MISSILE TESTBED

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SYSTEMS ENGINEERING

PROJECT GOALS

Year 2/4

- Design, build and test an educational experimental missile recoverable for:

  Research, testing and demonstrating missile technologies.

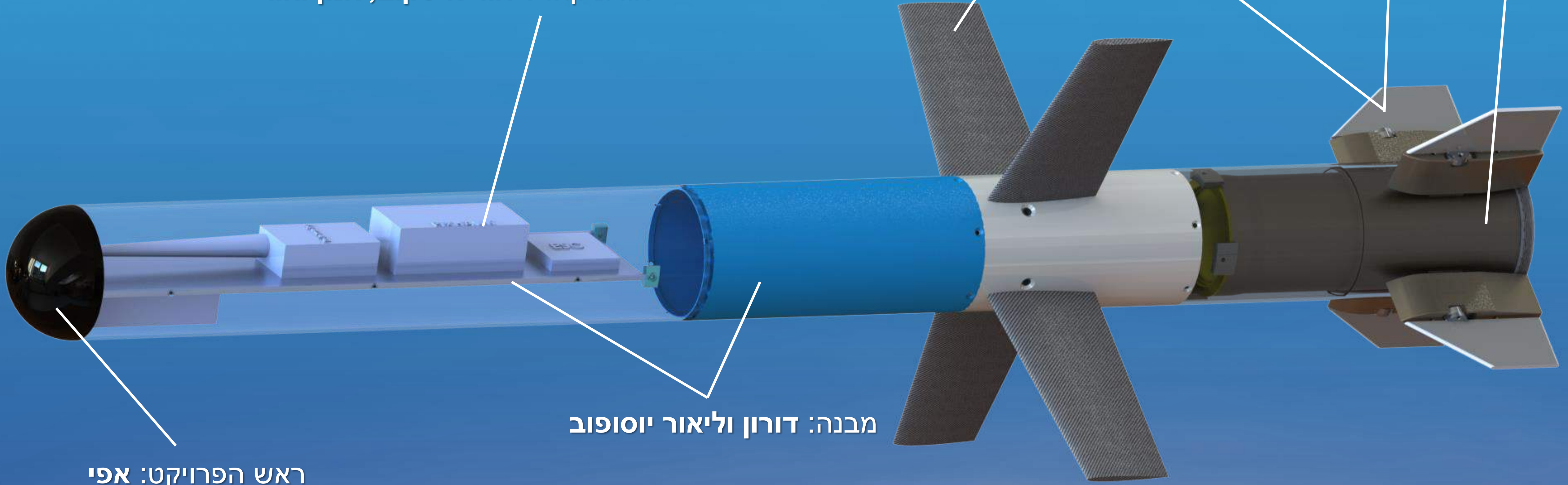
  The project is carried out by cooperation between the Technion and RAFAEL as well as the Technical University of Munich (TUM).

  Mission #1:

  Reach an altitude of $1,500\ [m]$

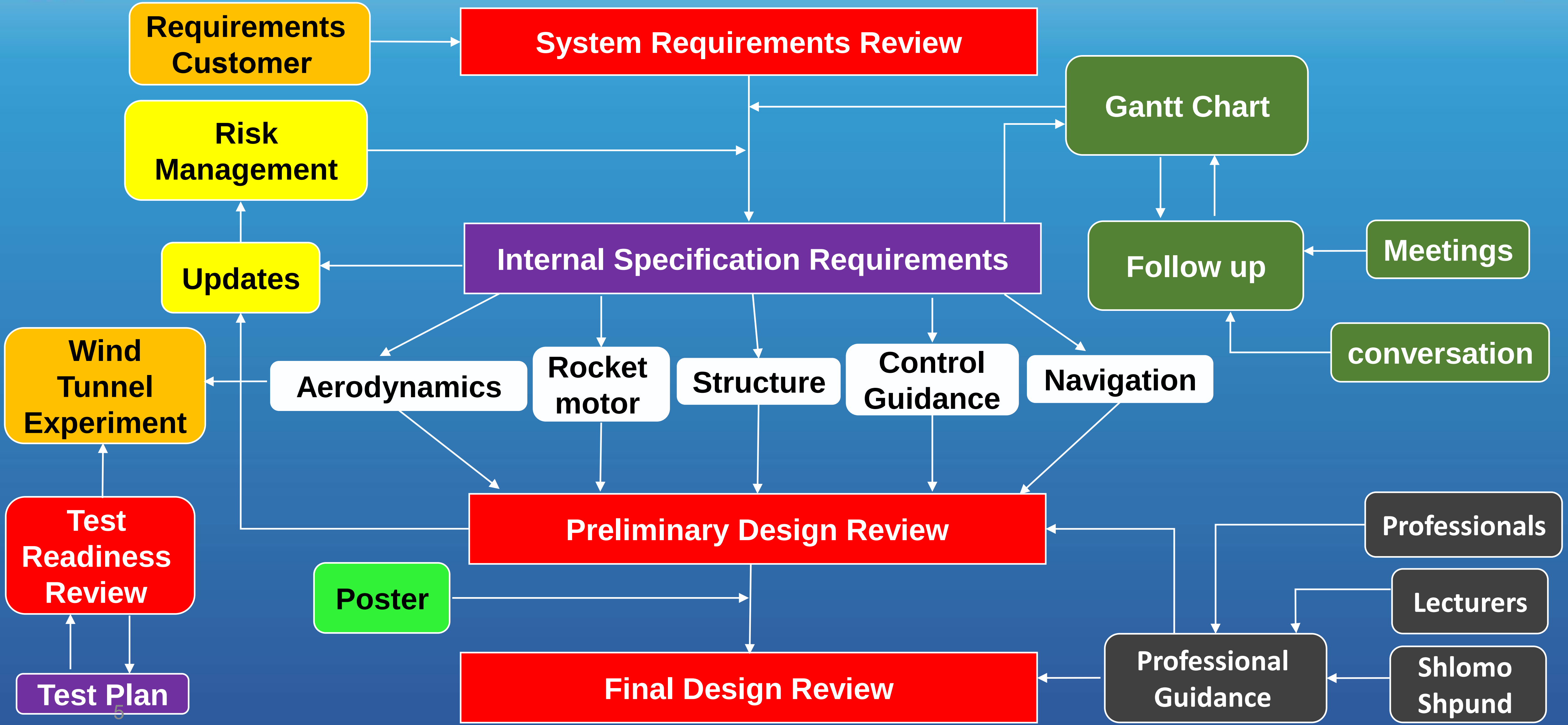
  Mission #2:

  Gliding (optimized for maximum distance)



בקרה: **ליאור איסקוב ואמן**
אווירודינמיקה: **דן ובועז**
הנעה רקטית:
תמיר ודורון
אוויוניקה: **ליאור איסקוב, אמן ואור**
מבנה: **דורון וליאור יוסופוב**
ראש הפרויקט: **אפי**

Project process



Cornetto GANTT CHART

TASK NAME	START DATE	END DATE	DURATION (WORK DAYS)	TEAM MEMBER	PERCENT COMPLETE	WEEK 1 3/17 S	3/18 M	3/19 T	3/20 W	3/21 Th	3/22 F	3/23 S	3/24 S	3/25 M
Aerodynamics														
Updating the aerodynamic model in the simulation, including fin deflection	3/17	3/31	14	דן ובועז יחד עם בקרה	100%									
Preparing MATLAB code for data analysis from the experiment (for 'on-the-spot' testing)	**3/17**	**3/31**	**14**	**דן ובועז**	**100%**									
Testing the model after it was manufactured (by wind tunnel personnel)	**3/20**	**4/20**	**30**	**דן ובועז**	**100%**									
Conducting the wind tunnel experiment and producing the aerodynamic models	**3/20**	**4/20**	**30**	**דן ובועז**	**100%**									
Planning an experiment together with a control team to test the Serve under fin's inertia	**3/20**	**5/20**	60	דן ובועז	100%									
Rocket propulsion														
Design a new engine	3/17	4/14	28	תמיר ודורון	100%									
Engine production and pressure testing	4/14	4/28	14	תמיר ודורון	20%									
Design of engine fixation for the missile's body	3/17	3/31	14	תמיר ודורון	80%									
Control guidanc and navigation														
Aerodynamic model bug fixing in the simulation	3/17	3/31	14	אמן, דן	100%									
Modeling and manufacturing a servo test-device and finding the new servo's transfer function	3/17	4/14	28	ליאור א.	100%									
Finding the fixed delay of the Pixhawk	3/17	4/14	28	ליאור א.	100%									
Model the navigation for the simulation & testing	3/17	4/7	21	אור	95%									
Integrating the Pixhawk model (block diagram)	4/7	6/2	56	אור	80%									
Configurations update for simulation after tunnel experiment (aerodynamic coefficients)	6/2	6/23	21	ליאור א. אמן	100%									
Combining the model of cabling in the simulation + validation	6/2	6/24	22	ליאור א. אמן	50%									
Integration of control to the Pixhawk, based on navigation model and experiment	6/2	6/25	23	ליאור א. אמן	20%									
Structure														
Design of connectors that connect the motor to the missile's body	3/17	3/31	14	יוסופוב	100%									
Finding the center of mass (weight, location)	3/17	3/31	14	תמיר דורון ליאור	80%									
Determine the material for the structure of the missile's body according to the required thickness	3/17	3/31	14	תמיר דורון ליאור	80%									
Determine the thickness of the side walls according to the material chosen	3/17	3/31	14	תמיר דורון ליאור	100%									
Finding the safety factor for the connection between the dome of the building and the body	3/17	3/31	14	תמיר דורון ליאור	50%									
DECISION AND MANUFACTURING AN APPARATUS FOR FIXING THE INTERNAL PARTS-RACING / CYCLING CELL	3/31	4/14	14	תמיר דורון ליאור יוסופוב	100%									

$$PF - Probability\ of\ risk\ (Normalized\ ,\ 1 \le PF \le 10)$$

$$CF - Severity\ of\ risk\ (Normalized\ ,\ 1 \le CF \le 10)$$

$$RF - Factor\ of\ risk$$

$$\boxed{RF = PF \cdot CF}\ \ ;\ \ 1 \le RF \le 100$$

10	20	30	40	50	60	70	80	90	100

Low risk	Mid risk	High risk

Risk Map

CF	10										
	9			2#		22#	6#				
	8			14#		10#					
	7		20#	13#	7#						
	6			21#			24#	25#			#1
	5		15#	8#						#26	11#
	4	16#						19#			
	3	5#				23#	12#	4#		9#	
	2								3#		
	1										
		1	2	3	4	5	6	7	8	9	10
	PF										

Project Risk List	Actions to minimize risk	Risk Map	treatment status
#1 Problems with the simulation	Validation of the simulation (physical handling of the missile)		
#17 Failure to meet the timetables designated for us in favor of tunnel experiments due to design problems and non-readiness of the model.	Start planning the model and requirements for the tests we want to experiment with the tunnel.		Deleted
#18 Failure to meet the timetables designated for us in favor of the tunnel experiments following the printing of the model in the Company	Contact the company and check how long it takes to print a tunnel model.		Deleted
#20 The bandwidth of the servo does not match the requirements.	Examine the old servo and order a new servo if necessary.		New servos were orders (savox) [8 to 2 PF]

FDR – Final Design Review

The Final Design Review is held when most of the design work has been completed.

Final Design Review allows for one last chance to review the design & discuss what is still left to be done before development release to Pilot can be accomplished.

SPRING SEMESTER GOALS

The detailed goals for the semester were decided upon after the PDR and served us as a guide for the specific actions that had to be taken in each field:

Spring semester goals	Compliance
Aerodynamic model update (according to the wind tunnel experiment results).	
Fully working **Simulation** with the possibility of testing sensitivity to different design parameters.	
Full design of the controllers after characterization of the new servo motors.	
Combined navigation model for simulations and the closure of a guiding circle for optimal routes.	
Production of a 1:1 scale model with all the components of the configuration, including the packaging of avionic components – for functional testing.	
Rocket propulsion system - completion of the motor case design, start of motor production and pressure testing in the propulsion laboratory.	

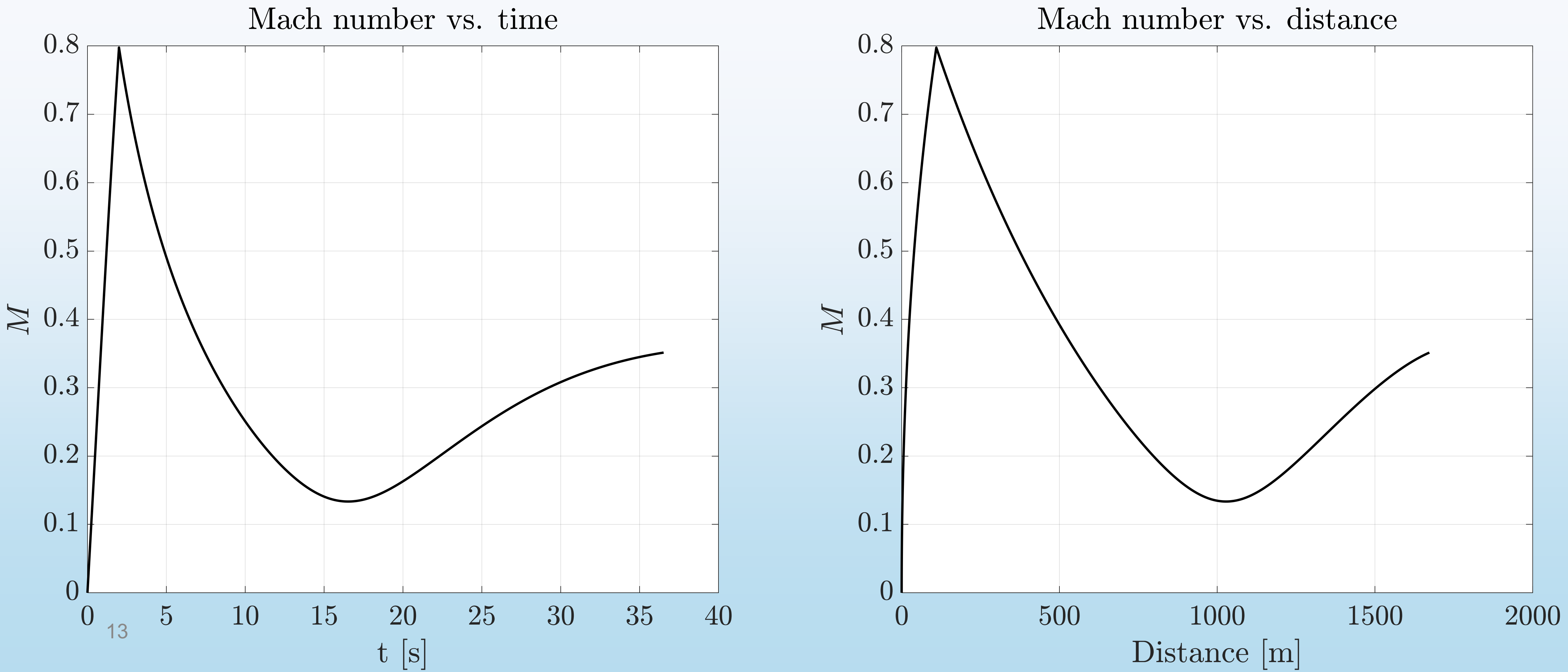
AERODYNAMICS

FLIGHT CONDITIONS

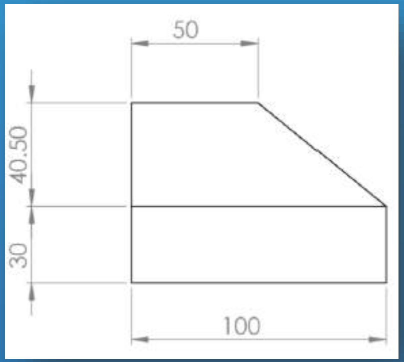
- Assuming **standard atmospheric conditions** (ISA).
- Missile will maneuver at low subsonic speeds $(M < 0.3)$.
- Missile will reach max. speed of $M \approx 0.8$ (right after rocket motor burnout).
- $\overline{R_{e_d}} \approx 3 \times 10^5$ (based on body diameter).

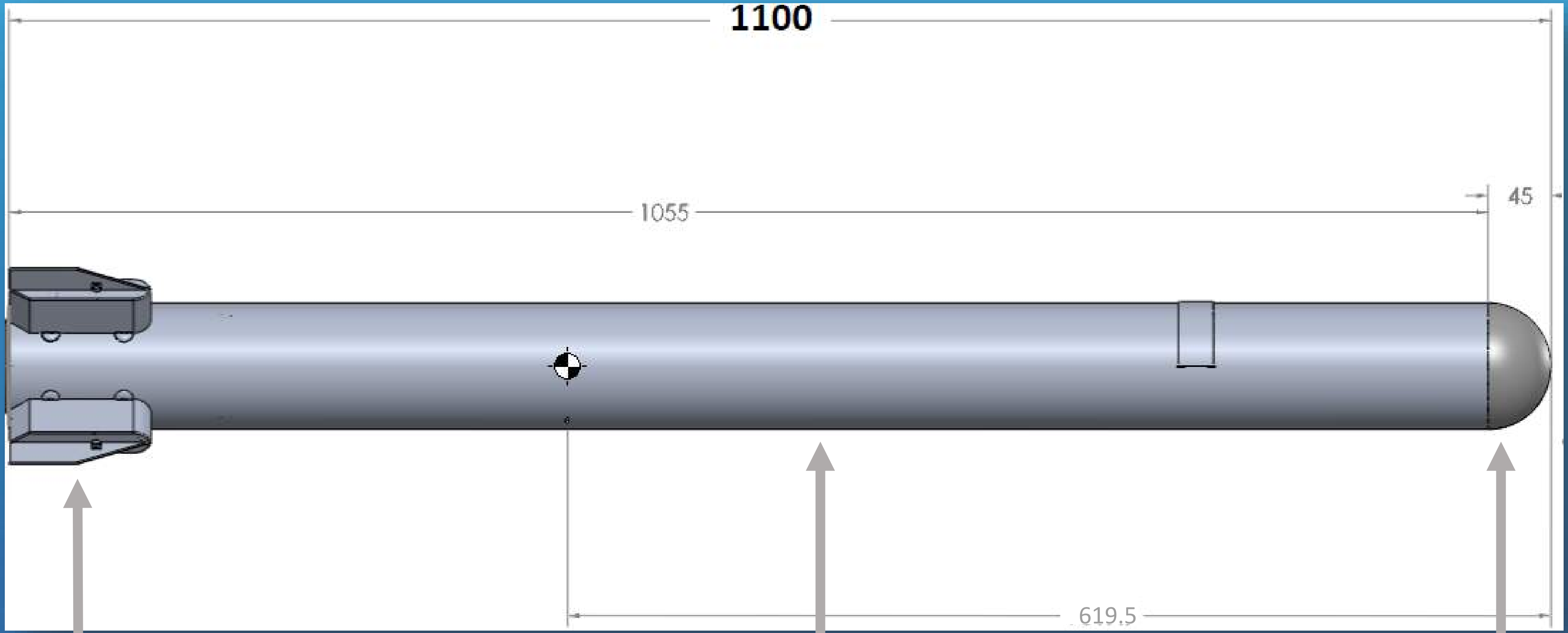
TYPICAL VELOCITY PROFILE

No control



INITIAL DIMENSIONS AND CONFIGURATION





Servo housing
& tail fins

Constant
diameter body
9 $[cm]$

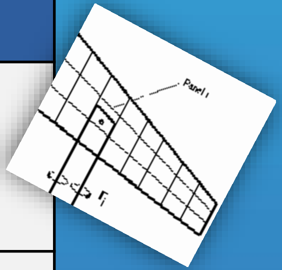
Spherical nose
(for a seeker)

MISSION	MEANS OF ACHIEVING MISSION GOALS
1. **Reach an altitude of 1,500 [m]** with a given propellent (i.e., a rocket engine that can produce around **740 [N]** of thrust for **2 [s]**).	1. Further reduction of the drag on the airframe (using thin surfaces, boat-tailing the back of the servo housing, etc.). C_D ↓ 2. Reducing weight by considering composite materials. $Mass$ ↓ 3. Addition of wings to the airframe. ✓ Wings
2. **Maximize the range** of the missile.	

