

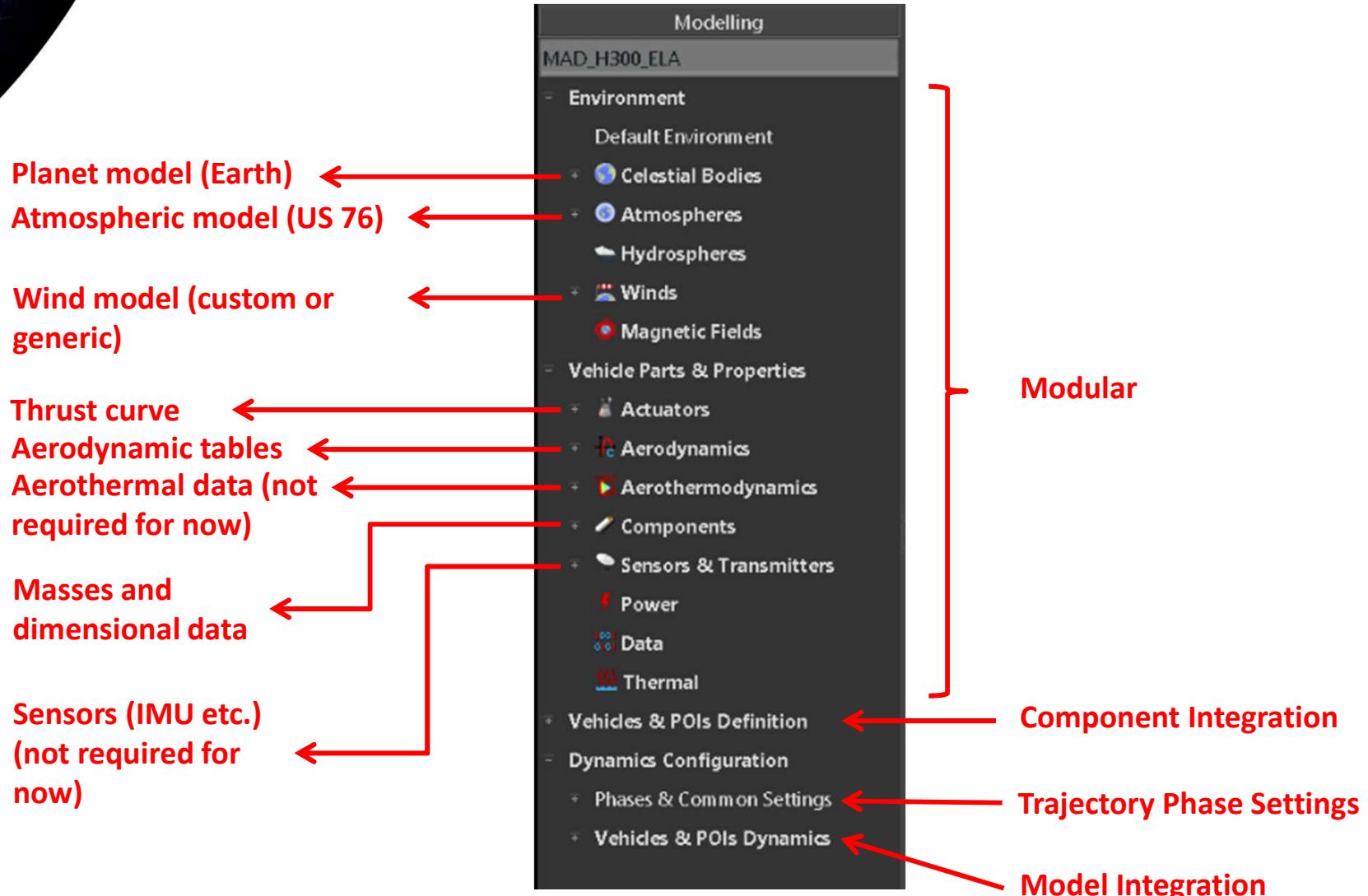


ASTOS Model Setup – Sub-Orbital Rocket Trajectory Modelling

Jason Ong



High Level Overview





Thrust Model

The screenshot shows the software's interface for defining a thrust model. On the left, a tree view lists vehicle parts and properties, with 'H300_20' selected under 'Actuators'. The main panel displays the following details:

- Identifier:** H300_20
- Type:** Rocket Engine
- Subtype:** Profile
- File:** model\astos\Model_Data.xml

Under the 'Performance defined by:' section, a dropdown menu is open, showing five options:

- Vacuum thrust and Mass flow
- Vacuum thrust and Mass flow
- Vacuum thrust and Exhaust velocity
- Vacuum thrust and Vacuum Isp
- Vacuum Isp and Mass flow

The first two options are highlighted with a red box and connected by a red arrow pointing to the second option.

