ ⚙ ⚙ ⚙ ⚙ ⚙ Preview

	1	Data
Name	Time	
Unit	Second	Kilogram*Meter**2
1	0.0	1285.77
2	15.77	523.84
*		

Default MoI (YY) (Same for ZZ)



Trajectory Parameters

Default Settings

Initial State **Default Settings** Ignition Rail Thrust Coast Coast_Above30km

Defined by:

Moments of inertia:

Defined by:

Profile XX:

Interpolation type: Out of bounds action:

Ordinate data scale: Scaling factor:

Data source:

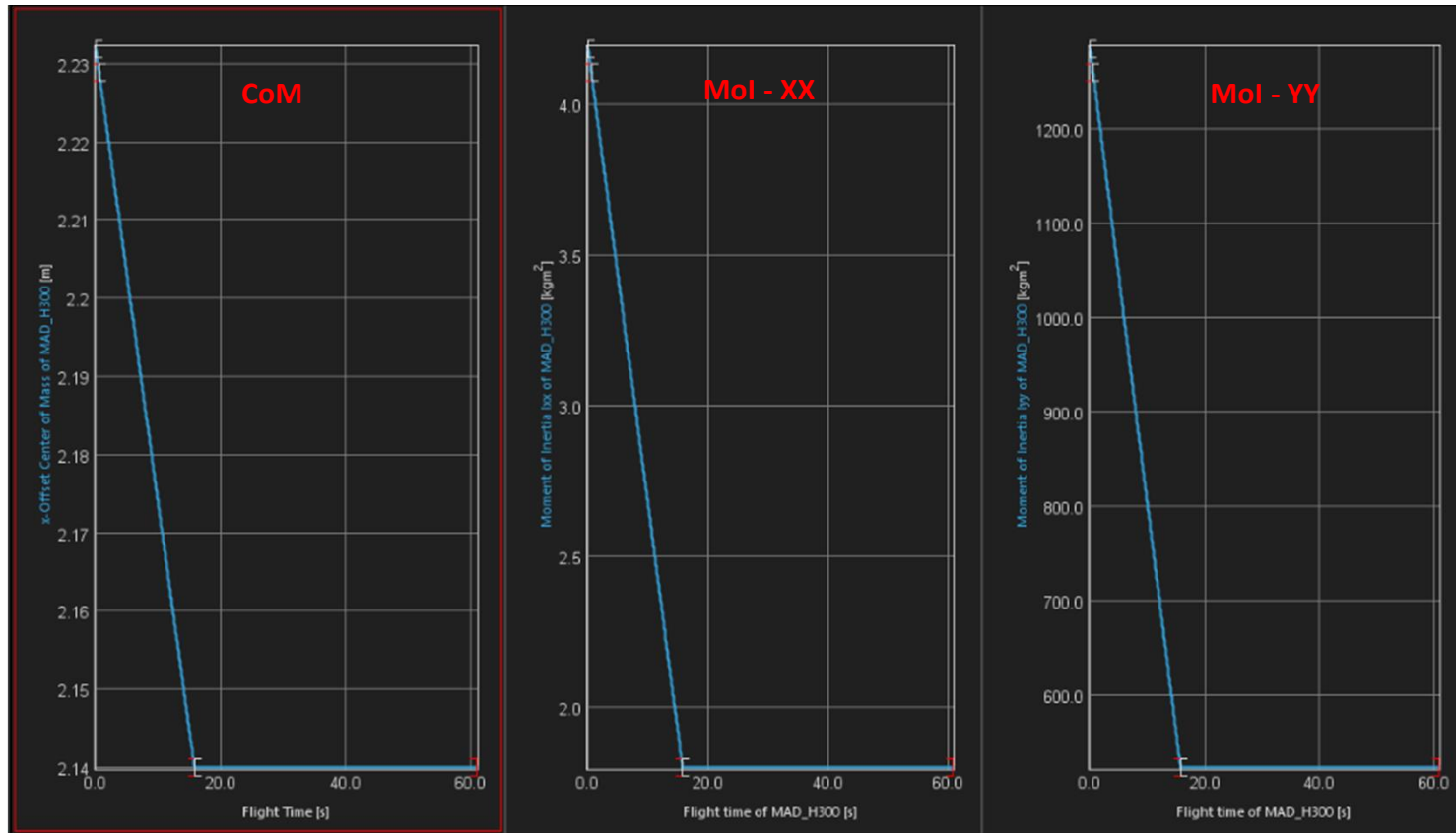
	1	Data
Name	Time	
Unit	Second	Kilogram*Meter**2
1	0.0	4.1845
2	15.77	1.8019