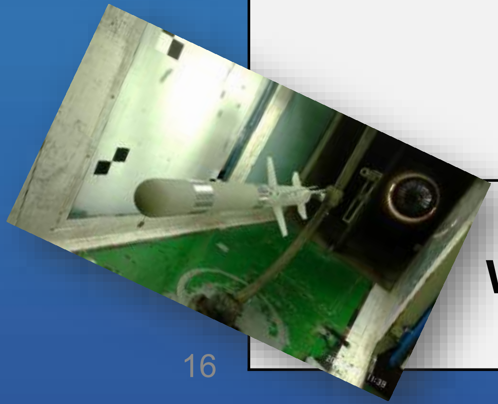
MAIN LIMITATION

IF MISSILE'S MASS EXCEEDS **5.5 [kg]** - IT WOULD NOT REACH THE **1,500 [m]** MARK FOR THE GIVEN MOTOR.

COMPUTATIONAL FOUNDATION

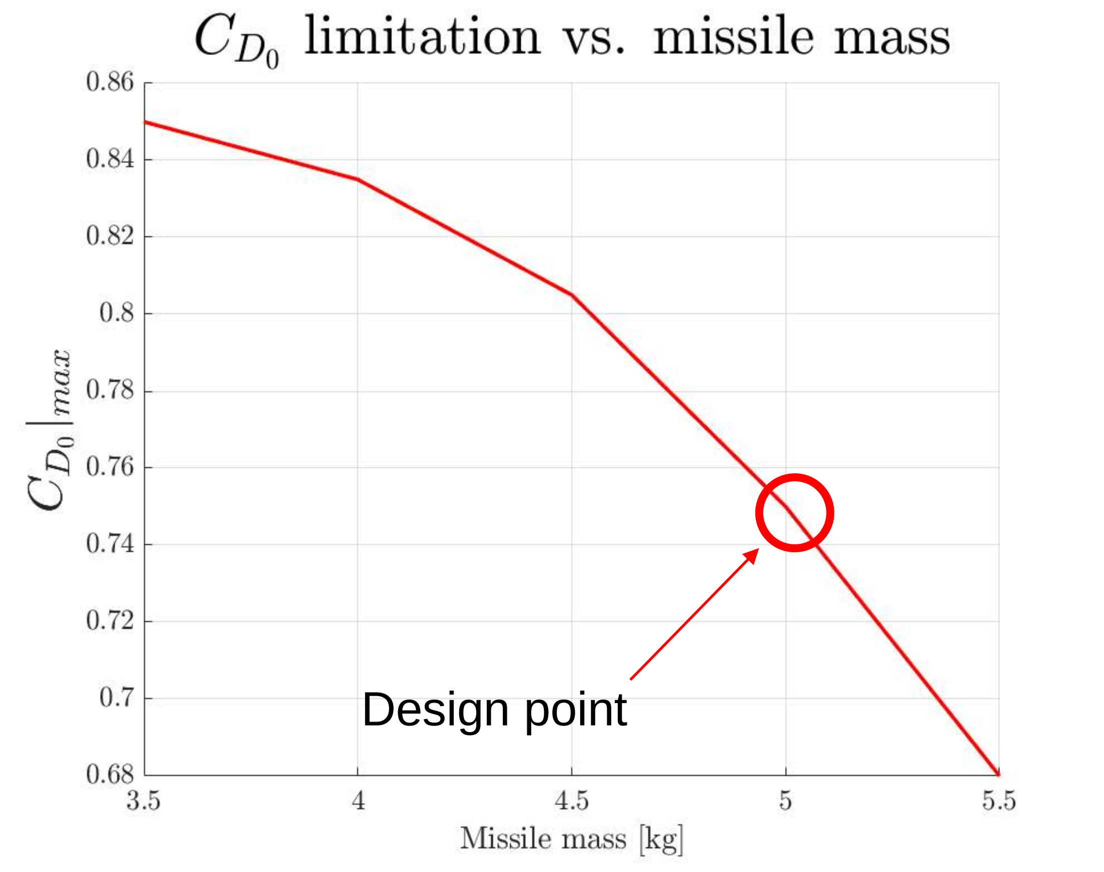


Method	Description
VLM (Vortex Lattice Method)	Used for estimating lifting surfaces, lift coefficients and center of pressure.
Component Build-up Method 'Nielsen's method'	Used for estimating aerodynamic performance of the entire missile.
Missile Datcom	Semi-empirical datasheet & complex component build-up program for a more in –depth analysis of various configurations (mainly for complimentary aerodynamic model coefficients).
Wind tunnel experiment	Used for validating the aerodynamic model derived from the theoretical analysis.



DRAG LIMITATIONS

First, using the simulation we can estimate the envelope of drag coefficient vs. missile mass for achieving the desired altitude*:



*Launching at θ_0=75°, altitude is ~1,560 [m] for ensuring reaching the required mark of 1,500 [m].

DRAG REDUCTION

Option	Feasibility	Comments
Nose shape shape drag reduction ogive / cone shapes instead of spherical		The payload which is located inside the nose has certain dimensions that require the shape to remain spherical.
Body boat-tail for base drag reduction		The rocket motor & cabling from the back are preventing the narrowing of the body.
Servo housing profile shape drag reduction Elongated leading edge, boat-tailed trailing edge, thinner profile		New (thinner) servos require re-design the servo housing. This gives us a chance to reduce their shape drag.
Wings Both parasitic & induced drag Thin airfoils, high aspect ratio		Wings are an added feature; we design them from scratch

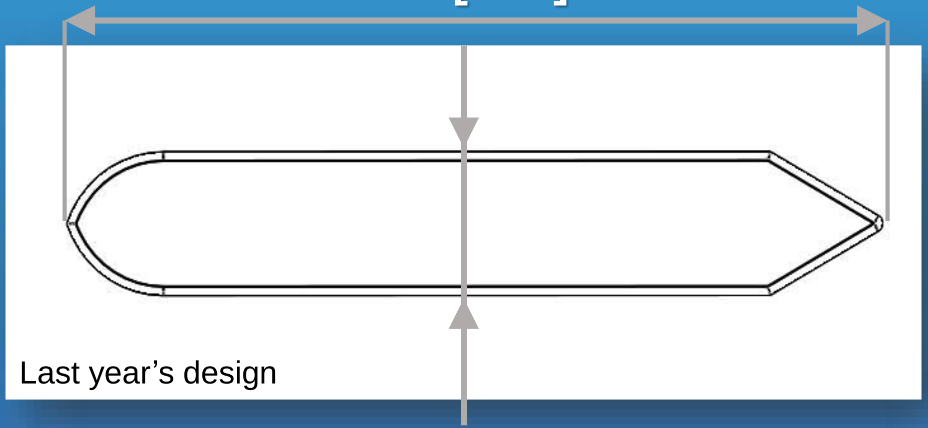
SERVO HOUSING COMPARISON

*Drag estimates are from Missile Datcom
Servo housings were modeled as block perturbances.

Boat-tail for reducing drag and preventing flow separation along rear of the housing

Larger l/d

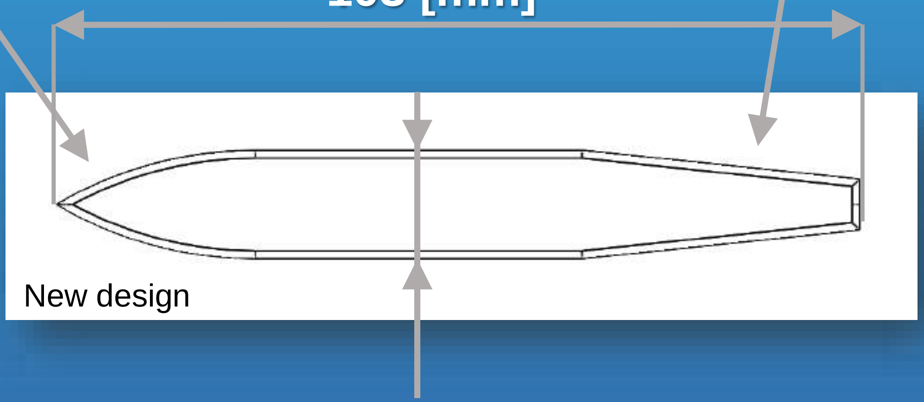
100 [mm]



Width: 21 [mm]

$$C_{D0}\Big|_{entire\ missile} = 0.671$$

103 [mm]



Width: 14 [mm]

$$C_{D0}\Big|_{entire\ missile} = 0.600$$

$$\Delta C_{D_0} = 10.6\%$$

WING DESIGN

This year, we added wings to the configuration.

The wing design includes:

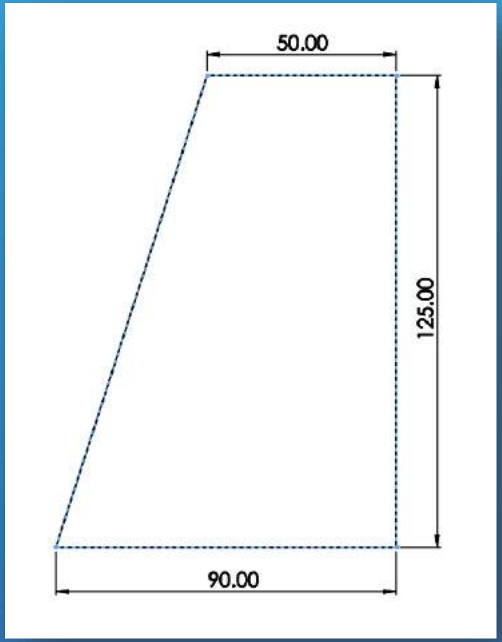
- Airfoil selection
- Wing positioning
- Planform geometry:
  - Span, b
  - Root chord, C_{root}
  - Taper ratio, λ

WING DESIGN

After analyzing different dimensions, we converged to **2 wing designs** that we wished to test in the wind tunnel:

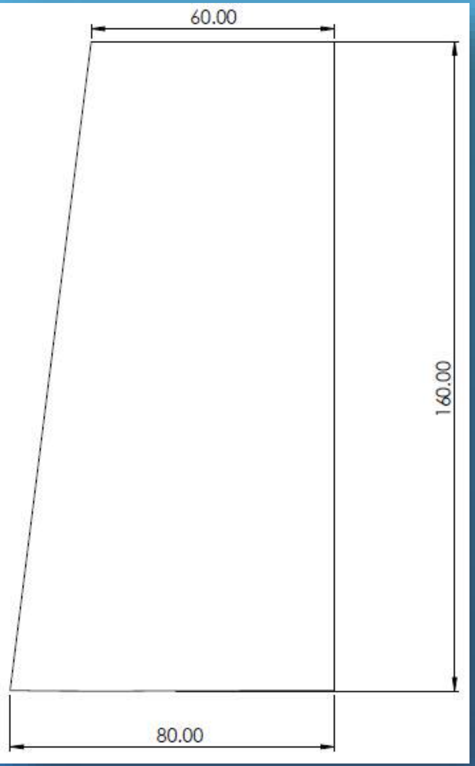
1) **Increasing L/D to at least 3**, while **minimizing the parasitic drag** coefficient.
2) **Maximizing L/D** while **keeping the parasitic drag coefficient within the envelope**.

WING DESIGN



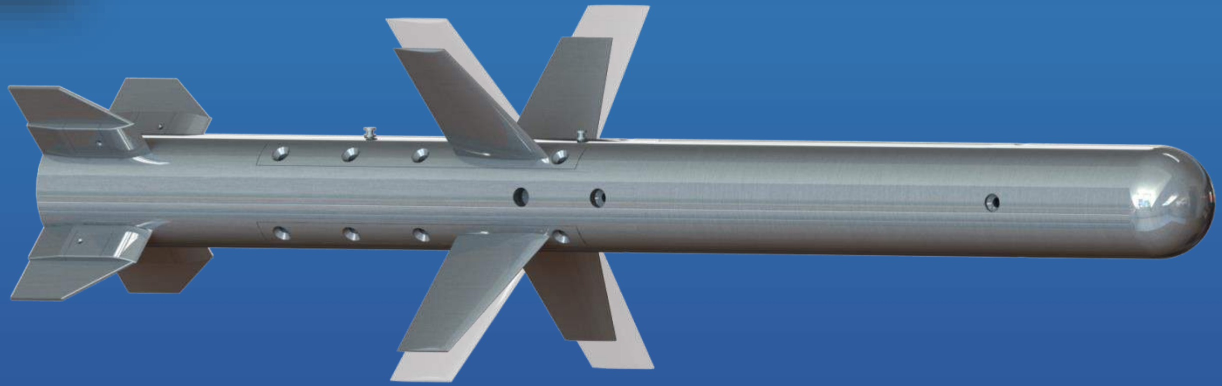
$C_{D_0} = 7.16$ $\quad \frac{L}{D}\Big|_{\alpha=7°} = 3.035$

$AR = 4.5$



$C_{D_0} = 7.49$ $\quad \frac{L}{D}\Big|_{\alpha=7°} = 3.690$

$AR = 5.5$

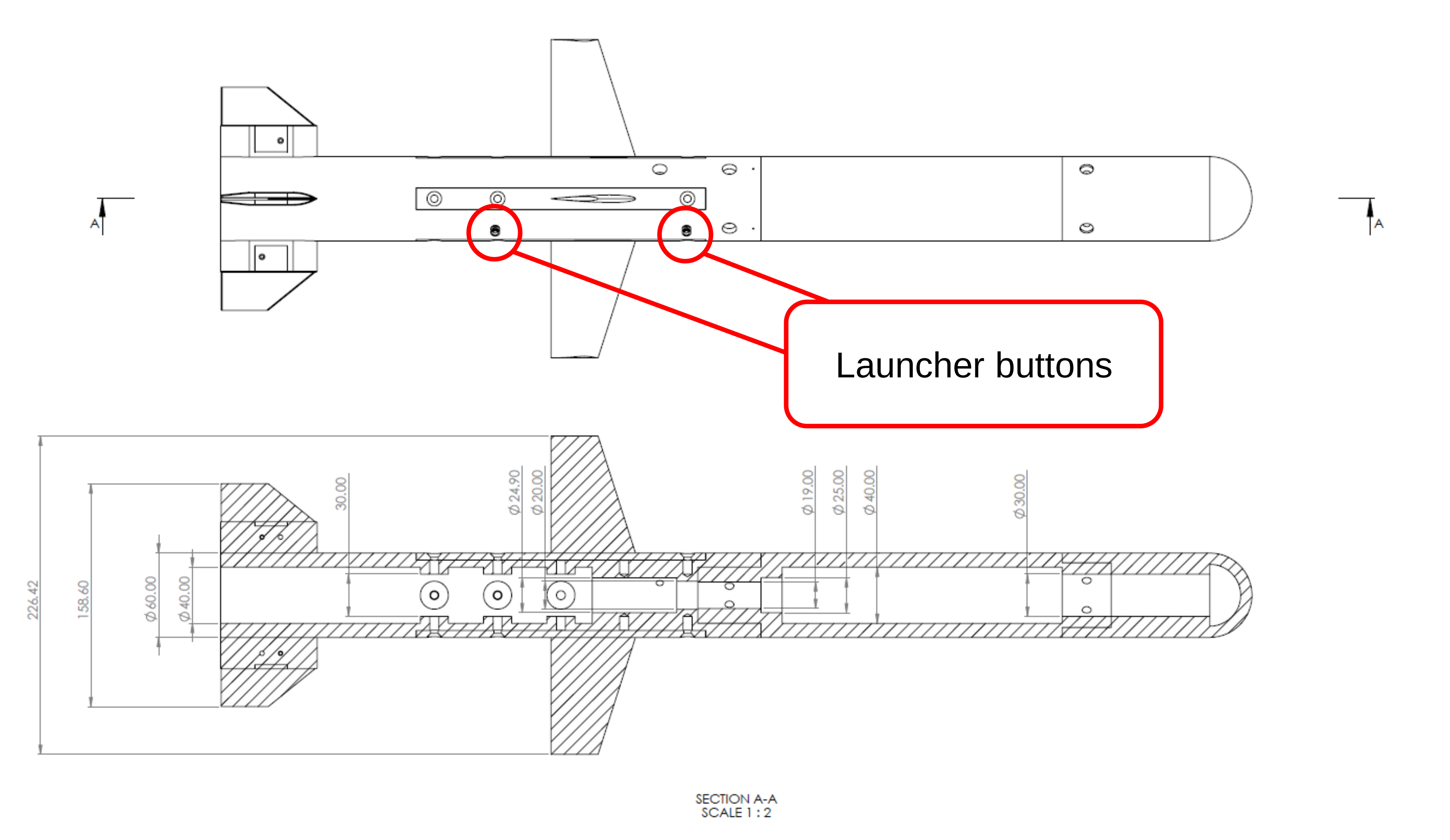


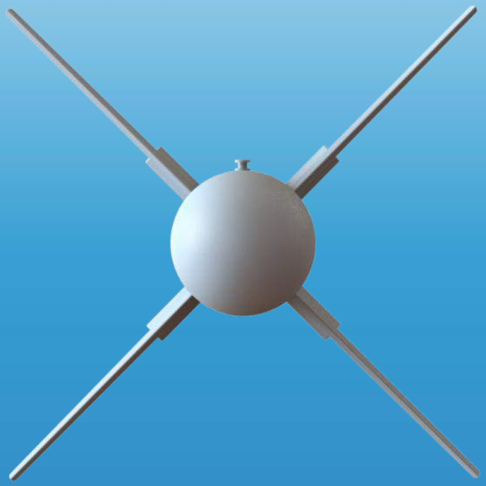
WIND TUNNEL EXPERIMENT

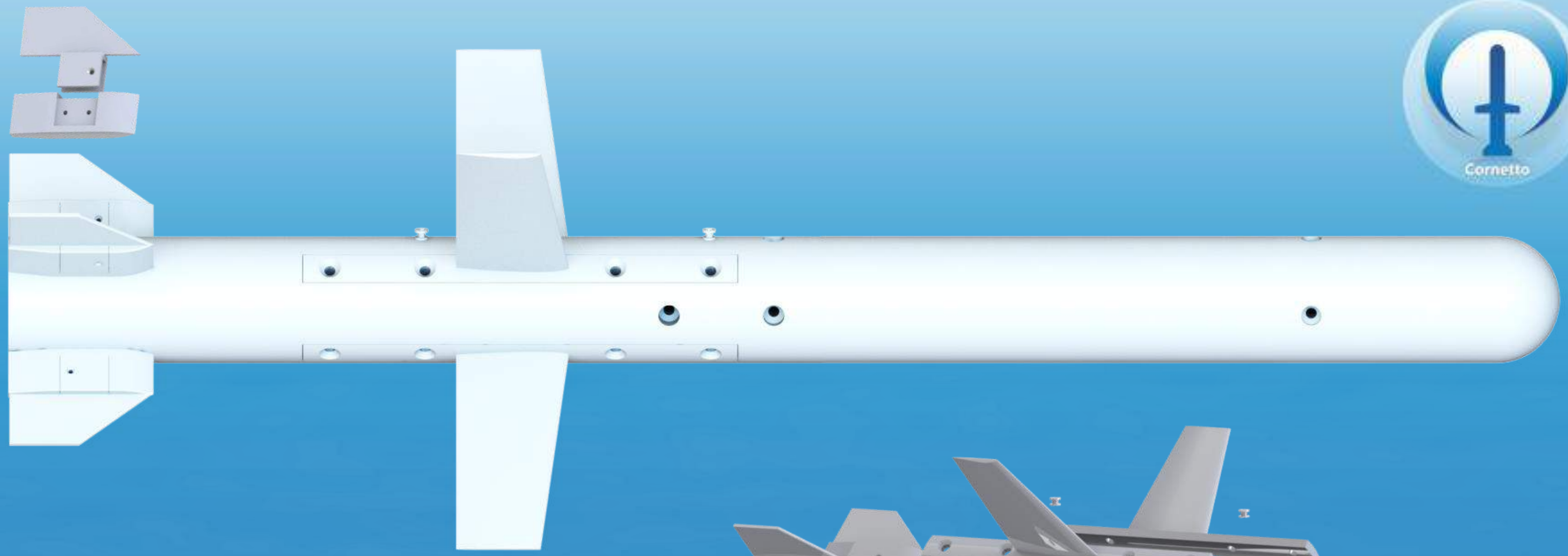
Experiment purposes:

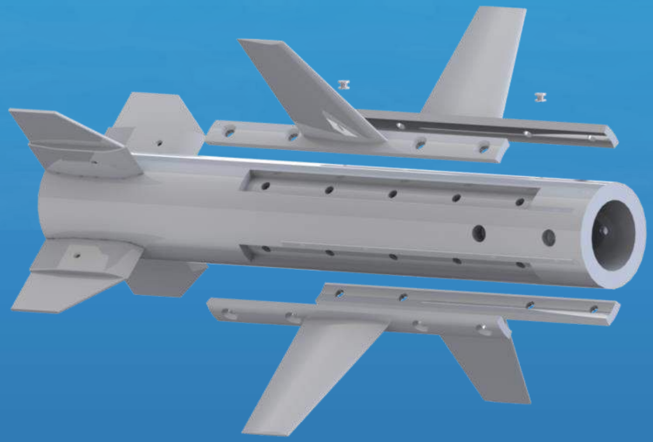
1. Find the actual **differences in drag** between this year's design and last year's design.
2. Find the **effects of wing location** on the aerodynamics.
3. **Validation** of the design concepts.
4. **Map** the new configurations based on real-time analysis at the tunnel (control surfaces deflection, symmetry checks).

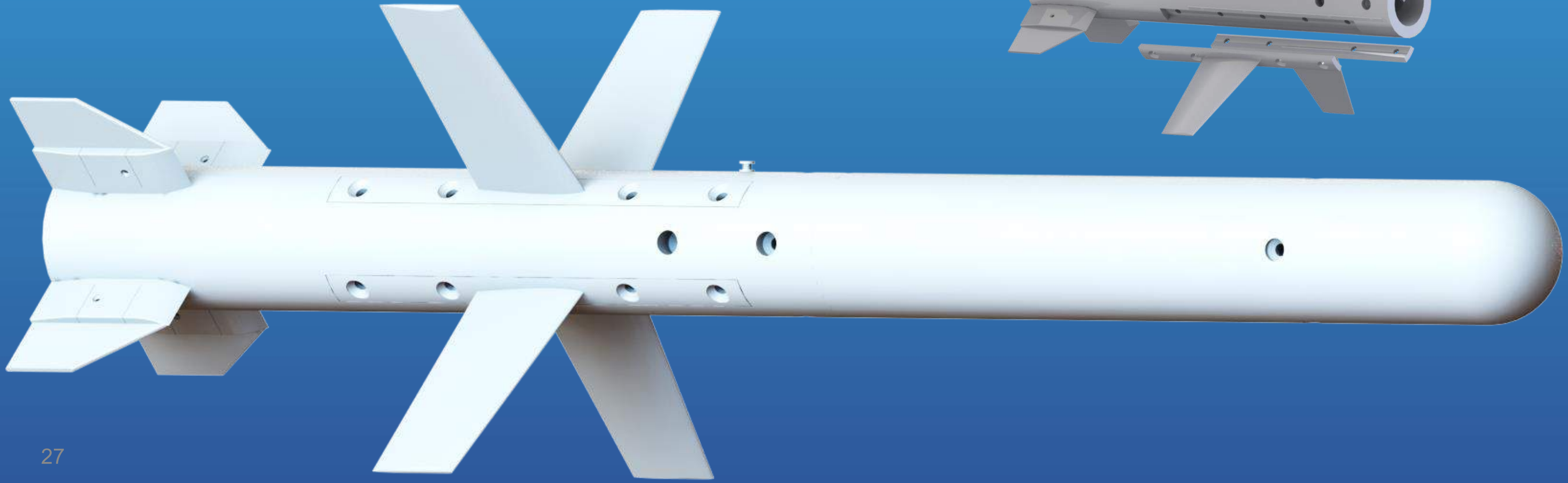
WIND TUNNEL MODEL











TEST PROGRAM

Project Cornetto

Wind tunnel test program

ALL EXPERIMENTS SHALL BE CONDUCTED AT 70 [m/s] UNLESS OTHERWISE SPECIFIED

l_ref = 0.06 [m] ; S_ref = 2.827E-3 [m^2] ; x_ref = 0.413 [m]

Experiment Number	Model setting	Control surfaces deflection				Angle(s) of Attack [deg]	Notes
		Delta 1	Delta 2	Delta 3	Delta 4		
1	*NO WINGS*	0	0	0	0	-10 → 20	Comparison to last year's results & mapping Experiments in orange shall be conducted in the event of unmatched resutls
2	*NO WINGS*	-5	5	5	-5	-10 → 20	
3	*NO WINGS*	5	5	5	5	-10 → 20	
5	*NO WINGS*	0	0	0	0	-10 → 20	Reynolds effect test ; *V = 50 [m/s]*
6	*NO WINGS*	0	0	0	0	-10 → 20	Reynolds effect test ; *V = 90 [m/s]*
7	*NO WINGS*	0	0	0	0	-10 → 20	Reynolds effect test ; Variable velocity
8	*NO WINGS*	-10	10	10	-10	-10 → 20	Reynolds effect test ; Variable velocity ; *Including control surfaces deflection*
9	*NO WINGS*	-10	10	10	-10	-10 → 20	Mapping
10	*NO WINGS*	10	10	10	10	-10 → 20	
11	*NO WINGS*	-15	15	15	-15	-10 → 20	
12	*NO WINGS*	15	15	15	15	-10 → 20	
13	*AFT SHORT WING*	0	0	0	0	-10 → 20	Reynolds effect test ; *V = 50 [m/s]*
14	*AFT SHORT WING*	0	0	0	0	-10 → 20	Reynolds effect test ; *V = 90 [m/s]*
15	*AFT SHORT WING*	0	0	0	0	-10 → 20	Checking moment derivative with alpha, L/D & Drag
16	*FWD SHORT WING*	0	0	0	0	-10 → 20	
17	*MID SHORT WING*	0	0	0	0	-10 → 20	
18	*AFT LONG WING*	0	0	0	0	-10 → 15	Checking moment derivative with alpha, L/D & Drag
19	*FWD LONG WING*	0	0	0	0	-10 → 15	
20	*MID LONG WING*	0	0	0	0	-10 → 15	
21	*TBD - Short Wing*	0	0	0	0	-10 → 20	Symmetry Check ; phi = 90 [deg]
22	*TBD - Short Wing*	5	5	5	5	-10 → 20	Mapping
23	*TBD - Short Wing*	-5	5	5	-5	-10 → 20	
24	*TBD - Short Wing*	10	10	10	10	-10 → 20	
25	*TBD - Short Wing*	-10	10	10	-10	-10 → 20	
26	*TBD - Short Wing*	15	15	15	15	-10 → 20	
27	*TBD - Short Wing*	-15	15	15	-15	-10 → 20	
28	*TBD - Long Wing*	0	0	0	0	-10 → 15	Symmetry Check ; phi = 90 [deg]
29	*TBD - Long Wing*	5	5	5	5	-10 → 15	Mapping
30	*TBD - Long Wing*	-5	5	5	-5	-10 → 15	
31	*TBD - Long Wing*	10	10	10	10	-10 → 15	
32	*TBD - Long Wing*	-10	10	10	-10	-10 → 15	
33	*TBD - Long Wing*	15	15	15	15	-10 → 15	
34	*TBD - Long Wing*	-15	15	15	-15	-10 → 15	

AERODYNAMIC CONSIDERATIONS

In choosing which wing configuration to fully map

For each wing location, we considered the following:

- Lowest drag coefficient.
- Highest $L/_D$.
- Must be stable at most aft CG location.

TEST CONDITIONS & SETUP

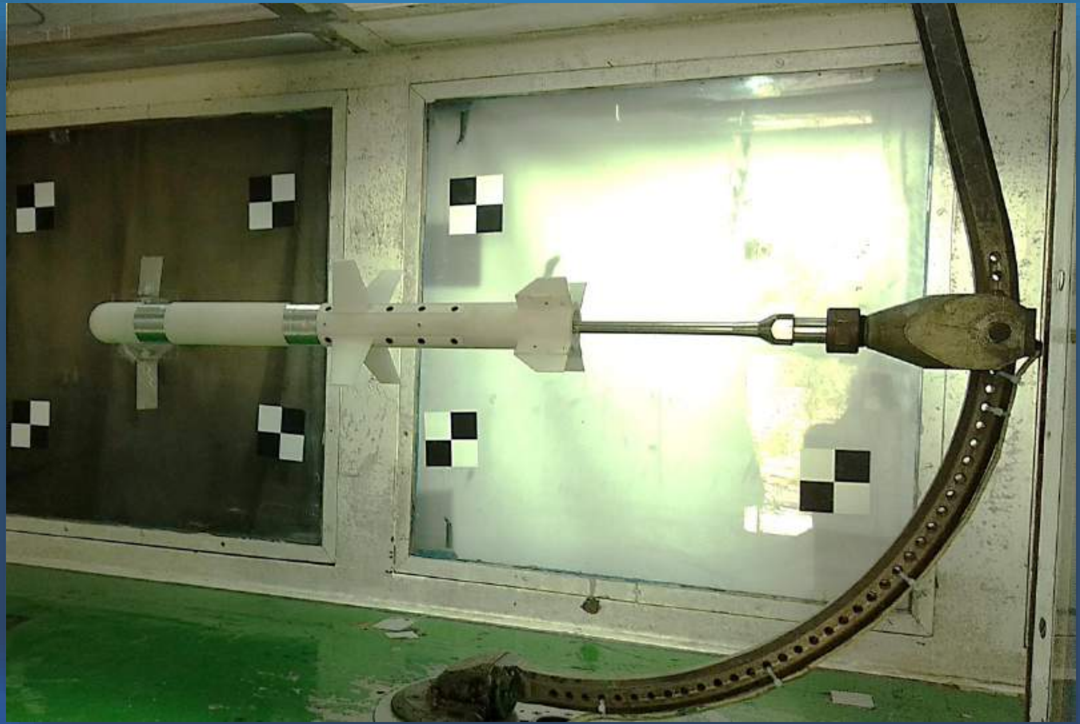
Parameter	Value
Air stream velocity	70 [m/s]
Angle of Attack range	-10° → 15°
Orientation	'X'
Mach number	0.2
Reynolds number (based on body diameter)	290,000
Balance center location	53.3 [cm]*
Moments reference location	41.3 [cm]*
Distance from the base to the end of the balance	24.8 [cm] or 4.13d

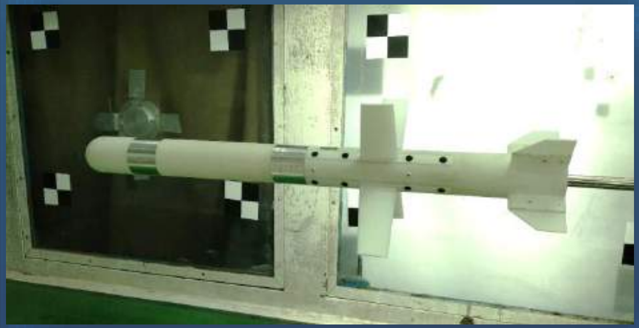
*Distances measured from the nose of the missile. In order to easily compare the results to last year's experiments, we took the same reference location and lengths for forces and moments.