Other settings visible include:

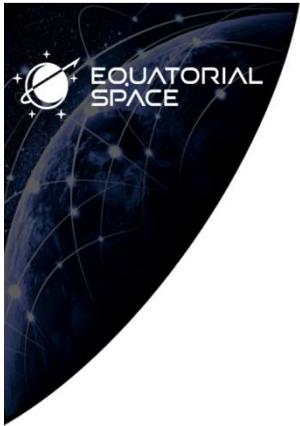
- Thrust scaling factor:** Enabled, value 1.0
- Nozzle ae:** Value 0.028353, Meter²
- Interpolation type:** Linear
- Ordinate data scale:** Linear to Linear
- Data source:** File
- Skip Lines:** 0

A table at the bottom shows data for the first row:

Name	Burn Time	Unit	Value
1		Second	Kilo-Newton
2			

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,

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

For sea level thrust,

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

Conversion of SL thrust to vacuum thrust:

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

↓ ↓ ↓

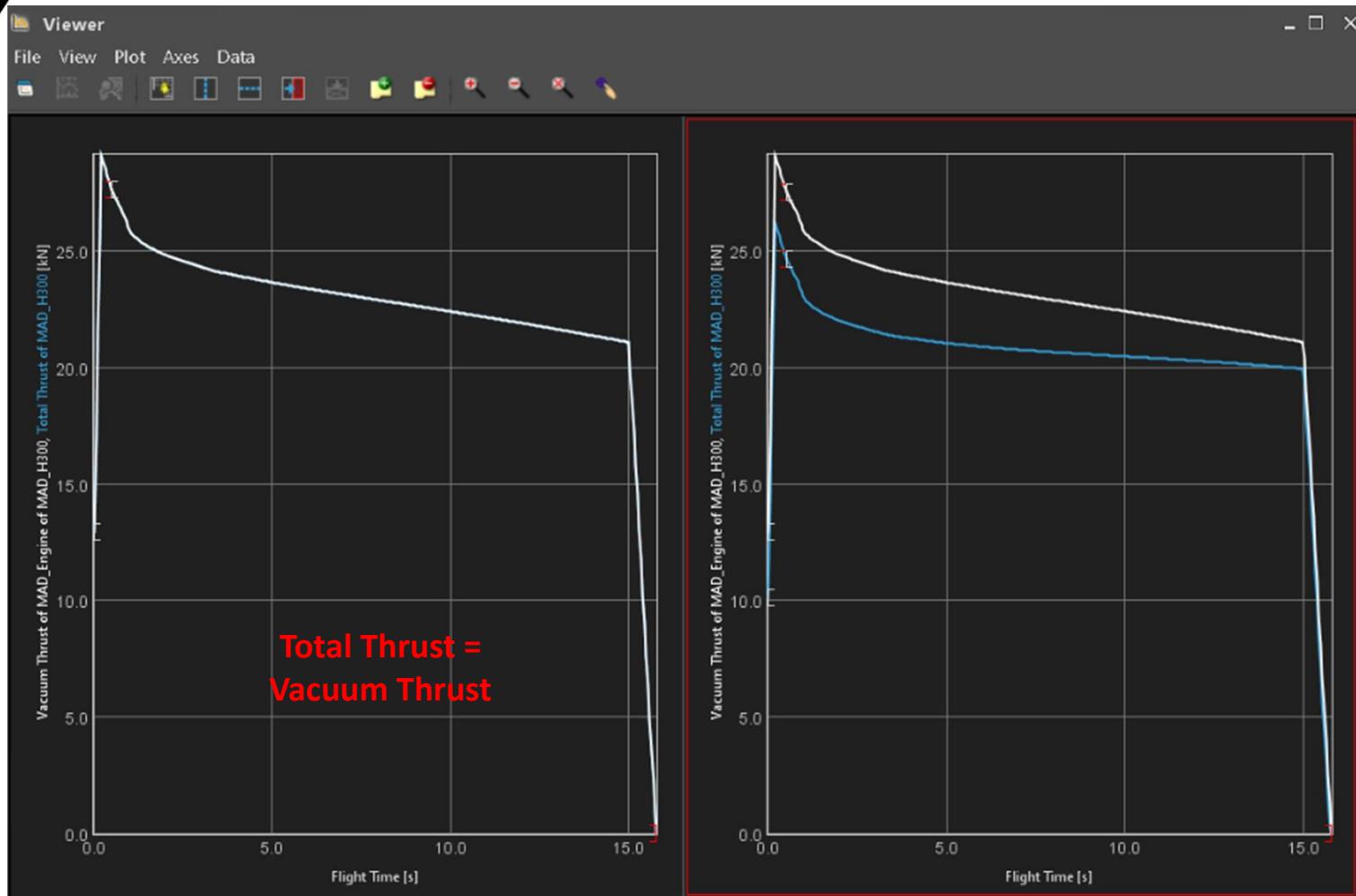
**Vacuum thrust
curve data as
Astos input**