Default Mol (XX)



Trajectory Parameters

Default Settings



Verification of default settings



Trajectory Parameters

Dynamics - Ignition

Modelling

- MAD_H300_JetOff_0km
- MAD_H300_JetOff_30km
- MAD_H300_JetOn
- Aerothermodynamics
- Components
- Sensors & Transmitters
- Power
- Data
- Thermal
- Vehicles & POIs Definition
 - MAD_H300
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Initial State | Default Settings | **Ignition** | Rail | Thrust | Coast | Coast_Above30km

Aerodynamics configuration: ☒ Default ☐ As Previous Phase ☐ Individual

Aerothermodynamics configuration: ☒ Default ☐ As Previous Phase ☐ Individual

Environment: ☒ Default ☐ As Previous Phase ☐ Individual

Equations of motion: ☐ Default ☐ As Previous Phase ☒ Individual

Attitude: ☐ Default ☐ As Previous Phase ☒ Individual

Magnetic moment: ☒ Default ☐ As Previous Phase ☐ Individual

Mass Distribution: ☒ Default ☐ As Previous Phase ☐ Individual

Flexible dynamics: ☒ Default ☐ As Previous Phase ☐ Individual

Aerodynamics configuration: MAD_H300_JetOn

Aerothermodynamics configuration: Dorado_thermo

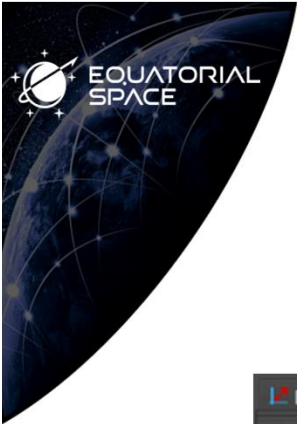
Active actuators:

Select	ID	
<input checked="" type="checkbox"/>	MAD_Engine	[1/1]

Jettisoned assemblies at end of phase:

Select	Assembly ID	
<input type="checkbox"/>	Nosecone	[0/2]
<input type="checkbox"/>	S_1	

Active motor



Trajectory Parameters

Dynamics - Ignition

Initial State | Default Settings | **Ignition** | Rail | Thrust | Coast | Coast_Above30km

Solar radiation pressure: Disabled

Solar radiation torque: Disabled

Gravity gradient: Disabled

Equations of motion:

Defined by: Launch Pad

Attitude:

Defined by: Euler Angles Control/State: Control Coordinate frame: L

Yaw angle:

Control law: Constant Law

Yaw: 225.0 Degree

☐ Use (final) value from previous phase (0.0 in case of the first phase).

Pitch angle:

Control law: Constant Law

Pitch: 85.0 Degree

☐ Use (final) value from previous phase (0.0 in case of the first phase).