DAY OF THE EXPERIMENT



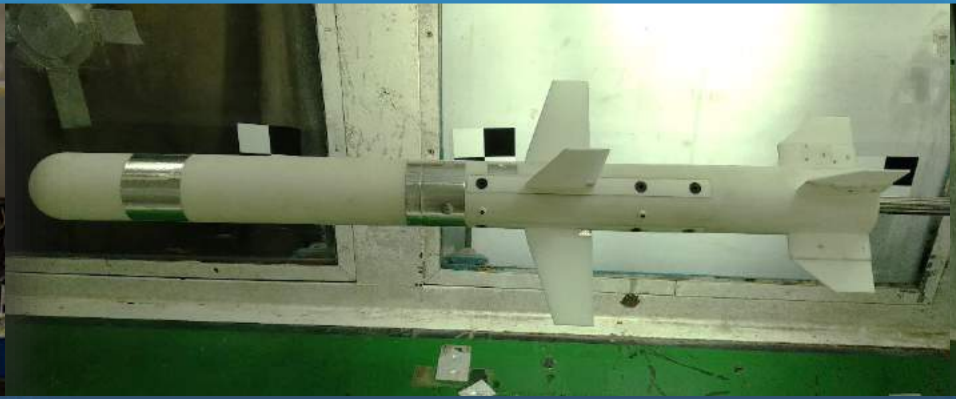


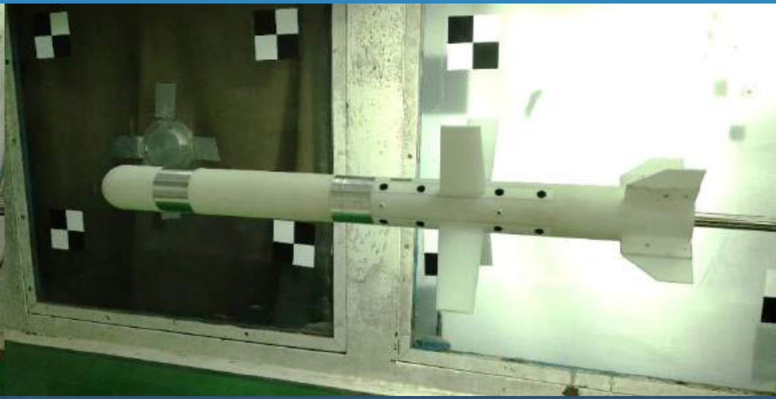




EXPERIMENT RESULTS

CONFIGURATIONS THAT WE HAVE TESTED





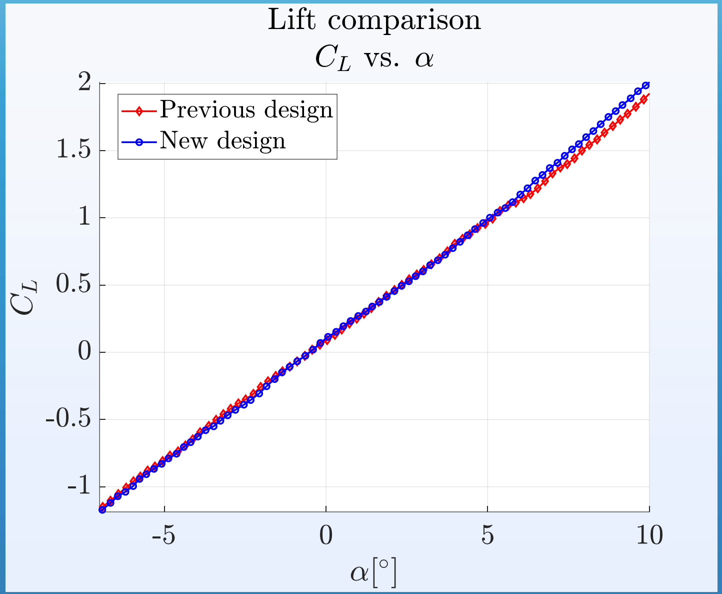
Body-Tail

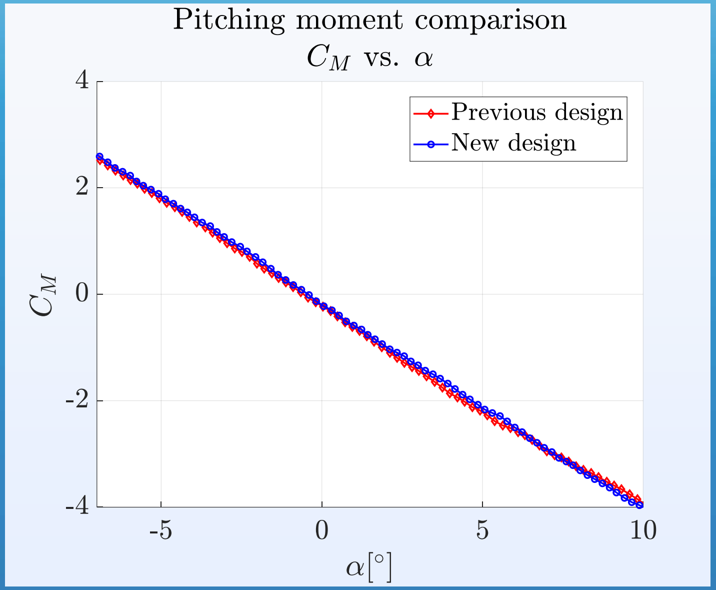
Short Wing-Body-Tail

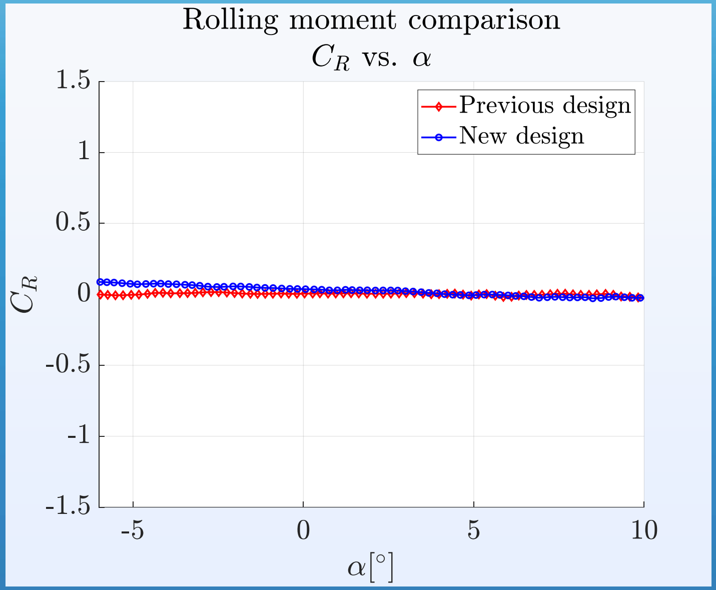
Long Wing-Body-Tail

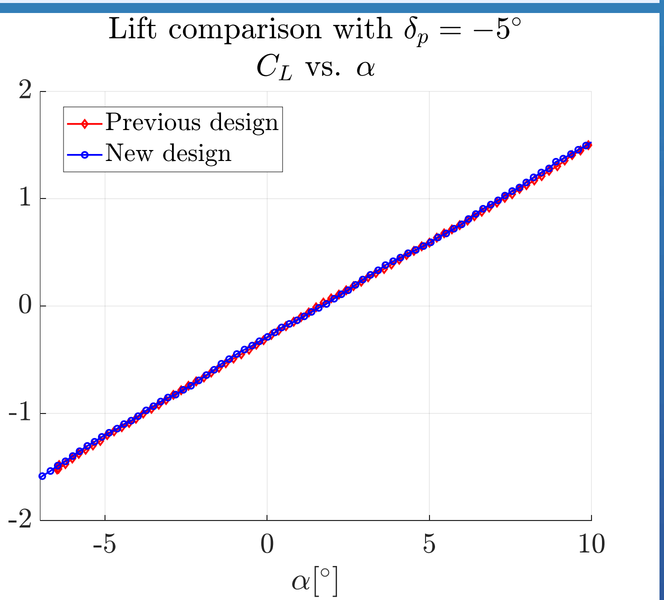
BODY-TAIL CONFIGURATION

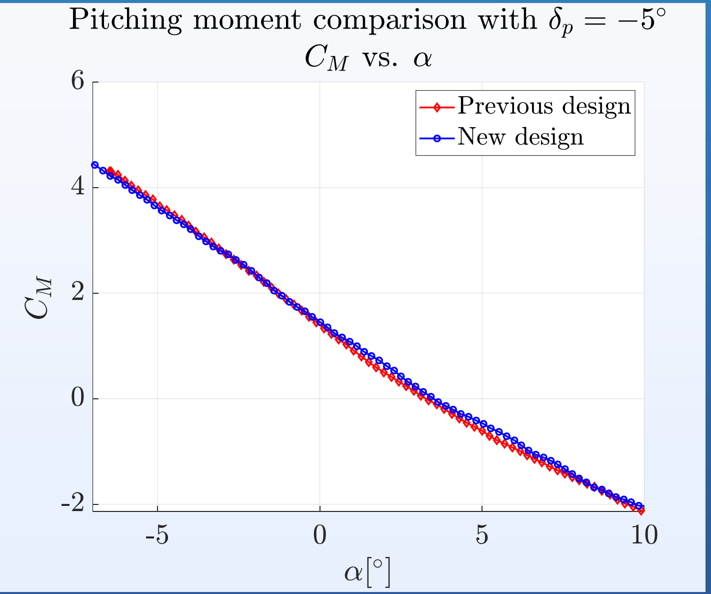
SIMILARITY TO LAST YEAR'S DESIGN

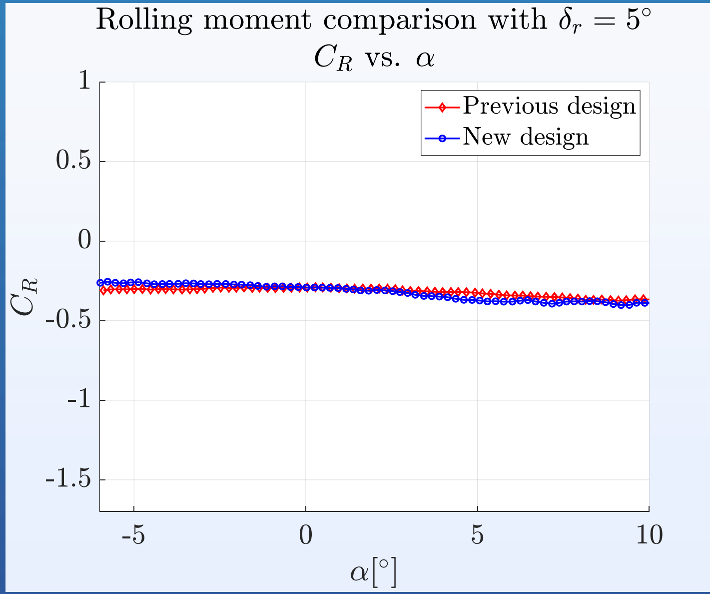


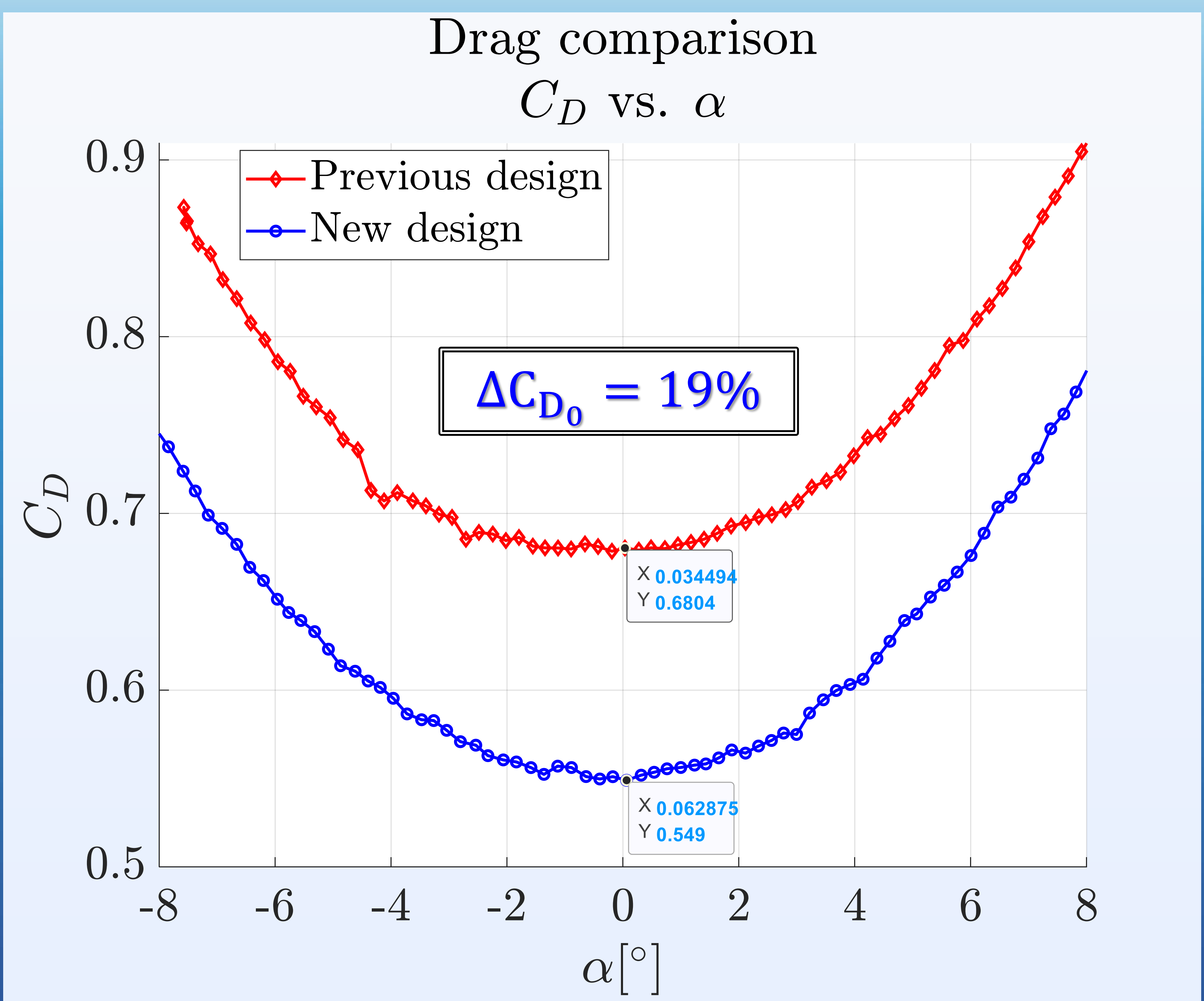




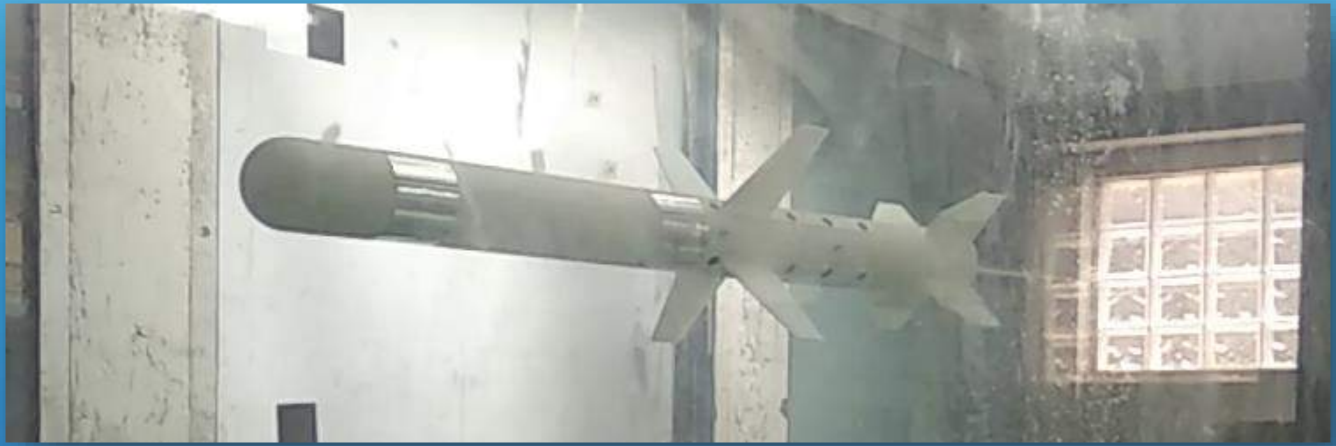


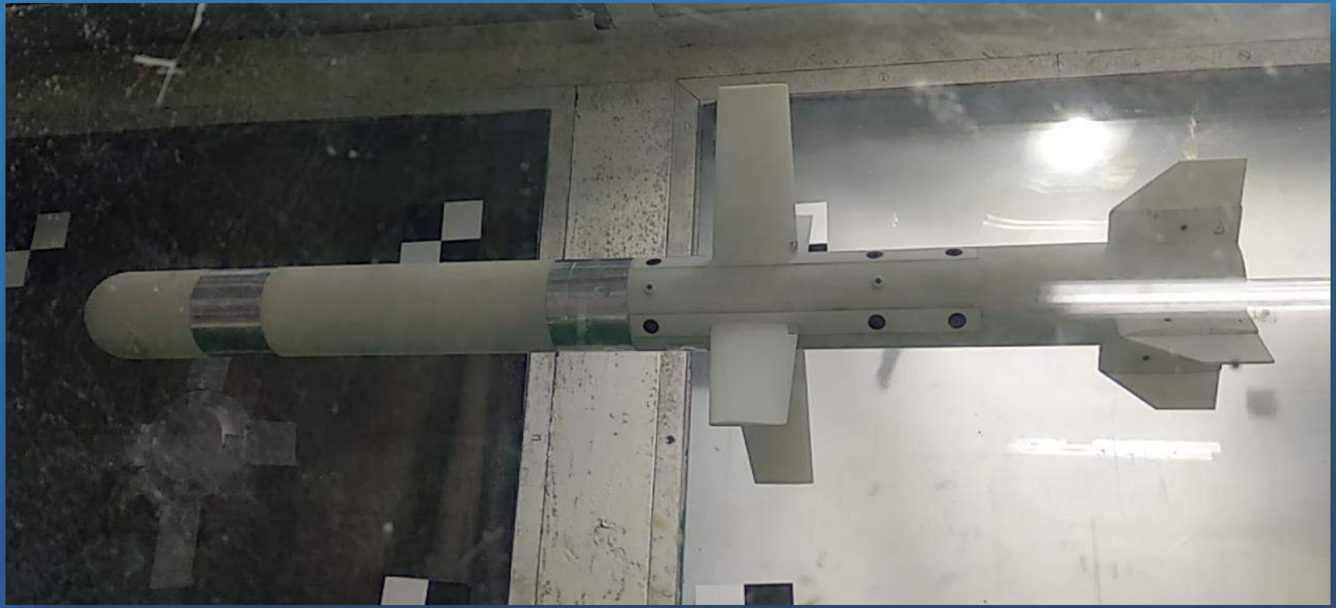





Drag comparison
C_D vs. α
Previous design
New design
$\Delta C_{D_0} = 19\%$
X 0.034494
Y 0.6804
X 0.062875
Y 0.549
C_D
$\alpha[^\circ]$
0.9
0.8
0.7
0.6
0.5
-8
-6
-4
-2
0
2
4
6
8