**Propulsion thrust
curve data**

**Nozzle exhaust
area as input**



Thrust Model

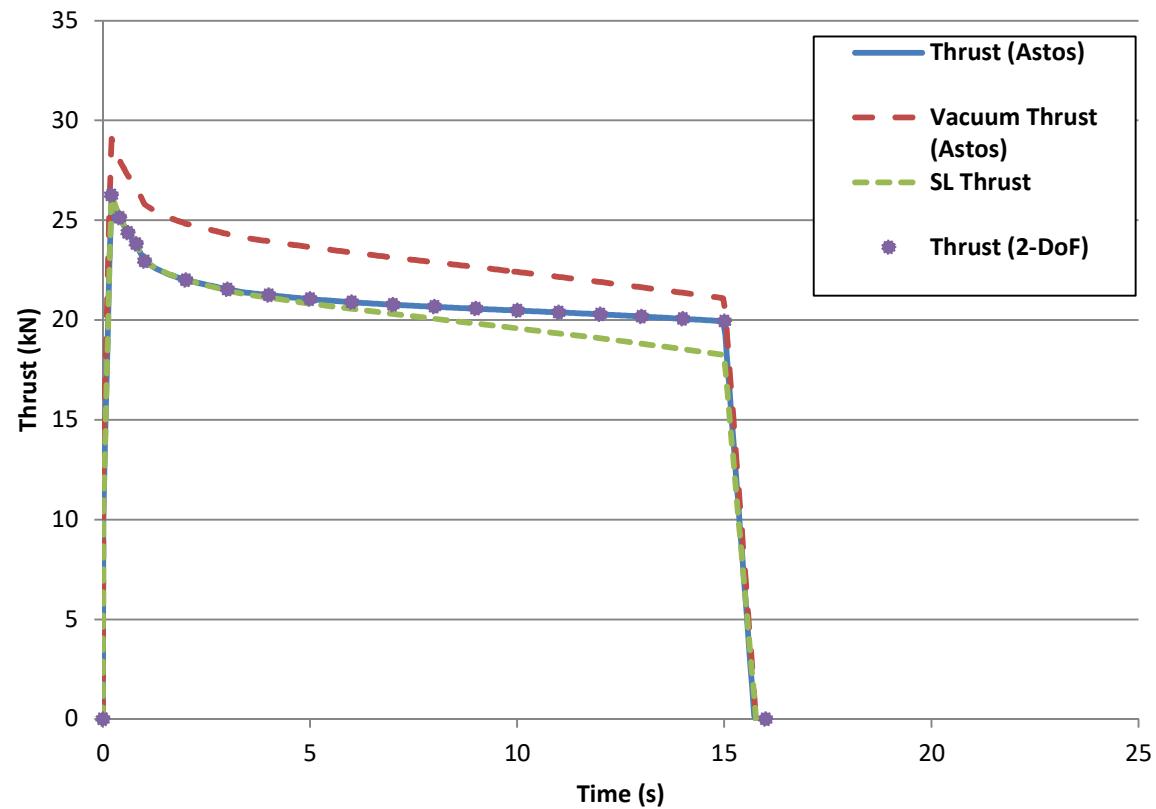


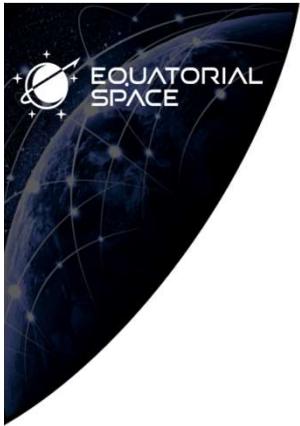
Nozzle exhaust
area = 0

Nozzle exhaust
area \neq 0



Thrust Model





Aerodynamics Model

Force and moment equations in body-fixed coordinates

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

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



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

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

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

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



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:

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

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

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

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



Aerodynamics Model

Definition of Reference Quantities

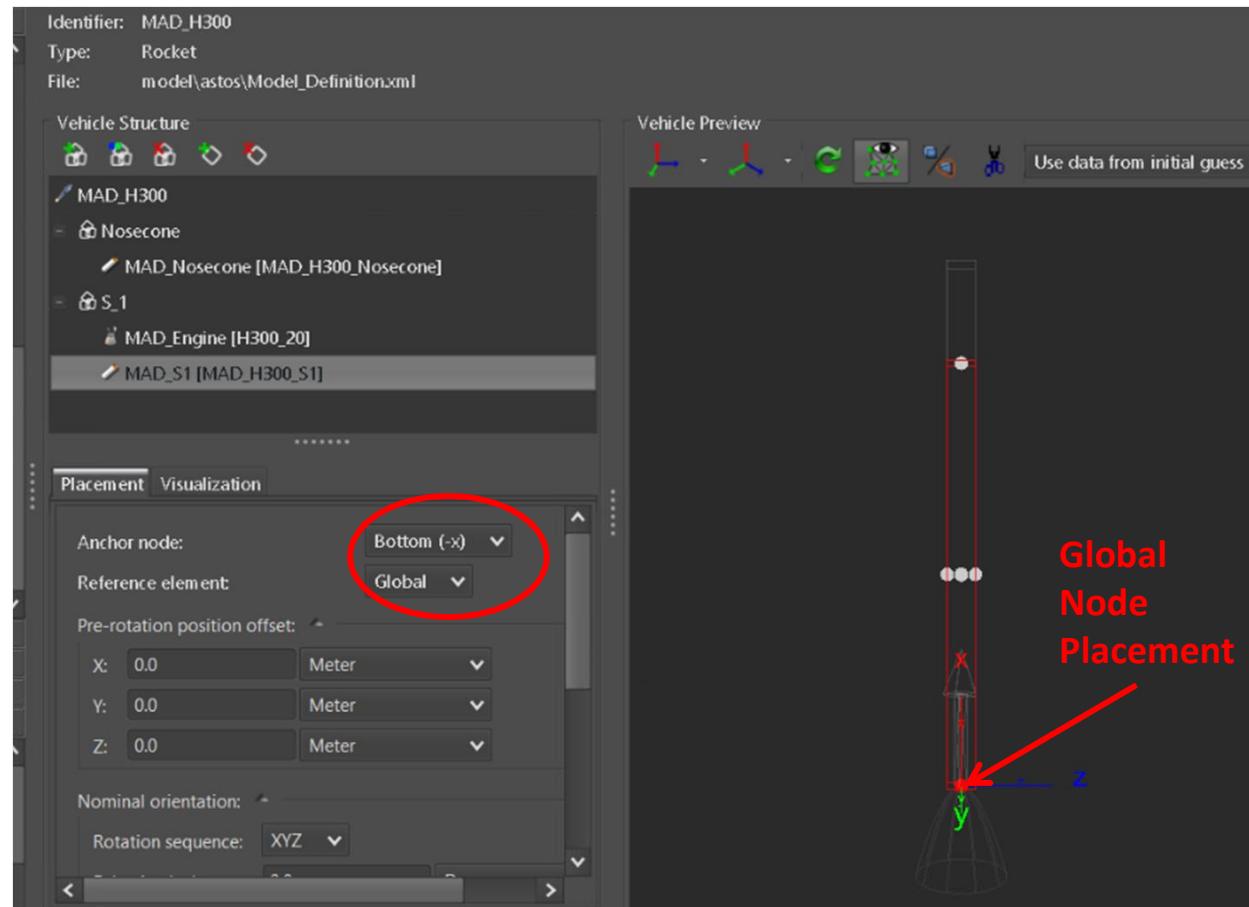
The screenshot shows the 'Aerodynamics' tab selected in the left-hand navigation tree. The main panel displays the 'Identifier' as 'MAD_H300_JetOff_0km', 'Type' as 'Tabular', and 'File' as 'model\astos\Model_Data.xml'. The 'Aerodynamic moments definition' is set to 'Centre of Pressure Position'. A red box highlights the 'Reference area' and 'Area' sections. The 'Reference area' is defined by 'Area' with a value of '0.0754' in 'Meter**2'. The 'Area' section is defined by 'Value' with a value of '0.0754'. Another red box highlights the 'Reference Length' field, which is set to '0.31' in 'Meter'. A third red box highlights the 'Center of pressure' section, which contains the note: 'The offset is specified with respect to the global node!'. A red arrow points from this note down to the text at the bottom of the slide.