Trajectory Parameters

Equations of Motion: Launch Pad (Astos Model Reference)

Table 4.2: Definition of flight path velocity state variables

State Variable	Definition
R	Radial distance from planet center
λ	East longitude / Angle between the Greenwich meridian and the meridian of the current position (positive east of Greenwich)
δ	Declination angle between the equatorial plane and the current position vector (positive on the northern hemisphere)

The kinematic state equations represent the kinematic relationship established by the definition of the position:

$$\frac{d}{dt} \begin{bmatrix} R \\ \lambda \\ \delta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (4.65)$$



Trajectory Parameters

Dynamics - Rail

Initial State				Default Settings				Ignition				Rail				Thrust				Coast				Coast_Above30km			
Aerodynamics configuration:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Aerothermodynamics configuration:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Maneuver at Beginning of Phase:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Environment:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Equations of motion:		<input type="radio"/> Default		<input type="radio"/> As Previous Phase		<input checked="" type="radio"/> Individual																					
Attitude:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Magnetic moment:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Mass Distribution:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Flexible dynamics:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Aerodynamics configuration:		MAD_H300 JetOn																									
Aerothermodynamics configuration:		Dorado thermo																									
Active actuators:		Select		ID																		[1/1]					
		<input checked="" type="checkbox"/>		MAD_Engine																							
		<input type="checkbox"/>																									
		<input type="checkbox"/>																									
Jettisoned assemblies at end of phase:		Select		Assembly ID																		[0/2]					
		<input type="checkbox"/>		Nosecone																							
		<input type="checkbox"/>		S_1																							
		<input type="checkbox"/>																									

Active motor



Trajectory Parameters

Dynamics - Rail

Initial State Default Settings Ignition **Rail** Thrust Coast Coast_Above30km

Formulation: General Relativity

Solar radiation pressure: Disabled

Solar radiation torque: Disabled

Gravity gradient: Disabled

Equations of motion:

Defined by: Accelerate Flightpath

Attitude:

Defined by: Euler Angles

Control/State: State



Trajectory Parameters

Equations of Motion: Accelerate Flight Path (Astos Model Reference)

Background

The Cartesian components of the velocity vector along the local L -frame are given by:

$$\hat{V}_k = V \begin{bmatrix} \sin\gamma \\ \cos\gamma\sin\chi \\ \cos\gamma\cos\chi \end{bmatrix}_L \quad (4.31)$$

The kinematic state equations represent the kinematic relationship established by the definition of the position and the velocity states:

$$\frac{d}{dt} \begin{bmatrix} R \\ \lambda \\ \delta \end{bmatrix} = \begin{bmatrix} V\sin\gamma \\ \frac{V\cos\gamma\sin\chi}{R\cos\delta} \\ \frac{V\cos\gamma\cos\chi}{R} \end{bmatrix} \quad (4.32)$$

The dynamic state equations follow Newton's second law

$$\frac{dV}{dt} = X + \Omega_E^2 R \cos\delta (\cos\delta\sin\gamma - \sin\delta\cos\gamma\cos\chi) \quad (4.33)$$

where Ω_E is the angular velocity of the central body about the inertial planet-centered z-axis. X , Y , Z are the components of the acceleration vector in the trajectory coordinate system (see Section 9.3.5.1):

$$\frac{\hat{F}}{m} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_T \quad (4.34)$$

The acceleration acting on the vehicle results from gravity, aerodynamic forces, thrust or other perturbations. Note that only X is considered in the dynamic, whereas Y and Z are neglected (i.e. supposed to be balanced by the rail structure).



Trajectory Parameters

Dynamics - Rail

Initial State				Default Settings				Ignition				Rail				Thrust				Coast				Coast_Above30km			
Aerodynamics configuration:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Aerothermodynamics configuration:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Maneuver at Beginning of Phase:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Environment:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Equations of motion:		<input type="radio"/> Default		<input type="radio"/> As Previous Phase		<input checked="" type="radio"/> Individual																					
Attitude:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Magnetic moment:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Mass Distribution:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Flexible dynamics:		<input checked="" type="radio"/> Default		<input type="radio"/> As Previous Phase		<input type="radio"/> Individual																					
Aerodynamics configuration:		MAD_H300 JetOn																									
Aerothermodynamics configuration:		Dorado thermo																									
Active actuators:		Select		ID																		[1/1]					
		<input checked="" type="checkbox"/>		MAD_Engine																							
		<input type="checkbox"/>																									
		<input type="checkbox"/>																									
Jettisoned assemblies at end of phase:		Select		Assembly ID																		[0/2]					
		<input type="checkbox"/>		Nosecone																							
		<input type="checkbox"/>		S_1																							
		<input type="checkbox"/>																									