WING-BODY-TAIL CONFIGURATIONS

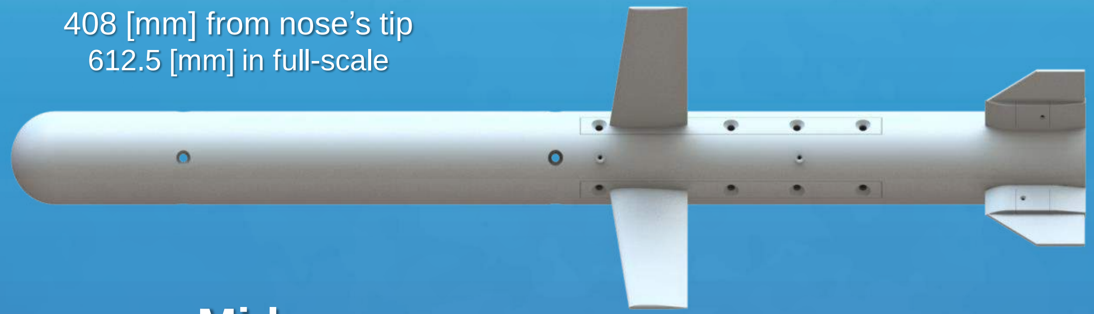




WING LOCATIONS

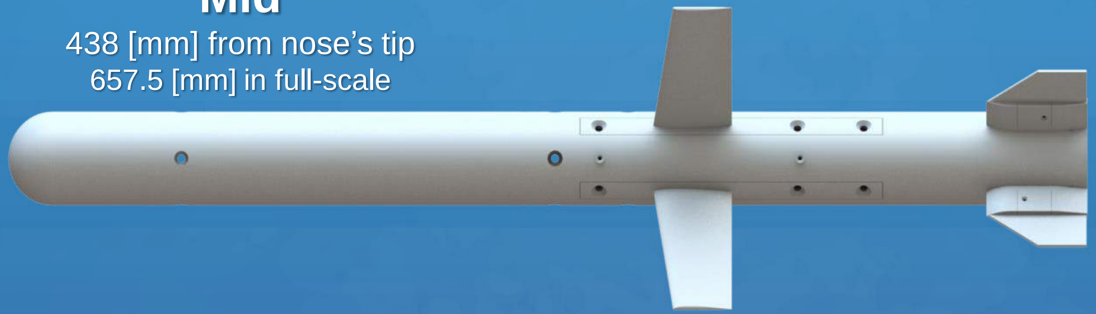
Fwd

408 [mm] from nose’s tip
612.5 [mm] in full-scale



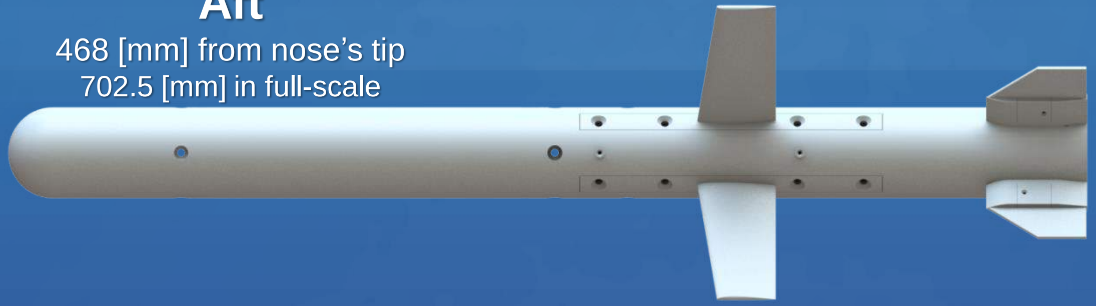
Mid

438 [mm] from nose’s tip
657.5 [mm] in full-scale



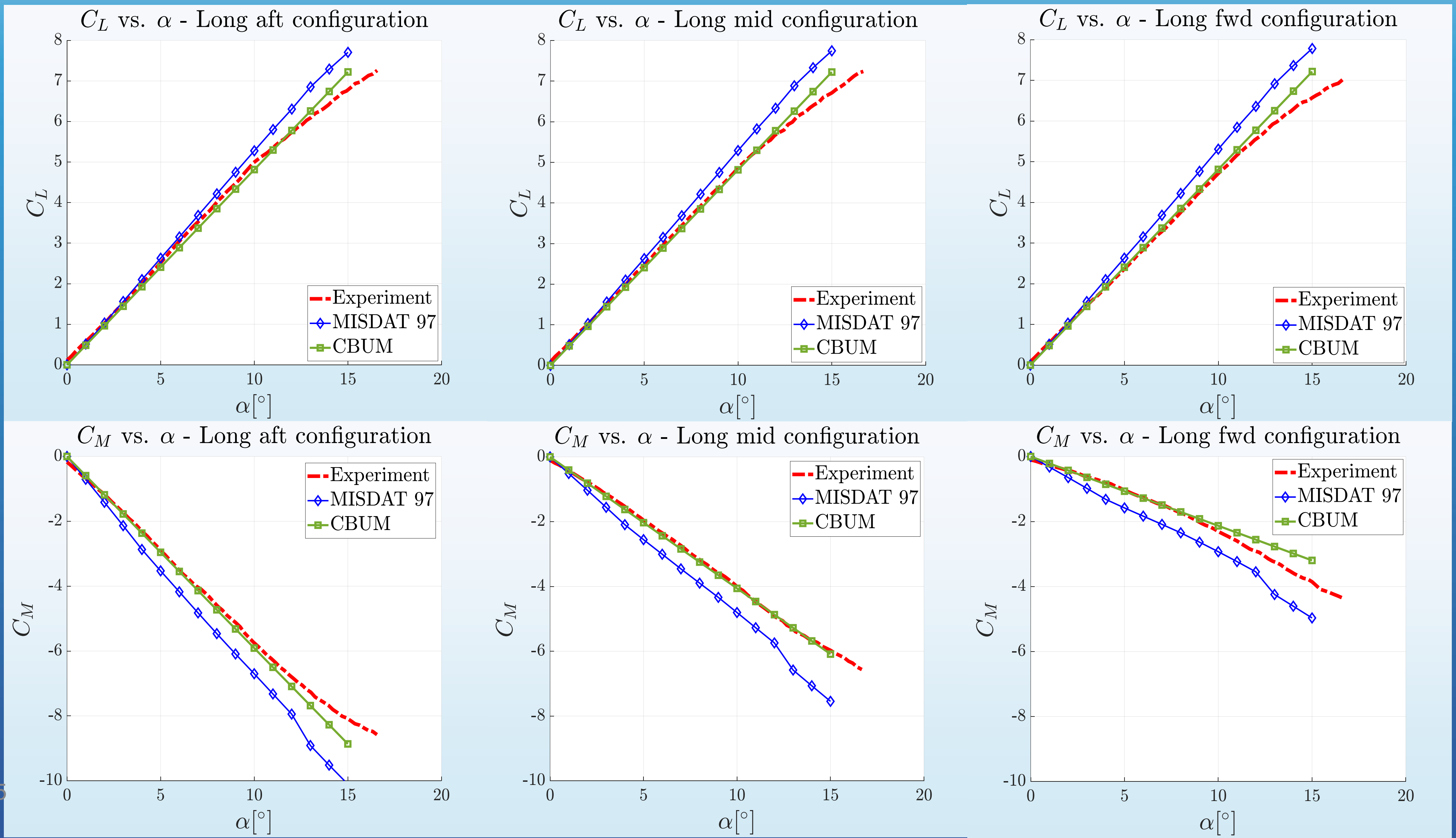
Aft

468 [mm] from nose’s tip
702.5 [mm] in full-scale



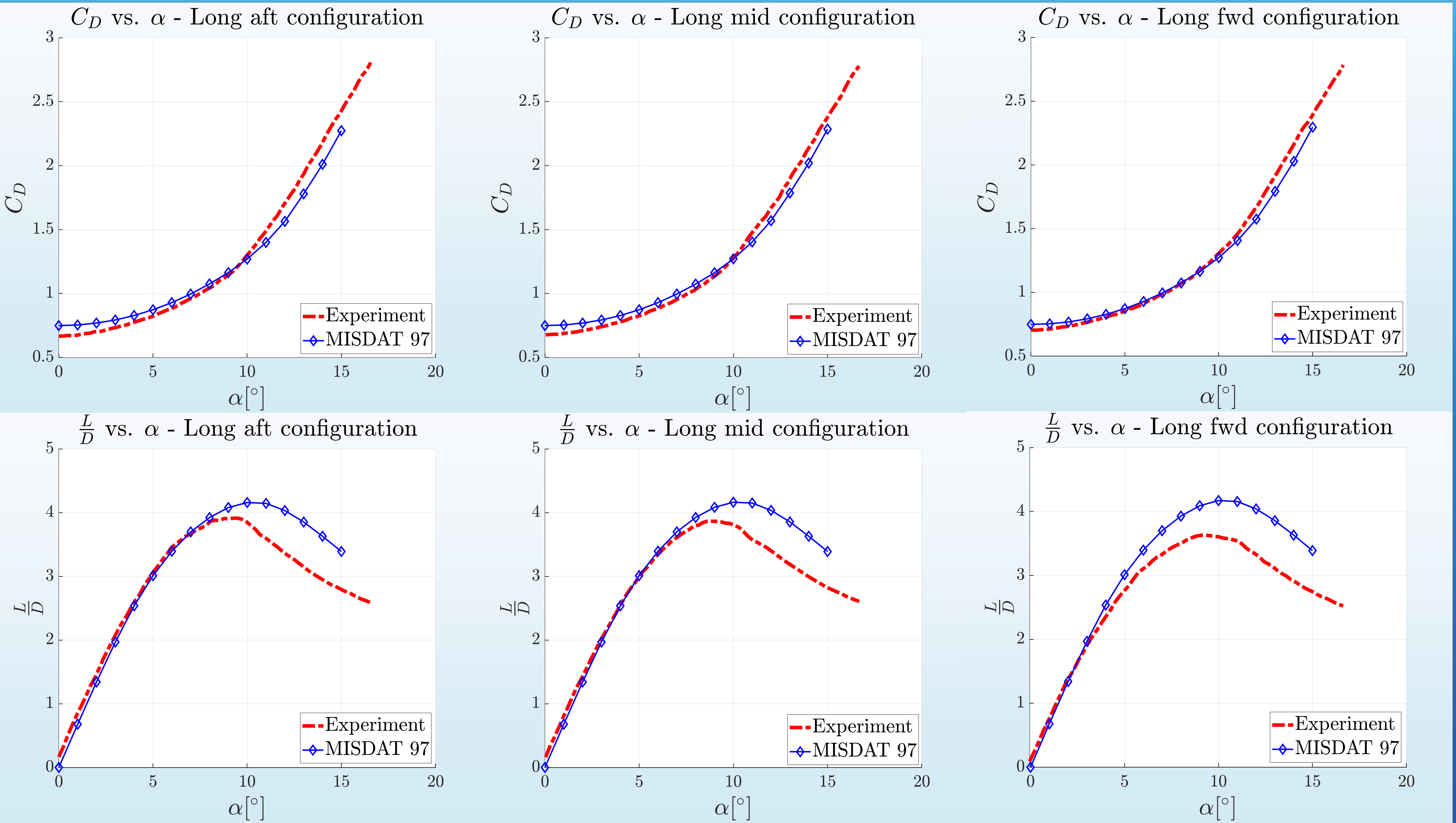
VALIDATION

Wing-Body-Tail aerodynamics – long wings