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	Mach	1	Data	2
Name	Mach	1		
Unit	None		Meter	
Column	1			2

Xcp.txt - Notepad

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

Absolute value (Force, Body-fixed (B), Axial direction (-X)):

Defined by: Profile

Profile: Angle of attack reverse lookup: Disabled

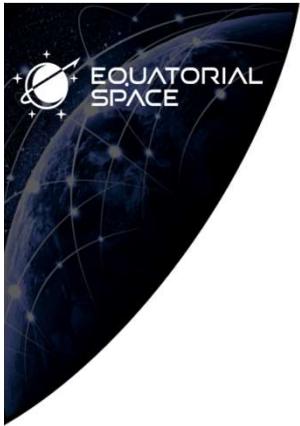
Interpolation type: Linear Out of bounds action: Nearest Value

Ordinate data scale: Linear to Linear Scaling factor: 1.0

Data source: File Filename: \data\CD_NoBaseDrag.txt

Skip Lines: 0

Name	Altitude	Mach
Unit	Kilo-Meter	None
Identifier	altitude	Mach



Aerodynamics Model

2D Interpolation (according to Astos)

Example 1: 4 x 5 data matrix

The tabular data

x y	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

Type	Frame	Axis	Character	
Force	Body-fixed (B)	Axial direction (-Z)	Absolute value	C_D
Force	Body-fixed (B)	Lateral direction (-Y)	Sideslip slope	$C_{y\beta}$
Force	Body-fixed (B)	Normal direction (+X)	Angle of attack slope	C_{N_A}
Moment	Body-fixed (B)	Roll moment (+X)	Aerodynamic surface	C_{L_P}
Moment	Body-fixed (B)	Roll moment (+X)	Body roll rate slope	C_{L_δ}
Moment	Body-fixed (B)	Pitch moment (+Y)	Body pitch rate slope	C_{M_Q}
Moment	Body-fixed (B)	Yaw moment (+Z)	Body yaw rate slope	C_{N_R}



Aerodynamics Model

Fin Cant

Aerodynamic surfaces:

ID
Surface_1

Add aerodynamic surface
Delete selected aerodynamic surface

Selected surface:

Identifier: Surface_1

Deflection:

Defined by: Value

Deflection: 0.5 Degree

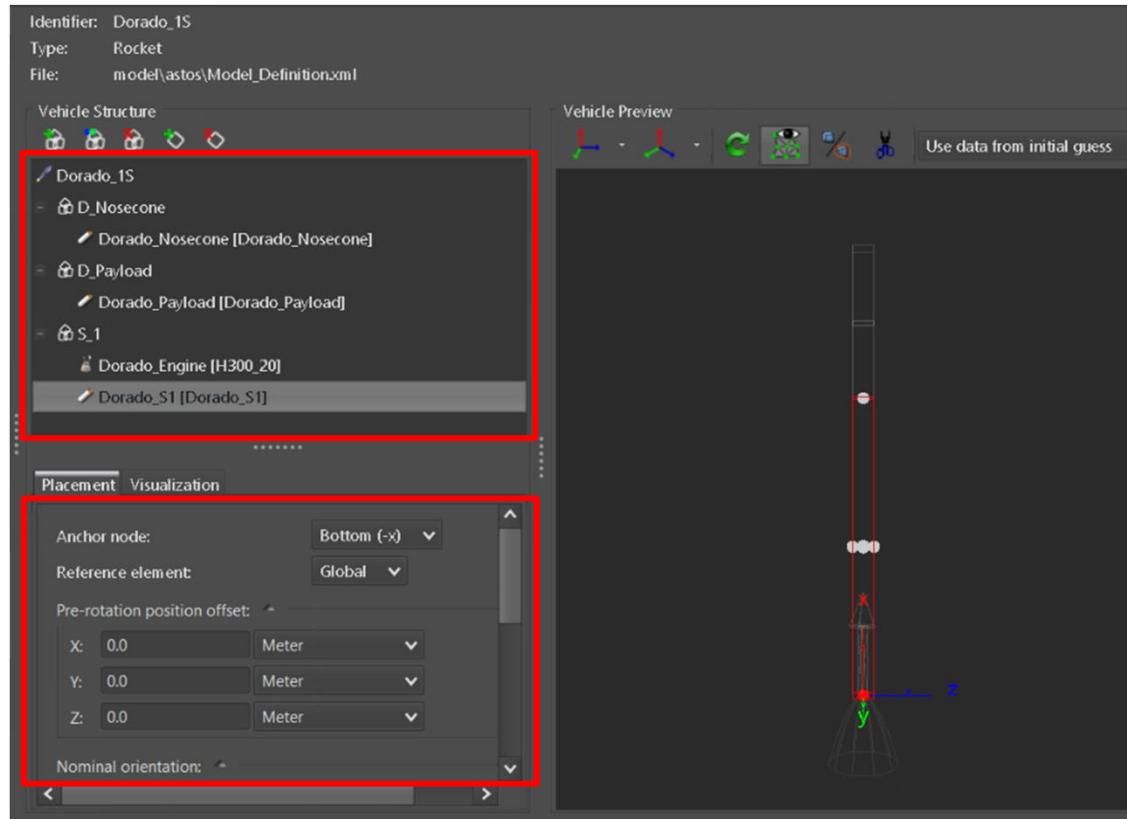
Define fin cant angle



Vehicle Definition

Specify components in use

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





Vehicle Definition

The screenshot shows a software interface for defining a vehicle. At the top is a tree view of vehicle components:

- Dorado_1S
 - D_Nosecone
 - Dorado_Nosecone [Dorado_Nosecone]
 - D_Payload
 - Dorado_Payload [Dorado_Payload]
 - S_1
 - Dorado_Engine [H300_20]
 - Dorado_S1 [Dorado_S1]
 -

Below the tree view is a configuration panel with tabs: Placement, Visualization, Propulsion. The Placement tab is selected.

The configuration panel includes the following settings:

- Nominal orientation:
 - Rotation sequence: XYZ
 - Euler Angle 1: 0.0 Degree
 - Euler Angle 2: 0.0 Degree
 - Euler Angle 3: 0.0 Degree
- Post-rotation position offset: Disabled
- Degrees of freedom: Enabled

For specifying thrust misalignments
during Monte Carlo simulations



Phase Definition

Overall

The screenshot shows the Phase Definition interface in a software application. The left sidebar contains a tree view of modeling categories: Aerodynamics, Aerothermodynamics, Components, Sensors & Transmitters, Power, Data, Thermal, Vehicles & POIs Definition, and Dynamics Configuration. Under Dynamics Configuration, Phases & Common Settings is expanded, showing Vehicles & POIs Dynamics, Analyses, Variables, Optimization, and Results.

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 (0)

Default simulation settings: 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]

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

A red box highlights the 'Phases' table, and a red arrow points to the 'Index' column header. A red arrow also points to the 'Interval length' input field with the label 'Timestep'. Another red arrow points to the 'Phase ID' column header with the label 'Phase selection for trajectory simulation'.



Phase Definition

Ignition Phase

The screenshot shows the software's interface for defining mission phases. On the left, a tree view under 'Modelling' shows the project structure. The 'Phases & Common Settings' section is expanded, with 'Ignition' selected. The main panel displays settings for the 'Ignition' phase:

- Description:** (Text input field)
- Phase span defined by:** (Dropdown menu set to 'Mission Time')
 - Value: 0.01
 - Unit: Second
- Additional phase end conditions:** (Buttons: 'Disabled' and 'Default')
- Simulation settings:** (Buttons: 'Default')

A red circle highlights the value '0.01' in the 'Mission Time' dropdown, and a red arrow points from this circle to the text 'Ignition start time on thrust curve' located below the panel.

Ignition start time on thrust curve



Phase Definition

Rail Phase

The screenshot shows the 'Phase Definition' dialog box with the following settings:

- Description:** (empty)
- Phase span defined by:** Mission Time 2.0 Second
- Additional phase end conditions:** Enabled (highlighted with a red circle and arrow)
- One condition or All conditions must be fulfilled:** One condition or (radio button selected)
- Position** (highlighted with a red box):
 - 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 (Frame: PCPF, Representation: Spherical, Coordinate: Altitude)

"Enabled" for boolean condition to work

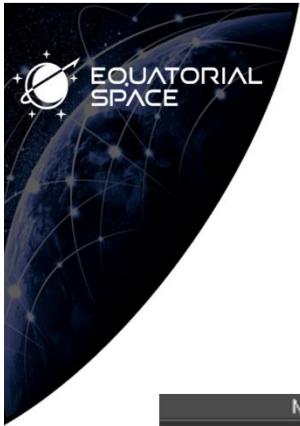
Boolean condition: phase ends when altitude > launch rail height



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

The screenshot shows the 'Modelling' tab selected in the left sidebar. Under 'MAD_H300_ELA', the 'Phases & Common Settings' section is expanded, with 'Thrust' highlighted. In the main panel, the 'Phase span defined by' section is set to 'Mission Time' with a value of '15.77' in 'Second'. A red circle highlights the value '15.77', and a red arrow points from it to the text 'End time on thrust curve' located below the panel.