Active motor



Trajectory Parameters

Dynamics - Thrust

Initial State Default Settings Ignition Rail **Thrust** Coast Coast_Above30km

Aerodynamics configuration: ☒ Default ☐ As Previous Phase ☐ Individual

Aerothermodynamics configuration: ☒ Default ☐ As Previous Phase ☐ Individual

Maneuver at Beginning of Phase: ☒ Default ☐ As Previous Phase ☐ Individual

Environment: ☒ Default ☐ As Previous Phase ☐ Individual

Equations of motion: ☒ Default ☐ As Previous Phase ☐ Individual

Attitude: ☒ Default ☐ As Previous Phase ☐ Individual

Magnetic moment: ☒ Default ☐ As Previous Phase ☐ Individual

Mass Distribution: ☒ Default ☐ As Previous Phase ☐ Individual

Flexible dynamics: ☒ Default ☐ As Previous Phase ☐ Individual

Aerodynamics configuration: MAD_H300_JetOn

Aerothermodynamics configuration: Dorado_thermo

	Select	ID	
Active actuators:	<input checked="" type="checkbox"/>	MAD_Engine	[1/1]
	<input type="checkbox"/>		

	Select	Assembly ID	
Jettisoned assemblies at end of phase:	<input type="checkbox"/>	Nosecone	[0/2]
	<input type="checkbox"/>	S_1	

Active motor



Trajectory Parameters

Dynamics - Coast

Initial State Default Settings Ignition Rail Thrust **Coast** Coast_Above30km

Aerodynamics configuration:	<input type="radio"/> Default	<input type="radio"/> As Previous Phase	<input checked="" type="radio"/> Individual
Aerothermodynamics configuration:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Maneuver at Beginning of Phase:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Environment:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Equations of motion:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Attitude:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Magnetic moment:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Mass Distribution:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Flexible dynamics:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual

Aerodynamics configuration: MAD_H300_JetOff_0km ▼

Aerothermodynamics configuration: Dorado_thermo_ ▼

Select	ID	
<input type="checkbox"/>	MAD_Engine	[0/1]

Active actuators:

Select	Assembly ID	
<input type="checkbox"/>	Nosecone	[0/2]
<input type="checkbox"/>	S_1	

Jettisoned assemblies at end of phase:

Full base drag – 0 km altitude

Inactive motor



Trajectory Parameters

Dynamics – 2nd Coast Phase

Initial State | Default Settings | Ignition | Rail | Thrust | Coast | Coast_Above30km

Aerodynamics configuration:	<input type="radio"/> Default	<input type="radio"/> As Previous Phase	<input checked="" type="radio"/> Individual
Aerothermodynamics configuration:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Maneuver at Beginning of Phase:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Environment:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Equations of motion:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Attitude:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Magnetic moment:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Mass Distribution:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual
Flexible dynamics:	<input checked="" type="radio"/> Default	<input type="radio"/> As Previous Phase	<input type="radio"/> Individual

Aerodynamics configuration: MAD_H300_JetOff_30km ▼

Aerothermodynamics configuration: Dorado_thermo ▼

	Select	ID	
Active actuators:	<input type="checkbox"/>	MAD_Engine	[0/1]

	Select	Assembly ID	
Jettisoned assemblies at end of phase:	<input type="checkbox"/>	Nosecone	[0/2]
	<input type="checkbox"/>	S_1	

Full base drag – 30 km altitude

Inactive motor



Modelling Guidelines

- Focus on a single phase at a time
 - Disable later phases in the “Phases & Common Settings”
- Use curve plots in the “Results” panel for verifying correctness of input/output data
- Large aerodynamic tables (i.e. 2D) can be split into series of 1D tables for simulation
 - Consequently, the same increase in the no. of trajectory phases are required since each phase utilizes a different aerodynamic table