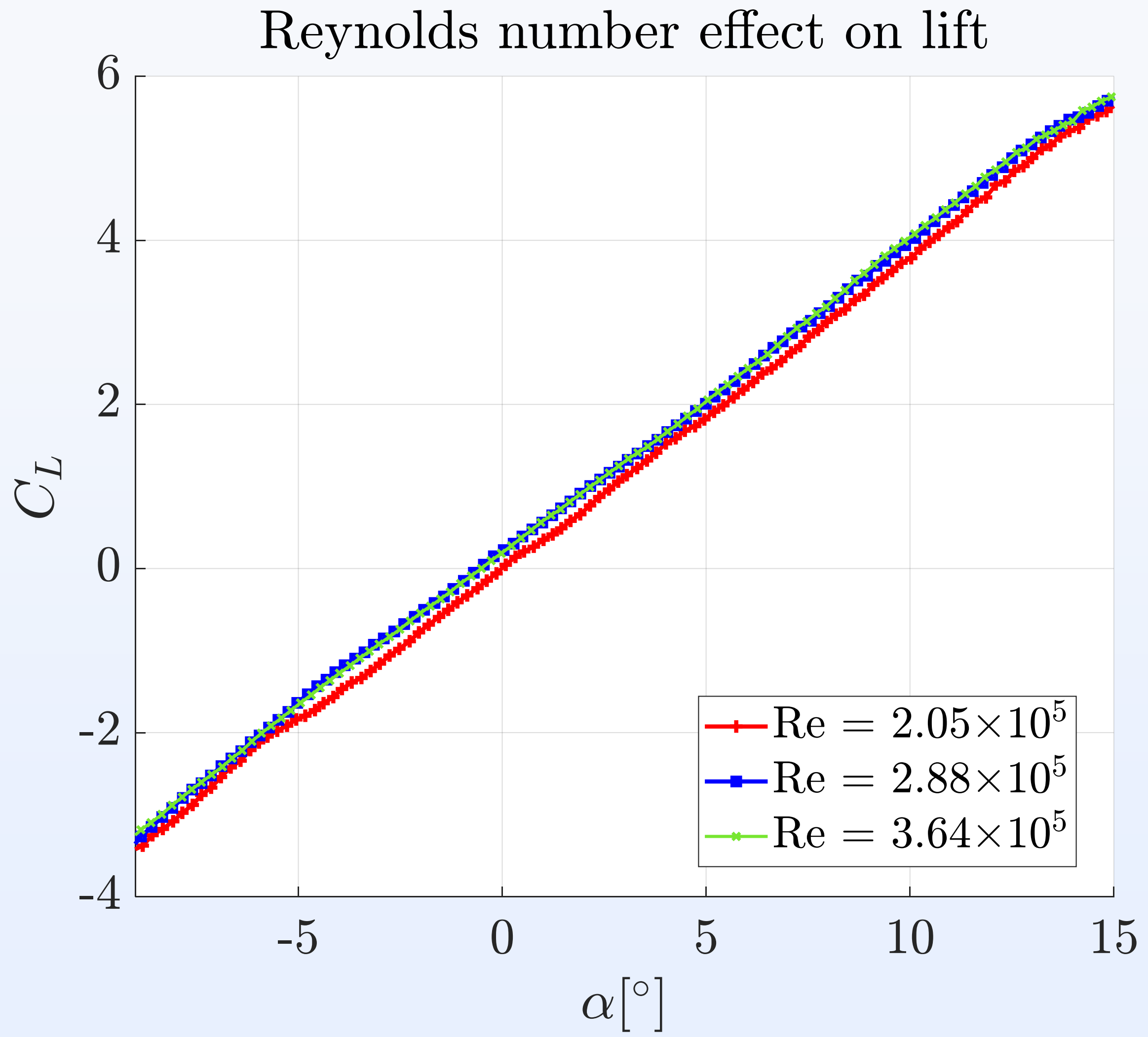


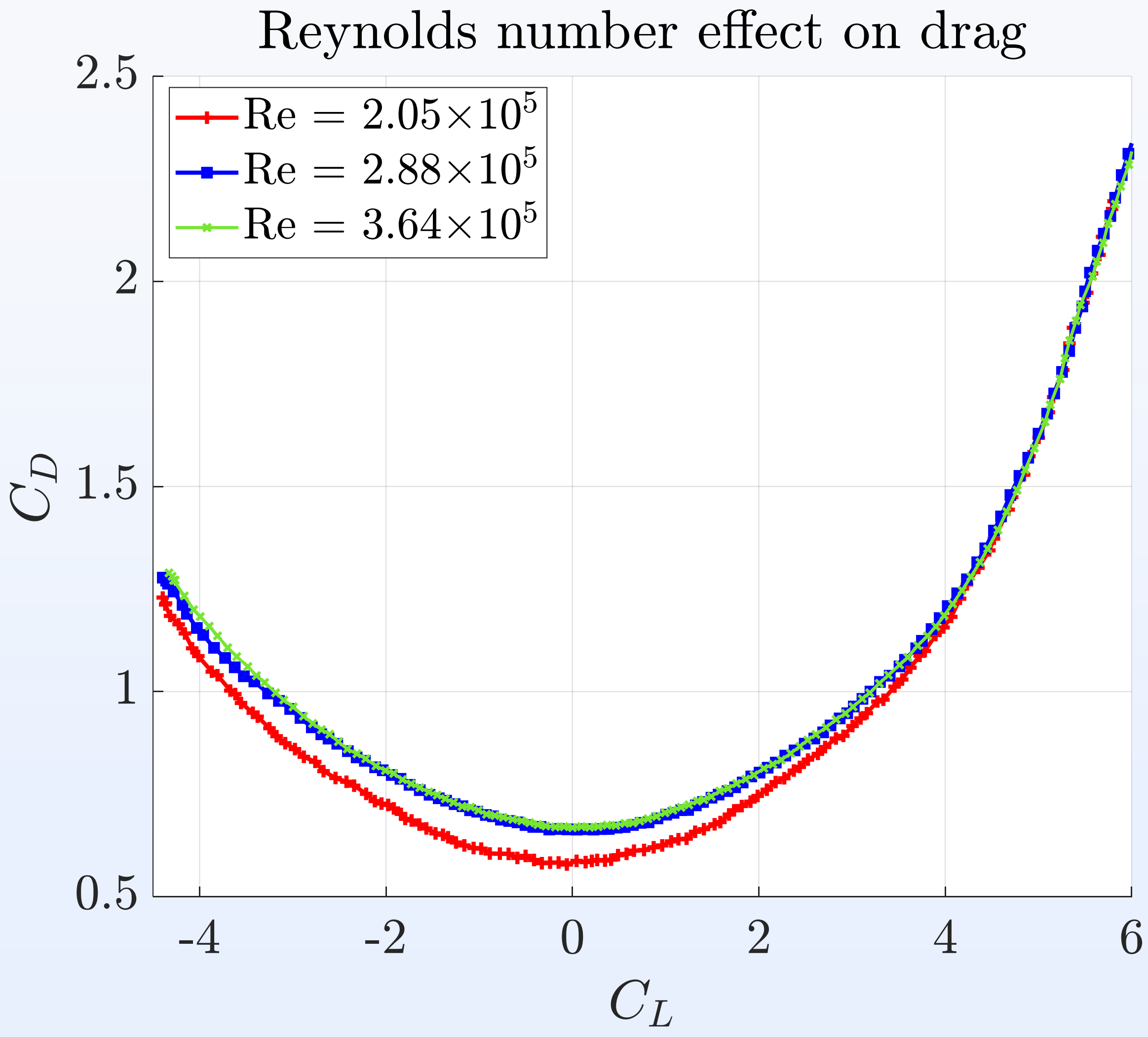
VALIDATION

Wing-Body-Tail aerodynamics – long wings

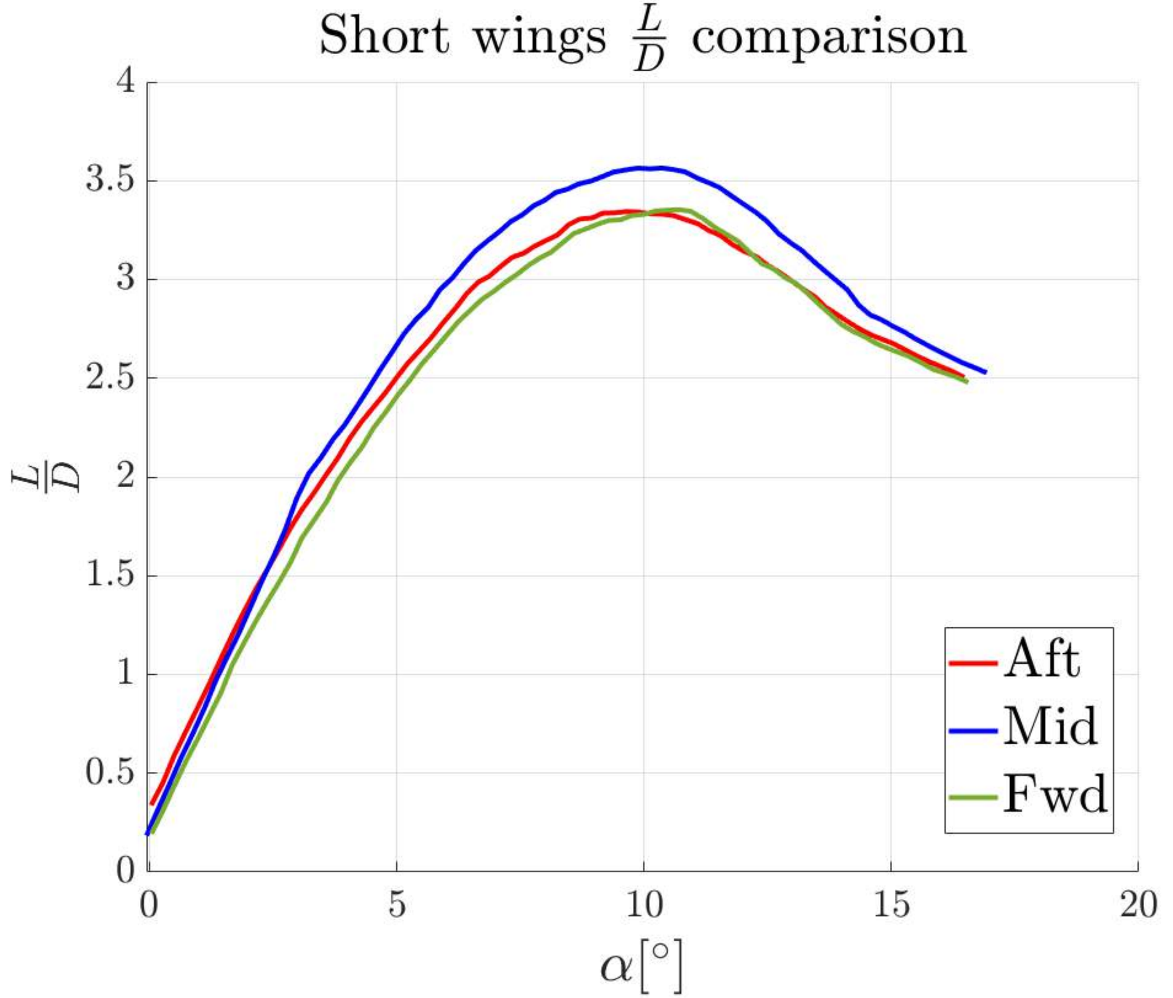


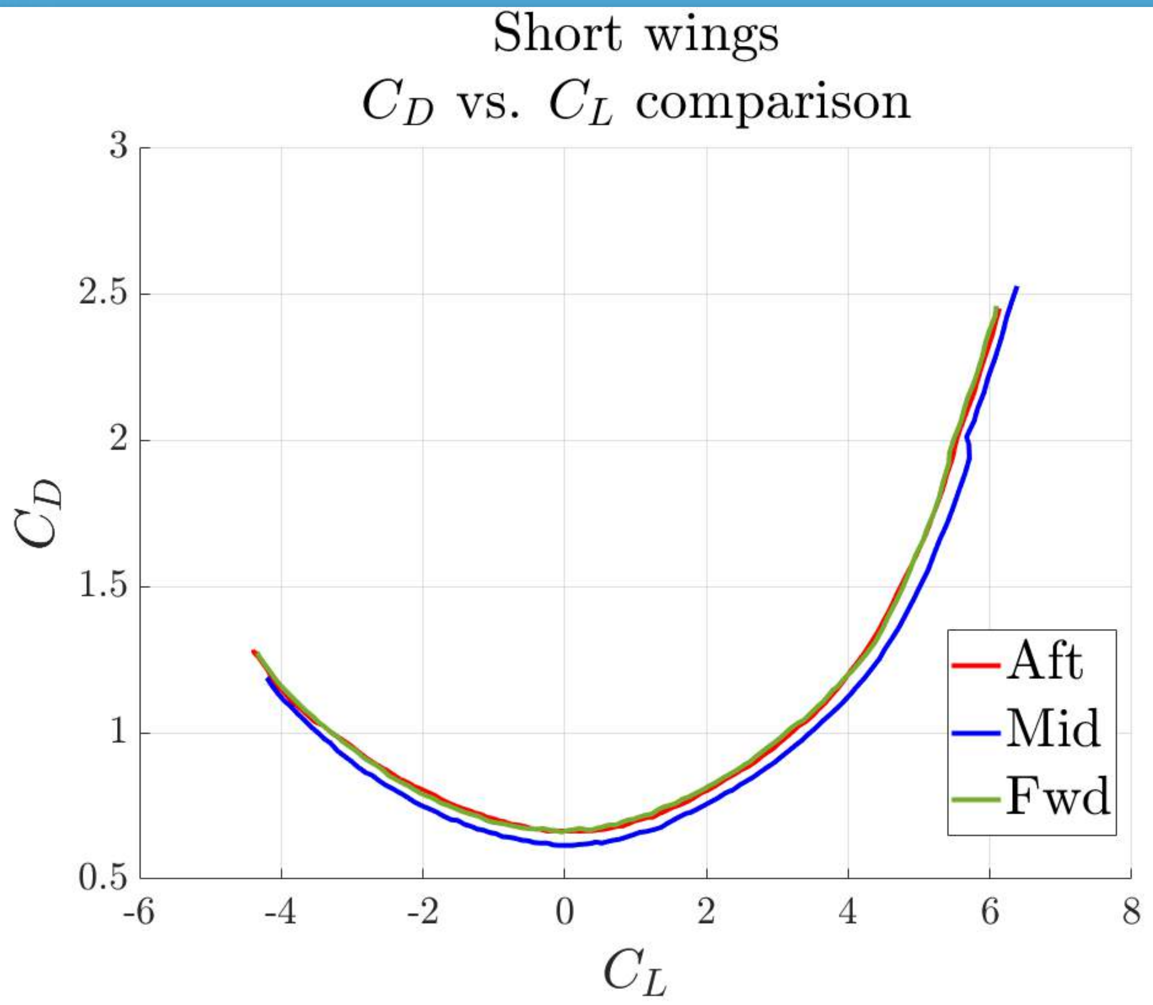
Reynolds number effects





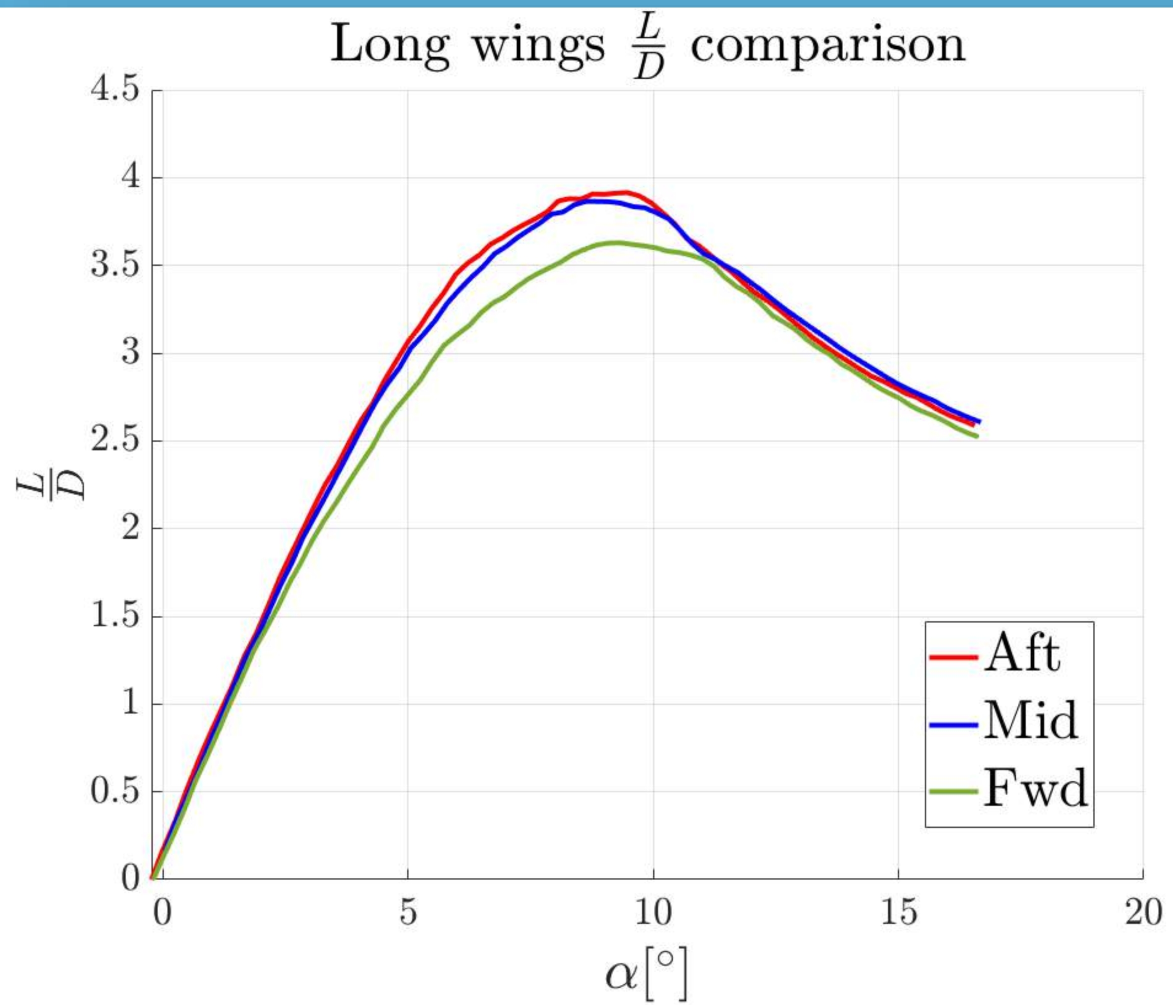
Wing location effects

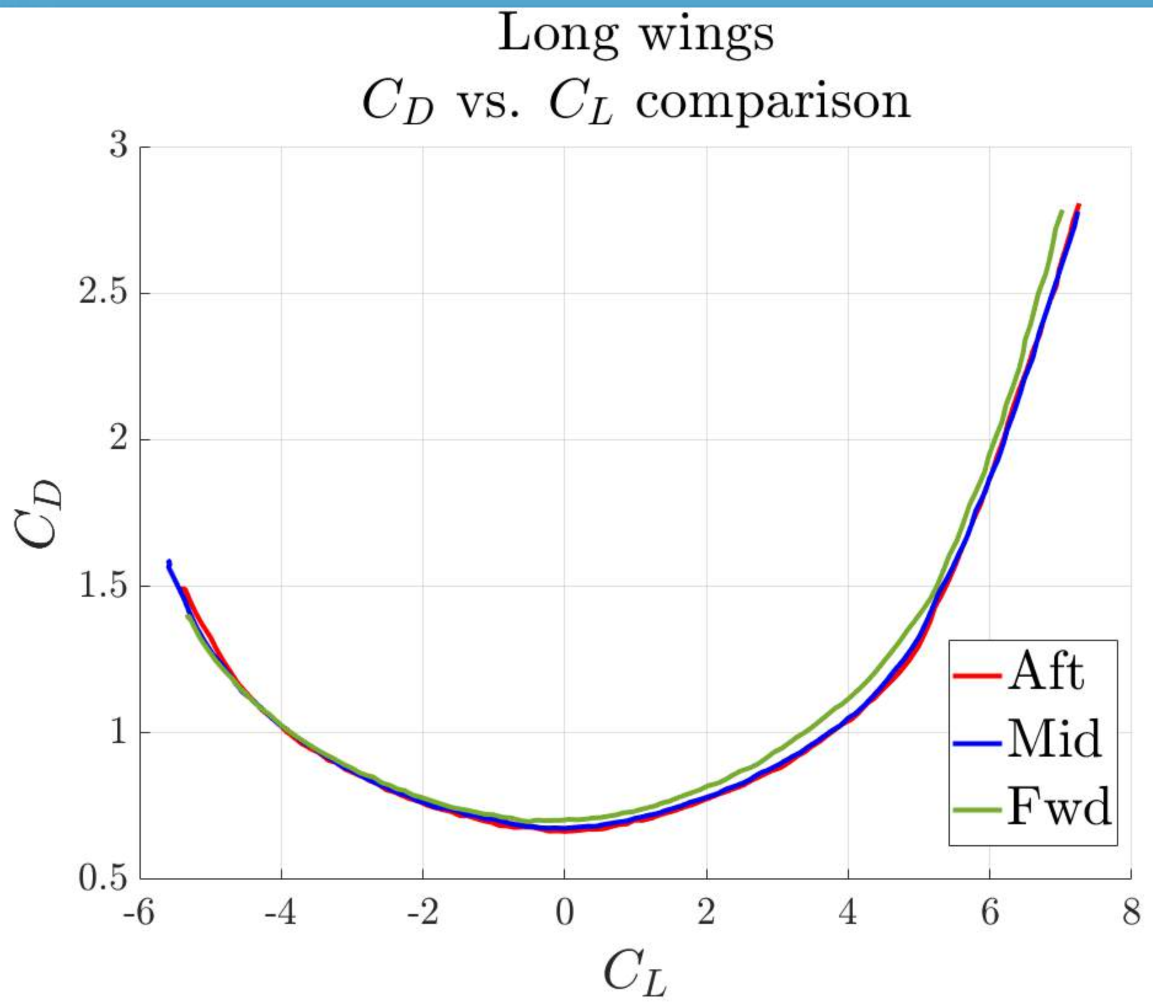




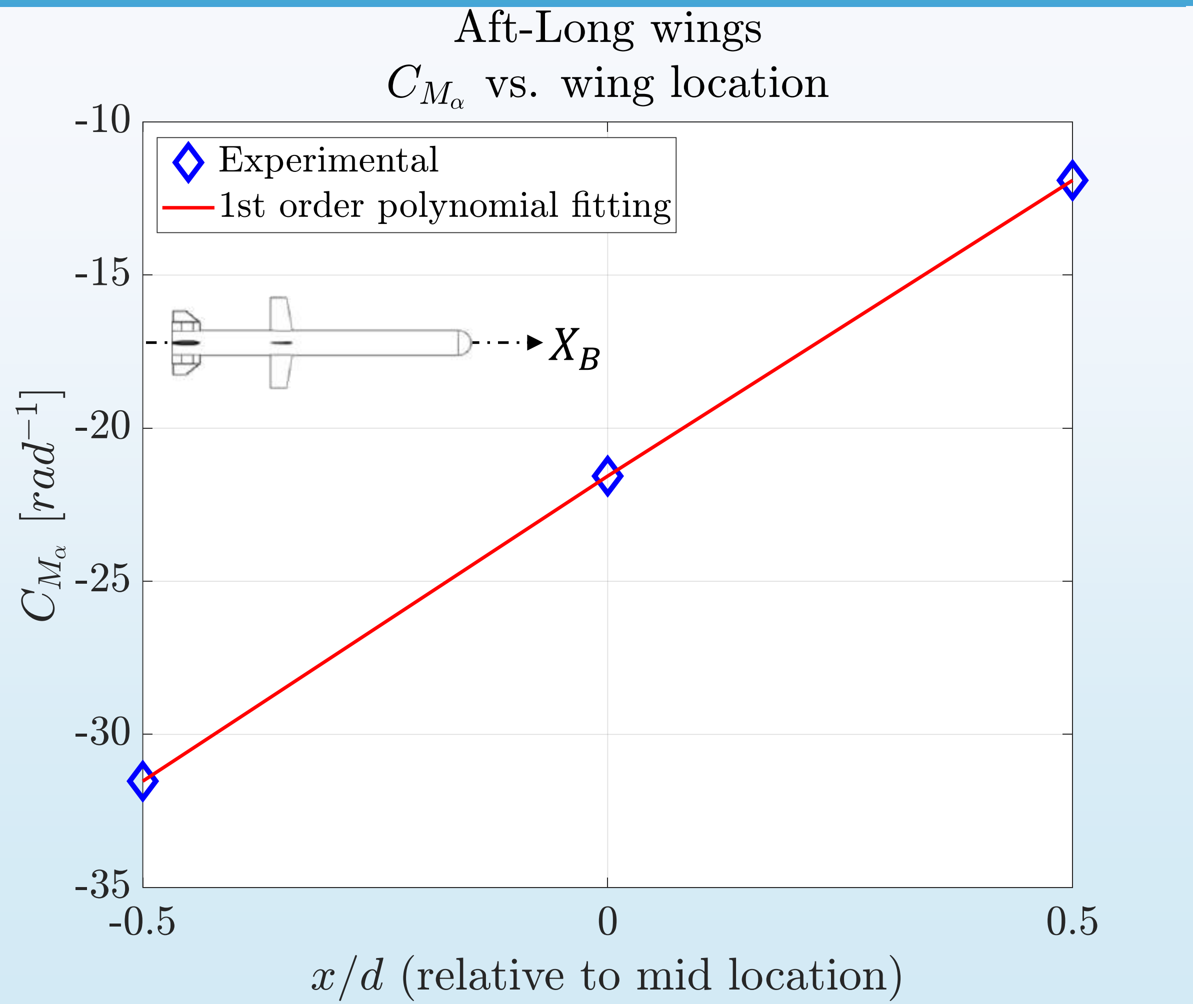
VALIDATION

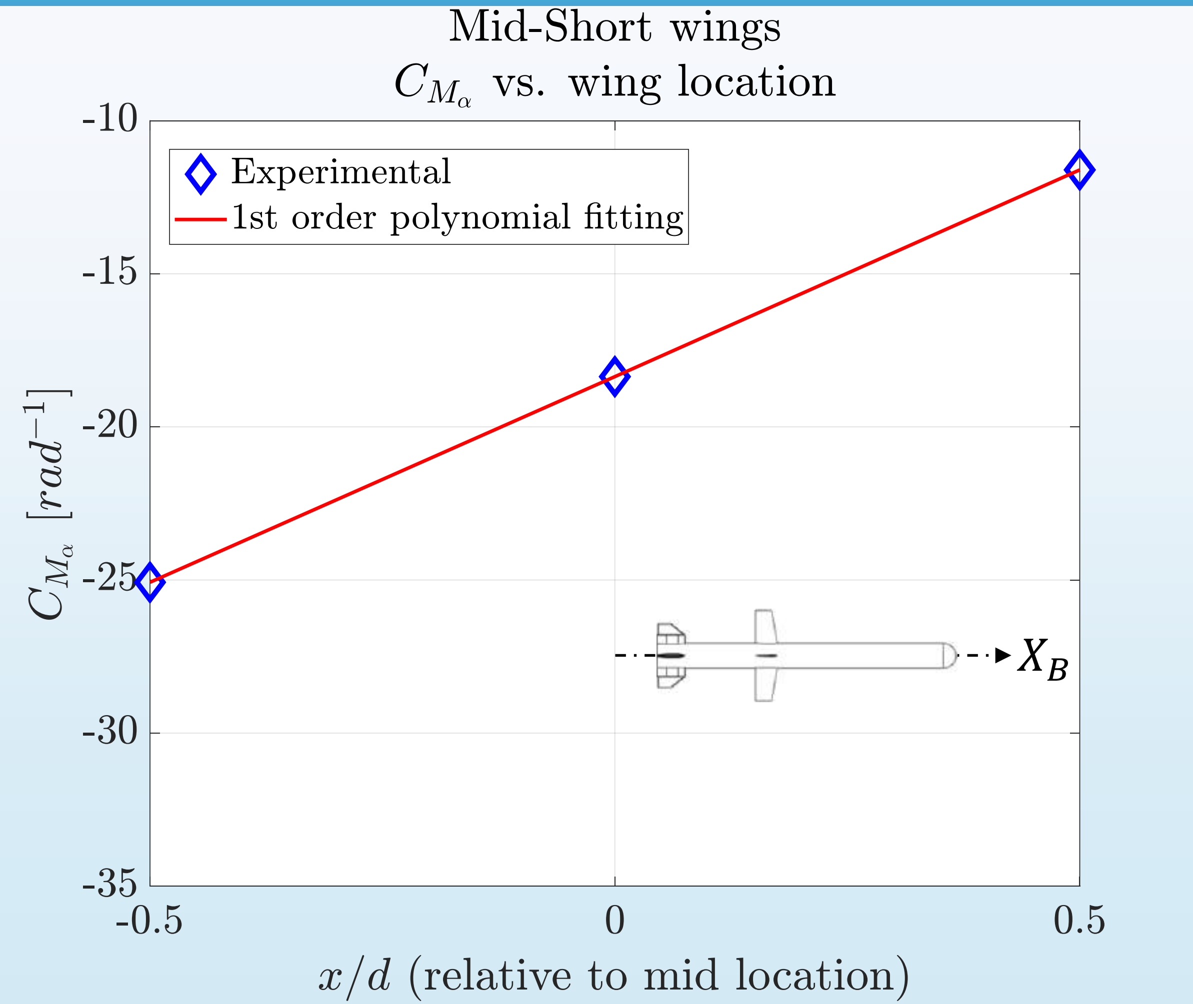
Wing-Body-Tail aerodynamics – long wings