Description:

Phase span defined by: Mission Time 15.77 Second

Additional phase end conditions: Disabled

Simulation settings: Default

End 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



Phase Definition

Coast Phase

The screenshot shows the 'Phase Definition' dialog box in a software application. On the left, a navigation tree under 'Modelling' includes sections like 'MAD_H300_ELA', 'Environment', 'Vehicle Parts & Properties', 'Vehicles & POIs Definition', 'Dynamics Configuration' (with 'Phases & Common Settings' expanded to show 'Ignition', 'Rail', 'Thrust', 'Coast' (selected), 'Coast_Above30km'), and 'Vehicles & POIs Dynamics' (with 'MAD_H300' selected). The main panel shows the configuration for the 'Coast' phase. The 'Description' field is empty. The 'Phase span defined by' section uses 'Mission Time' at 200.0 seconds. The 'Additional phase end conditions' section has 'Enabled' checked and 'One condition or' selected. A red box highlights the 'Position' section, which contains fields for 'Is active' (Enabled), 'Vehicle ID' (MAD_H300), 'Phase ends if' (value equal or greater than reference, Reference: 30.0 Kilo-Meter), and 'Constraint applies to' (Default configurations, Frame: PCPF, Representation: Spherical, Coordinate: Altitude). A red annotation text 'Boolean condition: phase ends when altitude > 30 km' is placed next to the 'Reference' field.

Description:

Phase span defined by: Mission Time 200.0 Second

Additional phase end conditions: Enabled

One condition or All conditions must be fulfilled

Position

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

Analyses

Variables

Optimization

Results

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: Polar

Representation frame: L

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

The screenshot shows the software's interface for defining trajectory parameters. The left sidebar lists various vehicle configurations and dynamics settings. The main window displays the 'Default Settings' tab, which includes sections for Environment, Maneuver at beginning of phase, and Gravitational perturbation. A red box highlights the 'Aerodynamics configuration' dropdown, which is set to 'MAD_H300_JetOn'. Other dropdowns in the environment section include 'Central body: Earth', 'Atmosphere: e_atmosphere', 'Wind: Wind', and 'Hydrosphere: - None -'. The 'Maneuver at beginning of phase' section has 'Impulse:' and 'Spin impulse:' both set to 'Disabled'. The 'Gravitational perturbation' section contains a table with columns 'Select' and 'ID', currently empty.

Default aerodynamics model: No base drag



Trajectory Parameters

Default Settings

The screenshot shows the 'Default Settings' tab of a trajectory planning application. The interface is dark-themed with light-colored text and buttons. At the top, there are several tabs: 'Initial State', 'Default Settings' (which is selected and highlighted in blue), 'Ignition', 'Rail', 'Thrust', 'Coast', and 'Coast_Above30km'. Below the tabs, there are several configuration sections:

- Celestial bodies:** A dropdown menu.
- Formulation:** Set to 'General Relativity'.
- Solar radiation pressure:** Set to 'Disabled'.
- Solar radiation torque:** Set to 'Disabled'.
- Gravity gradient:** Set to 'Disabled'.

At the bottom of the settings area, there is a section with two main parts, both of which are enclosed in a red rectangular box:

- Equations of motion:** Set to 'Defined by: Inertial Velocity'.
- Attitude:** Set to 'Defined by: Euler Angles'.

Next to the attitude section are two dropdown menus: 'Control/State: State' and 'Coordinate frame: 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: Custom

Structure and consumables: Combined

Combined:

Center of mass:

X Offset

Defined by: Profile

Profile X_Offset:

Interpolation type: Linear

Out of bounds action: Nearest Value

Ordinate data scale: Linear to Linear

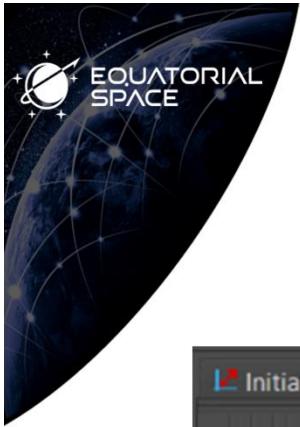
Scaling factor: 1.0

Data source: Local

Preview

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

Default CoM



Trajectory Parameters

Default Settings

The screenshot shows the 'Default Settings' tab selected in a software interface. The top bar includes tabs for 'Initial State', 'Default Settings' (which is active), 'Ignition', 'Rail', 'Thrust', 'Coast', and 'Coast_Above30km'. Below the tabs, the 'Gain' is set to 'Disabled'. The main area is titled 'YY' and shows settings for a profile. It includes fields for 'Defined by' (set to 'Profile'), 'Interpolation type' (set to 'Linear'), 'Out of bounds action' (set to 'Nearest Value'), 'Ordinate data scale' (set to 'Linear to Linear'), 'Scaling factor' (set to '1.0'), and 'Data source' (set to 'Local'). A preview section shows a graph with two points. A data table below is highlighted with a red box:

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

Default Mol (YY) (Same for ZZ)



Trajectory Parameters

Default Settings

The screenshot shows a software interface for trajectory parameters. At the top, there is a toolbar with several icons: Initial State, Default Settings (which is selected), Ignition, Rail, Thrust, Coast, and Coast_Above30km. Below the toolbar, the main panel displays 'Moments of inertia: XX'. Under this heading, there are settings for 'Defined by' (Profile), 'Profile XX' (Interpolation type: Linear, Out of bounds action: Nearest Value), 'Ordinate data scale' (Linear to Linear, Scaling factor: 1.0), and 'Data source' (Local). A preview section shows a graph with two data points. Below the preview is a table titled 'Default Mol (XX)' with the following data:

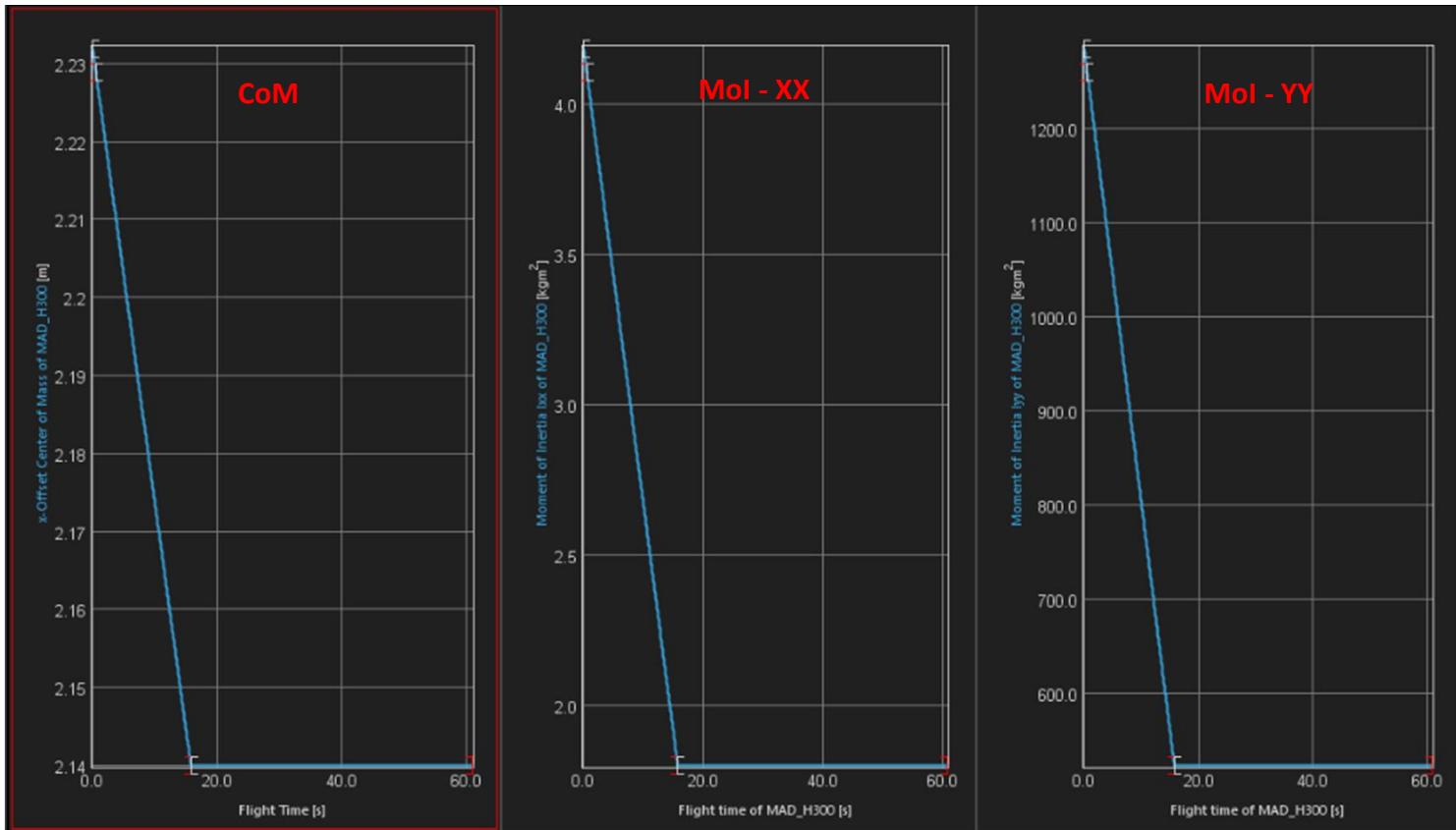
Name	Time	Data
Unit	Second	Kilogram*Meter**2
1	0.0	4.1845
2	15.77	1.8019

Default Mol (XX)



Trajectory Parameters

Default Settings



Verification of default settings



Trajectory Parameters

Dynamics - Ignition

The screenshot shows the software's navigation bar at the top with tabs: Initial State, Default Settings, Ignition (selected), Rail, Thrust, Coast, and Coast_Above30km. On the left, a tree view of the project structure includes Modelling, Aerothermodynamics, Components, Sensors & Transmitters, Power, Data, Thermal, Vehicles & POIs Definition, and Dynamics Configuration. Under Dynamics Configuration, Phases & Common Settings and Vehicles & POIs Dynamics are expanded, with MAD_H300 selected. The main panel displays various configuration options for the Ignition phase. Two sections are highlighted with red boxes:

- Equations of motion:** A radio button group where "Default" is selected. To its right are three radio buttons: "As Previous Phase", "Individual", and another "Individual".
- Active actuators:** A table with two columns: "Select" and "ID". It contains one row with a checked checkbox next to "MAD_Engine" and the ID "[1/1]".

A red box also highlights the "Active motor" label to the right of the "Active actuators" table.

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

Below the active actuators table, there is another table for "Jettisoned assemblies at end of phase" with columns "Select" and "Assembly ID". It lists "Nosecone" and "S_1" with checkboxes.