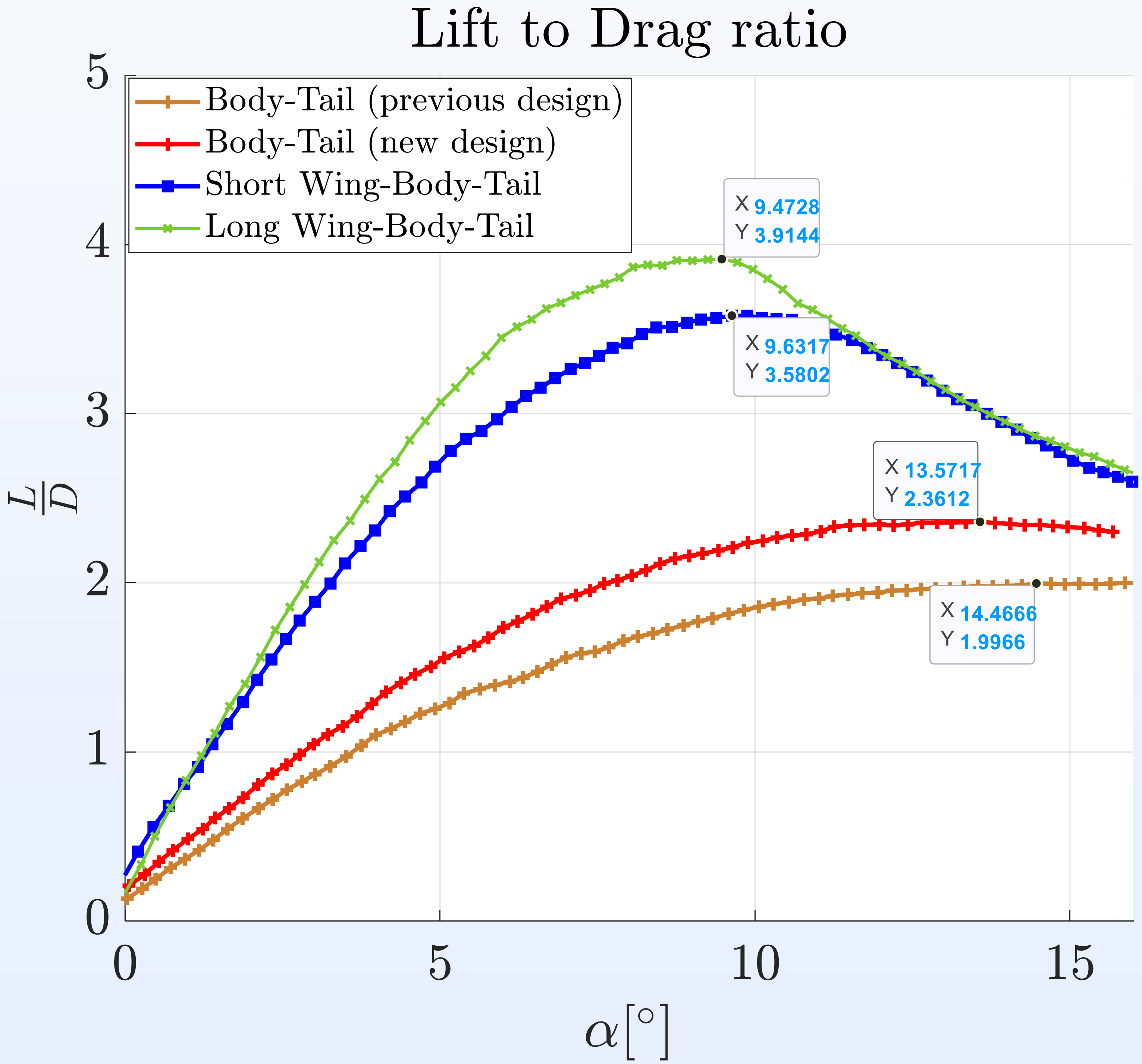


WING LOCATION EFFECTS





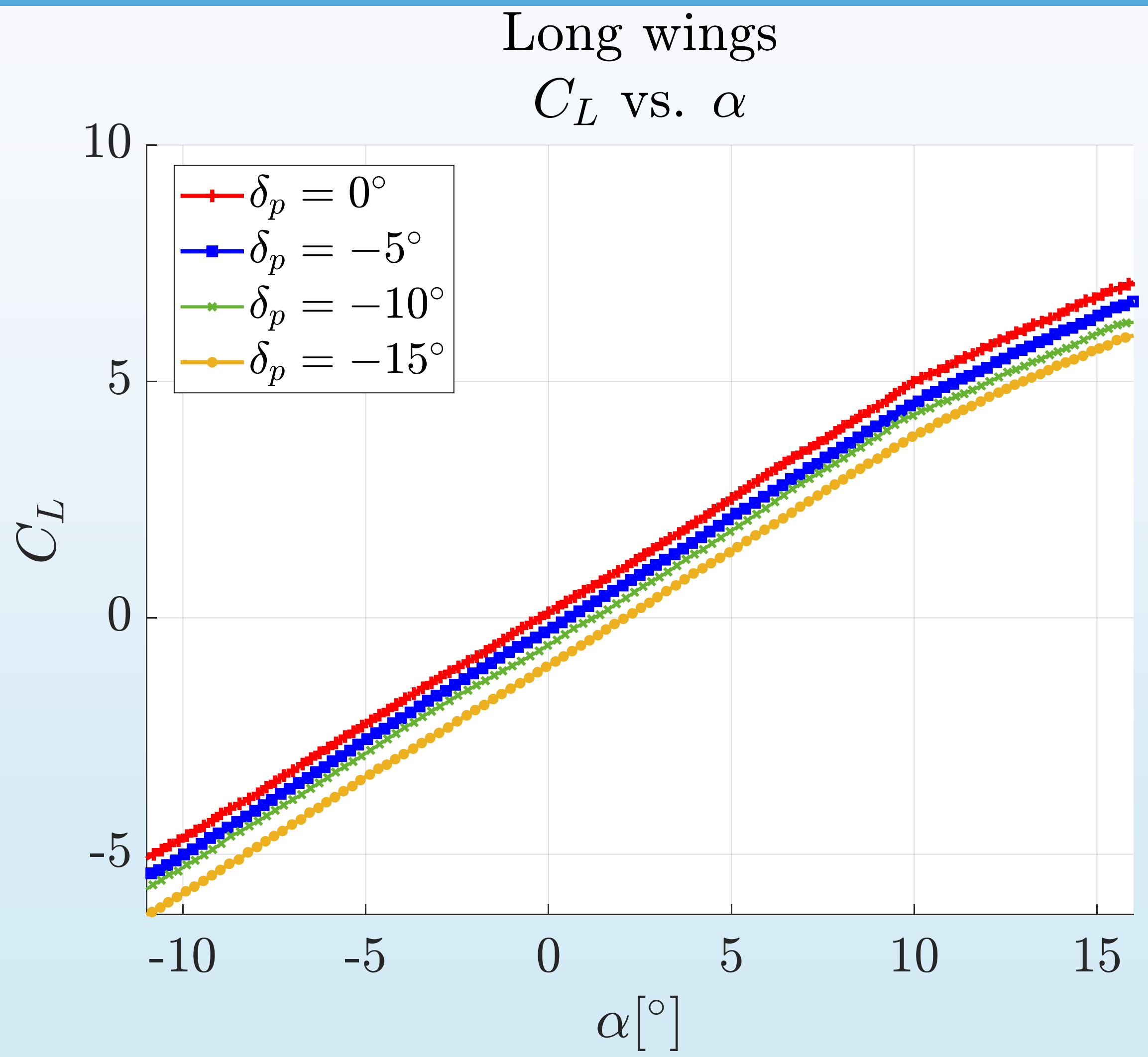
Mid location ('0' on the horizontal axis) represents the leading edge's longitudinal distance from the nose tip, which is 65.75 [cm]

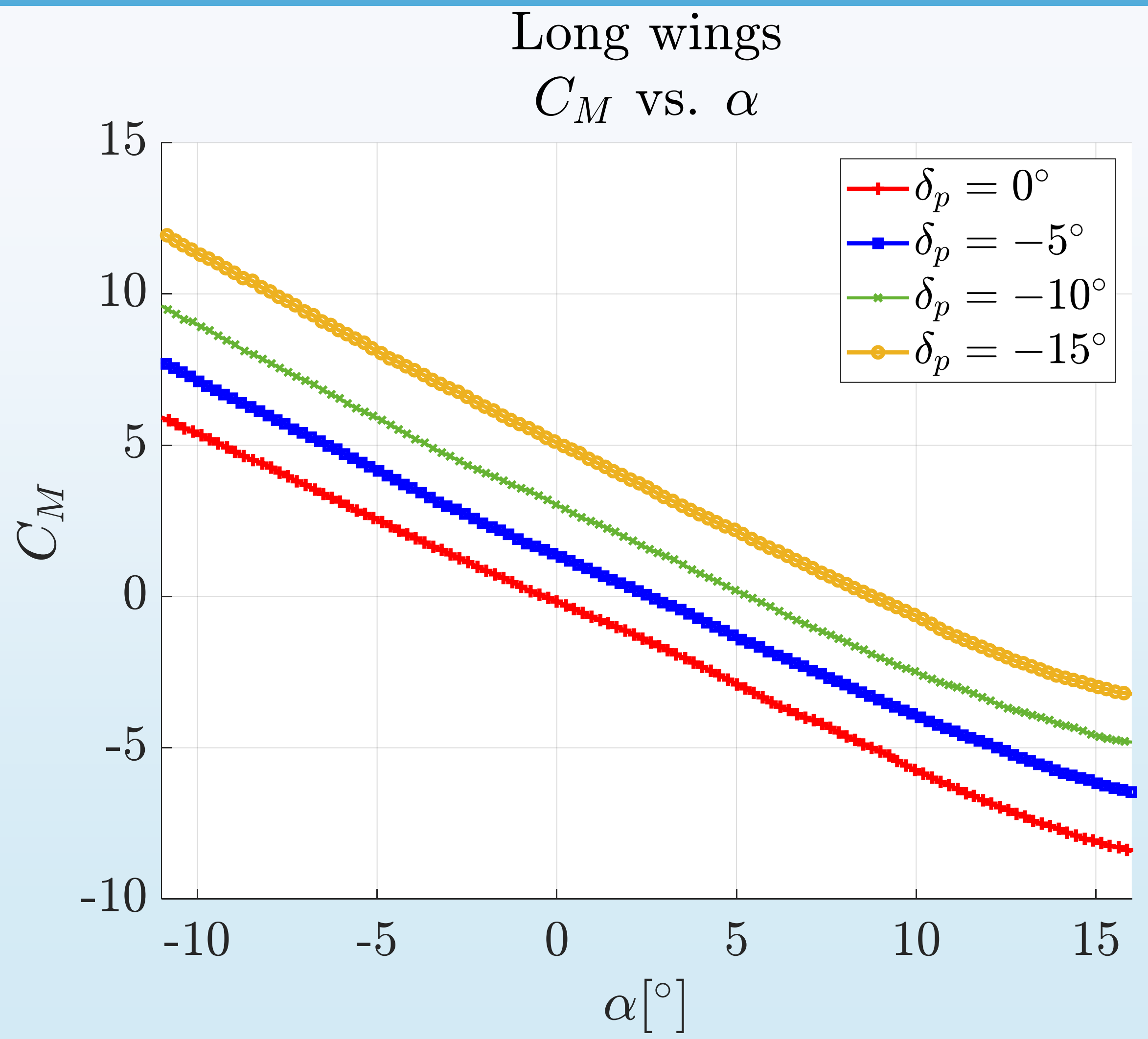


Lift to Drag ratio
Body-Tail (previous design)
Body-Tail (new design)
Short Wing-Body-Tail
Long Wing-Body-Tail
X 9.4728
Y 3.9144
X 9.6317
Y 3.5802
X 13.5717
Y 2.3612
X 14.4666
Y 1.9966
$\frac{L}{D}$
$\alpha[^\circ]$
0
1
2
3
4
5
0
5
10
15

PITCH STEERING

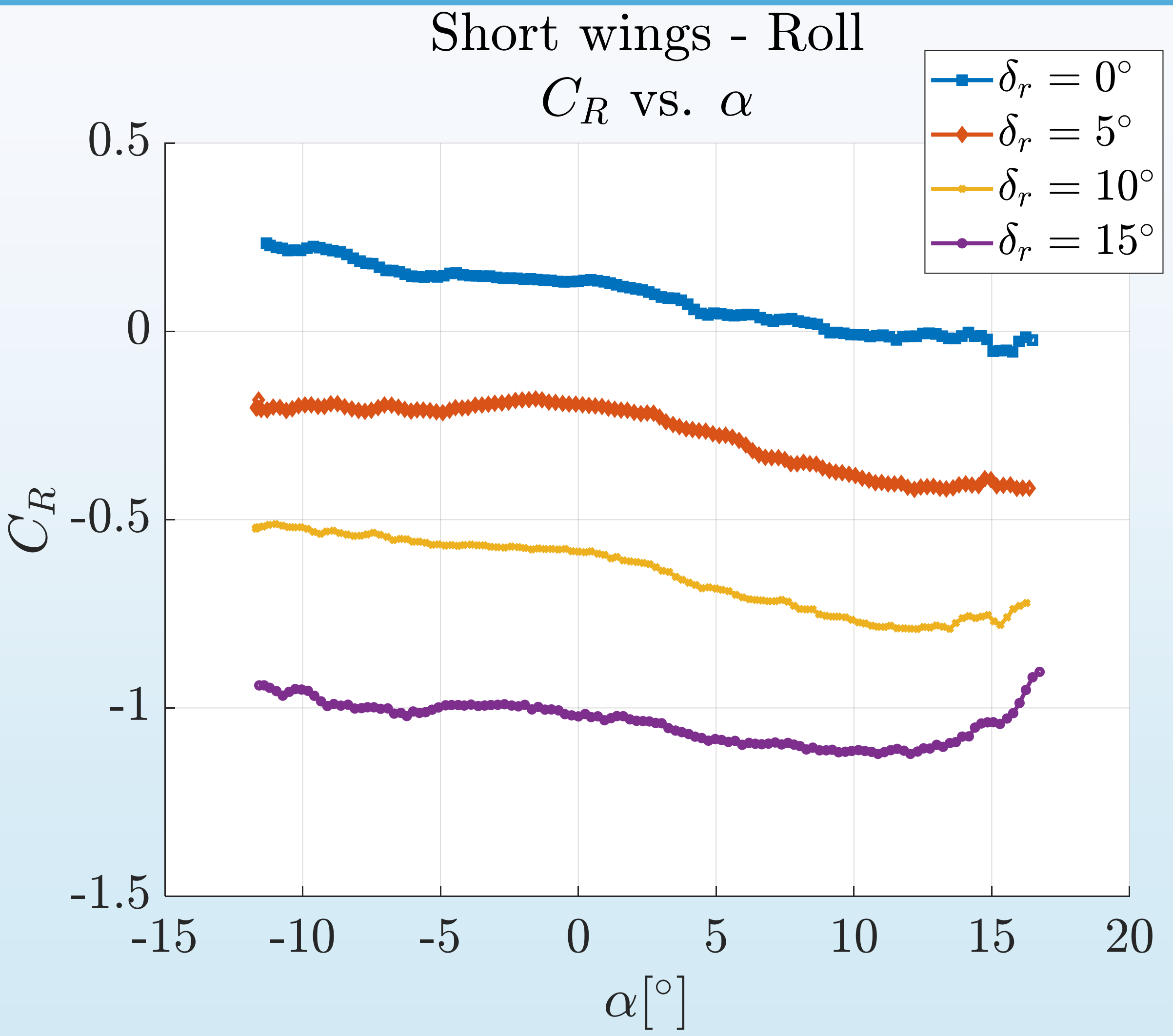
Long wings

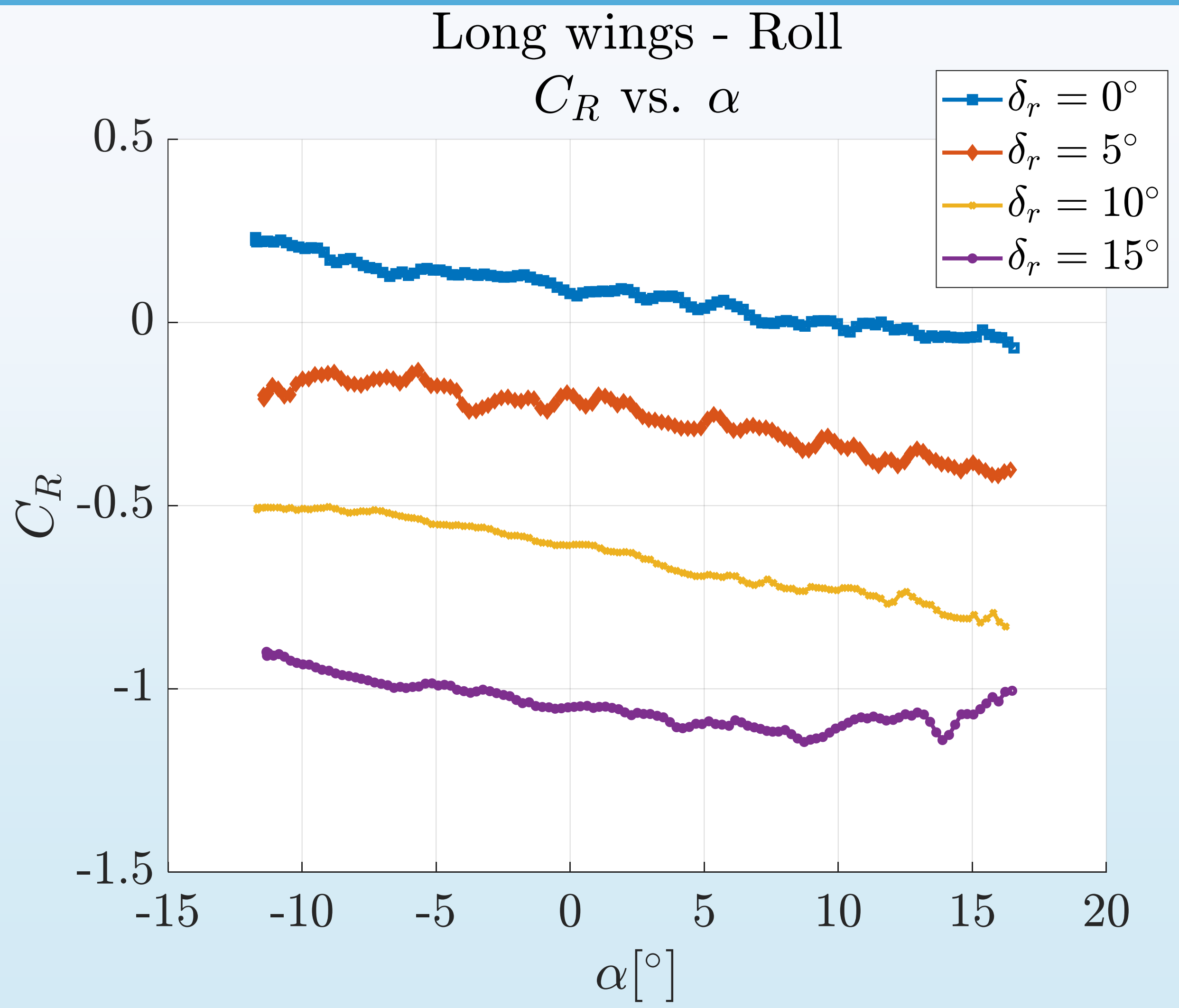




PITCH STEERING STRENGTH

ROLL STEERING



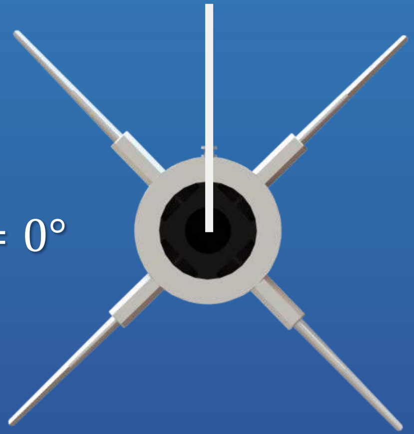


SYMMETRY CHECK

The idea behind a symmetry check is to see whether pitch & yaw control can be assumed the same.

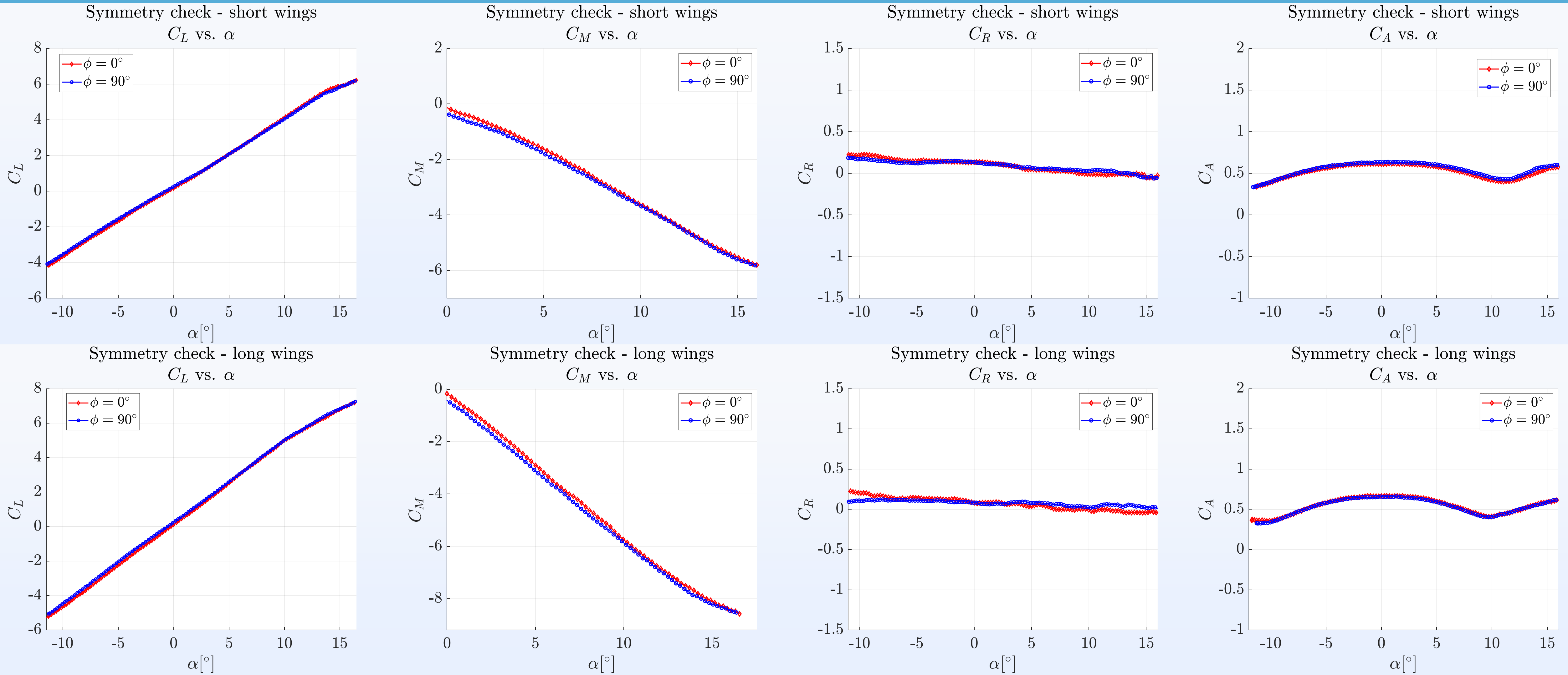
The missile's symmetry is disturbed by the launcher buttons that are located only on one side of the configuration.