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

Active motor



Trajectory Parameters

Dynamics - Ignition

The screenshot shows the 'Dynamics - Ignition' configuration screen. At the top, there are several tabs: Initial State, Default Settings, Ignition (which is selected), Rail, Thrust, Coast, and Coast_Above30km. Below the tabs, there are three disabled options: Solar radiation pressure, Solar radiation torque, and Gravity gradient. The 'Equations of motion' section is highlighted with a red box. It shows 'Defined by: Launch Pad'. The 'Attitude' section is also highlighted with a red box. It shows 'Defined by: Euler Angles', 'Control/State: Control', 'Coordinate frame: L', and 'Yaw angle: 225.0 Degree'. There is a checkbox for 'Use (final) value from previous phase (0.0 in case of the first phase)'. The 'Pitch angle' section shows 'Control law: Constant Law', 'Pitch: 85.0 Degree', and the same checkbox.

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

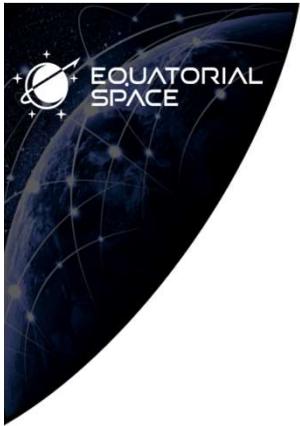
Use (final) value from previous phase (0.0 in case of the first phase).

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:	<table border="1"><thead><tr><th>Select</th><th>ID</th></tr></thead><tbody><tr><td><input checked="" type="checkbox"/></td><td>MAD_Engine</td></tr></tbody></table>	Select	ID	<input checked="" type="checkbox"/>	MAD_Engine	[1/1]
Select	ID					
<input checked="" type="checkbox"/>	MAD_Engine					

Jettisoned assemblies at end of phase:

Select	Assembly ID
<input type="checkbox"/>	Nosecone
<input type="checkbox"/>	S_I

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

Altitude:

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):

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

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:	<table border="1"><thead><tr><th>Select</th><th>ID</th></tr></thead><tbody><tr><td><input checked="" type="checkbox"/></td><td>MAD_Engine</td></tr></tbody></table>	Select	ID	<input checked="" type="checkbox"/>	MAD_Engine	[1/1]
Select	ID					
<input checked="" type="checkbox"/>	MAD_Engine					

Jettisoned assemblies at end of phase:

Select	Assembly ID
<input type="checkbox"/>	Nosecone
<input type="checkbox"/>	S_I

Active motor



Trajectory Parameters

Dynamics - Thrust

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 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_JetOn

Aerothermodynamics configuration: Dorado_thermo

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

Active motor

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



Trajectory Parameters

Dynamics - Coast

The screenshot shows the 'Dynamics - Coast' configuration screen. At the top, there are several tabs: Initial State, Default Settings, Ignition, Rail, Thrust, Coast, and Coast_Above30km. The Coast tab is active.

The main area contains several configuration options with radio button groups:

- Aerodynamics configuration: Default, As Previous Phase, Individual (Individual is selected)
- Aerothermodynamics configuration: Default, As Previous Phase, Individual (Individual is selected)
- Maneuver at Beginning of Phase: Default, As Previous Phase, Individual (Individual is selected)
- Environment: Default, As Previous Phase, Individual (Individual is selected)
- Equations of motion: Default, As Previous Phase, Individual (Individual is selected)
- Attitude: Default, As Previous Phase, Individual (Individual is selected)
- Magnetic moment: Default, As Previous Phase, Individual (Individual is selected)
- Mass Distribution: Default, As Previous Phase, Individual (Individual is selected)
- Flexible dynamics: Default, As Previous Phase, Individual (Individual is selected)

Below these, there are two dropdown menus:

- Aerodynamics configuration: MAD_H300_JetOff_0km
- Aerothermodynamics configuration: Dotato_thermo

The 'Active actuators' section is highlighted with a red box. It contains a table:

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

The 'Jettisoned assemblies at end of phase' section contains another table:

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

Full base drag – 0 km altitude

Inactive motor



Trajectory Parameters

Dynamics – 2nd Coast Phase

The screenshot shows the 'Dynamics – 2nd Coast Phase' configuration screen. At the top, there are tabs for Initial State, Default Settings, Ignition, Rail, Thrust, Coast, and Coast_Above30km. The Coast tab is selected.

The main area contains several configuration options with radio button groups:

- Aerodynamics configuration: Default, As Previous Phase, Individual (Individual is selected)
- Aerothermodynamics configuration: Default, As Previous Phase, Individual (Default is selected)
- Maneuver at Beginning of Phase: Default, As Previous Phase, Individual (Default is selected)
- Environment: Default, As Previous Phase, Individual (Default is selected)
- Equations of motion: Default, As Previous Phase, Individual (Default is selected)
- Attitude: Default, As Previous Phase, Individual (Default is selected)
- Magnetic moment: Default, As Previous Phase, Individual (Default is selected)
- Mass Distribution: Default, As Previous Phase, Individual (Default is selected)
- Flexible dynamics: Default, As Previous Phase, Individual (Default is selected)

Below these, there is a dropdown for Aerodynamics configuration set to MAD_H300_JetOff_30km. A red arrow points from the 'Individual' label above to this dropdown.

Further down, there is a section for Active actuators with a table:

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

A red box highlights this entire section, and a red arrow points from the 'Inactive motor' label below to the table header.

At the bottom, there is a section for Jettisoned assemblies at end of phase with a table:

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