$\phi = 0°$



$\phi = 90°$

SYMMETRY CHECK



SUMMARY OF AERODYNAMIC DESIGN

- Launch for **maximum altitude**:

Body-Tail

- Launch for **maximum gliding distance**:

Long Wing-Body-Tail

SUMMARY

Wingless configuration

$$C_L = C_{L_\alpha}\alpha + C_{L_{\delta_p}}\delta_p = 10.6092 \cdot \alpha + 4.5899 \cdot \delta_p$$

$$C_D = C_{D_{C_L^2}} C_L^2 + C_{D_{C_Y^2}} C_Y^2 + C_{D_0} = 0.0918 \cdot (C_L^2 + C_Y^2) + 0.5544$$

$$C_Y = C_{Y_\beta}\beta + C_{Y_{\delta_y}}\delta_y = -10.6092 \cdot \beta + 4.5899 \cdot \delta_y$$

$$C_M = C_{M_\alpha}\alpha + C_{M_{\delta_p}}\delta_p = -22.4793 \cdot \alpha - 18.6823 \cdot \delta_p$$

$$C_R = C_{R_{\delta_r}}\delta_r = 3.9123 \cdot \delta_r$$

$$C_N = C_{N_\beta}\beta + C_{N_{\delta_y}}\delta_y = -22.4793 \cdot \beta + 18.6823 \cdot \delta_y$$

$$C_{m_q} = C_{n_r} = -375.901 \left[\frac{1}{rad}\right] \qquad C_{r_p} = -7.085 \left[\frac{1}{rad}\right]$$

SUMMARY

Short wings configuration

$$C_L = C_{L_\alpha}\alpha + C_{L_{\delta_p}}\delta_p = 21.8622 \cdot \alpha + 4.9663 \cdot \delta_p$$

$$C_D = C_{D_{C_L^2}} C_L^2 + C_{D_{C_Y^2}} C_Y^2 + C_{D_0} = 0.0315 \cdot (C_L^2 + C_Y^2) + 0.6236$$

$$C_Y = C_{Y_\beta}\beta + C_{Y_{\delta_y}}\delta_y = -21.8622 \cdot \beta + 4.9663 \cdot \delta_y$$

$$C_M = C_{M_\alpha}\alpha + C_{M_{\delta_p}}\delta_p = -18.3588 \cdot \alpha - 19.3142 \cdot \delta_p$$

$$C_R = C_{R_{\delta_r}}\delta_r = 4.037 \cdot \delta_r$$

$$C_N = C_{N_\beta}\beta + C_{N_{\delta_y}}\delta_y = -18.3588 \cdot \beta + 19.3142 \cdot \delta_y$$

$$C_{m_q} = C_{n_r} = -380.077 \left[\frac{1}{rad}\right] \qquad C_{r_p} = -50.861 \left[\frac{1}{rad}\right]$$

SUMMARY

Long wings configuration

$$C_L = C_{L_\alpha}\alpha + C_{L_{\delta_p}}\delta_p = 27.5464 \cdot \alpha + 4.2942 \cdot \delta_p$$

$$C_D = C_{D_{C_L^2}} C_L^2 + C_{D_{C_Y^2}} C_Y^2 + C_{D_0} = 0.0235 \cdot (C_L^2 + C_Y^2) + 0.66535$$

$$C_Y = C_{Y_\beta}\beta + C_{Y_{\delta_y}}\delta_y = -27.5464 \cdot \beta + 4.2942 \cdot \delta_y$$

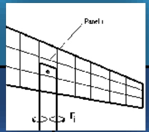
$$C_M = C_{M_\alpha}\alpha + C_{M_{\delta_p}}\delta_p = -31.5283 \cdot \alpha - 18.4916 \cdot \delta_p$$

$$C_R = C_{R_{\delta_r}}\delta_r = 3.7763 \cdot \delta_r$$

$$C_N = C_{N_\beta}\beta + C_{N_{\delta_y}}\delta_y = -31.5283 \cdot \beta + 18.6905 \cdot \delta_y$$

$$C_{m_q} = C_{n_r} = -479.557 \left[\frac{1}{rad}\right] \qquad C_{r_p} = -102.48 \left[\frac{1}{rad}\right]$$

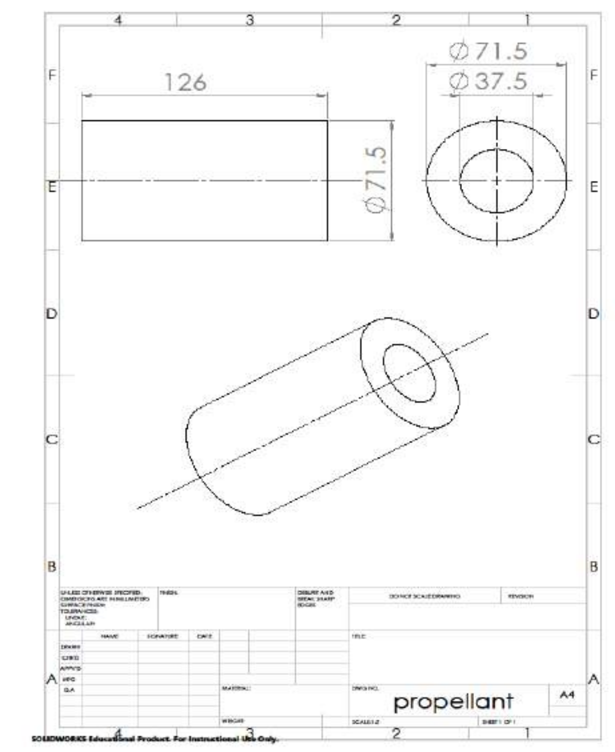
Control surfaces hinge moments



	VLM	MISSILE DATCOM
Moment around the hinge line [kgf • cm]	**- 0.1224**	**- 1.224**
Servo’s maximum torque at 7.4V [kgf • cm]	**± 5**	

ROCKET MOTOR

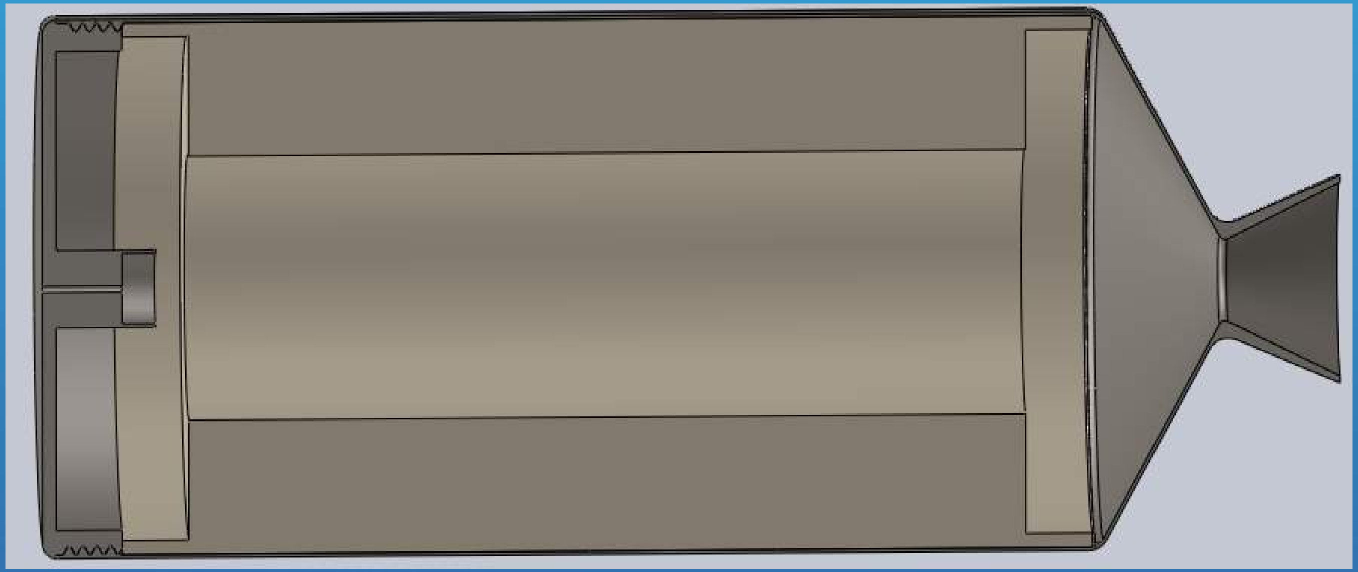
PROPELLANT FROM RAFAEL



$m_p = 620\ [g]$	$\gamma = 1.2$
$C^{\star} = 1530 \left[\frac{m}{s}\right]$	$r_{@50\ bar} = 9 \left[\frac{mm}{s}\right]$
$\rho_p = 1.71 \times 10^{-3} \left[\frac{g}{mm^3}\right]$	$T_C = 2970\ [K]$
$n = 0.39$	$W_C = 25.5 \left[\frac{g}{mole}\right]$

The propellant is casted into a metal case, it is optional to cast in dense rubber or plastic casing.

Last Year's MOTOR design – 2-part motor



Flight direction

CALCULATIONS

Motor Casing

$MOP = 61.5\ [bar]$	$C_2 \approx 1.11$	$C_1 \approx 1.12$
Real maximal pressure for nominal conditions	High propellant temperature coefficient	Different propellant properties due to manufacturing differences

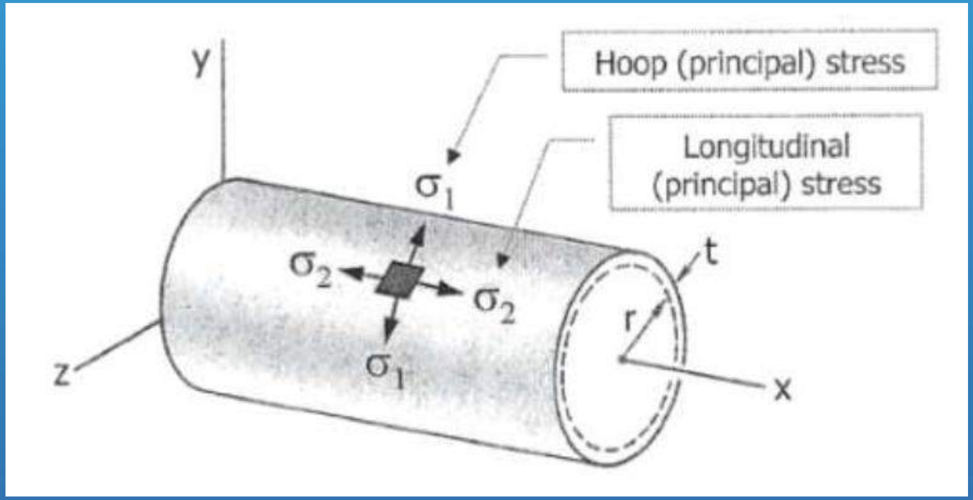
$$\boxed{MEOP = MOP \cdot C_1 \cdot C_2 \approx 76.5\ [bar]}$$

$$\boxed{t_{min} = \frac{MEOP \cdot S.F \cdot D \cdot K}{2 \cdot \sigma_{UTS}}} \Rightarrow$$

$tube\ material:$
$stainless\ steel\ 304\ - cold\ rolled$
$minimum\ of\ 0.3\ mm\ thickness$

CALCULATIONS

Tube thickness



$$\sigma_1 = \frac{P \cdot r}{t} \quad ; \quad \sigma_2 = \frac{P \cdot r}{2 \cdot t} \quad ; \quad \sigma_{DE} = \sqrt{\sigma_1^2 - \sigma_1 \cdot \sigma_2 + \sigma_2^2} \; ; \quad n = \frac{S_y}{\sigma_{DE}}$$

Thickness	$\sigma_1[MPa]$	$\sigma_2[MPa]$	$\sigma_{DE}[MPa]$	n
$t_1 = 0.3\ mm$	782.1	391.05	677.3	$\mathbf{1.63}$
$t_2 = 0.5\ mm$	469.24	234.62	406.37	$\mathbf{2.71}$
$t_3 = 1\ mm$	234.64	117.32	203.2	$\mathbf{5.43}$

Nozzle design

$$A_b = \overbrace{\pi \cdot L \cdot D}^{\text{Radial burn}} + \overbrace{2 \times [0.25 \cdot \pi \cdot (D^2 - d^2)]}^{\text{Axial burn}}$$

$$A_b(mean) = \frac{A_b(t = 0\ s) + A_b(t = 1.89\ s)}{2} = 14{,}152[mm^2]$$

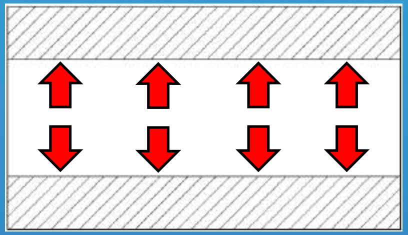
$$\dot{m}_{@50\ bar} = A_b(mean) \cdot \dot{r} \cdot \rho$$

$$P_c = 50\ [\ bar] \Rightarrow A_t = \frac{\dot{m} \cdot C^\star}{P_C} \quad \Rightarrow \boxed{D_t \approx 11\ [mm]}$$

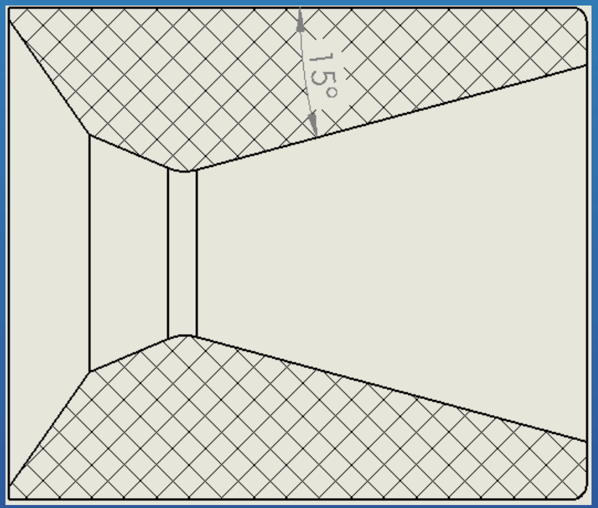
$$\boxed{C_F = \frac{I_{sp} \cdot g_0}{C^\star} = \frac{240 \cdot 9.81}{1530} = 1.538}$$

$$\boxed{D_e \approx 26\ [mm]}$$

<u>Our propellant burns in a radial & axial directions</u>


Radial burn


Axial burn



Preliminary design

3-part motor: one tube & two domes.

Pros:

Robust design

thick walls & high safety factors – every part is made from steel.

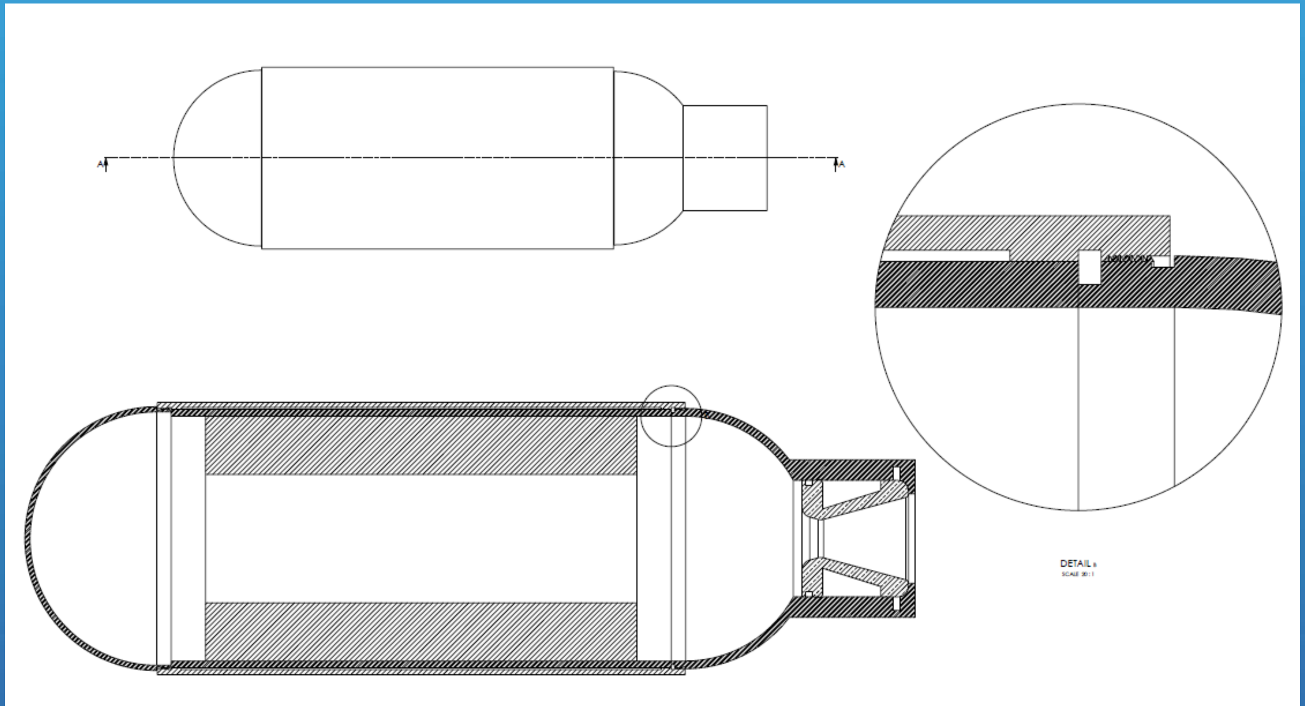
Cons:

Pressure differences inside the motor – will cause the motor to fail.

Very heavy.

Low efficiency.

Domes stress calculation isn't an accurate model.



Flight direction

FINAL design

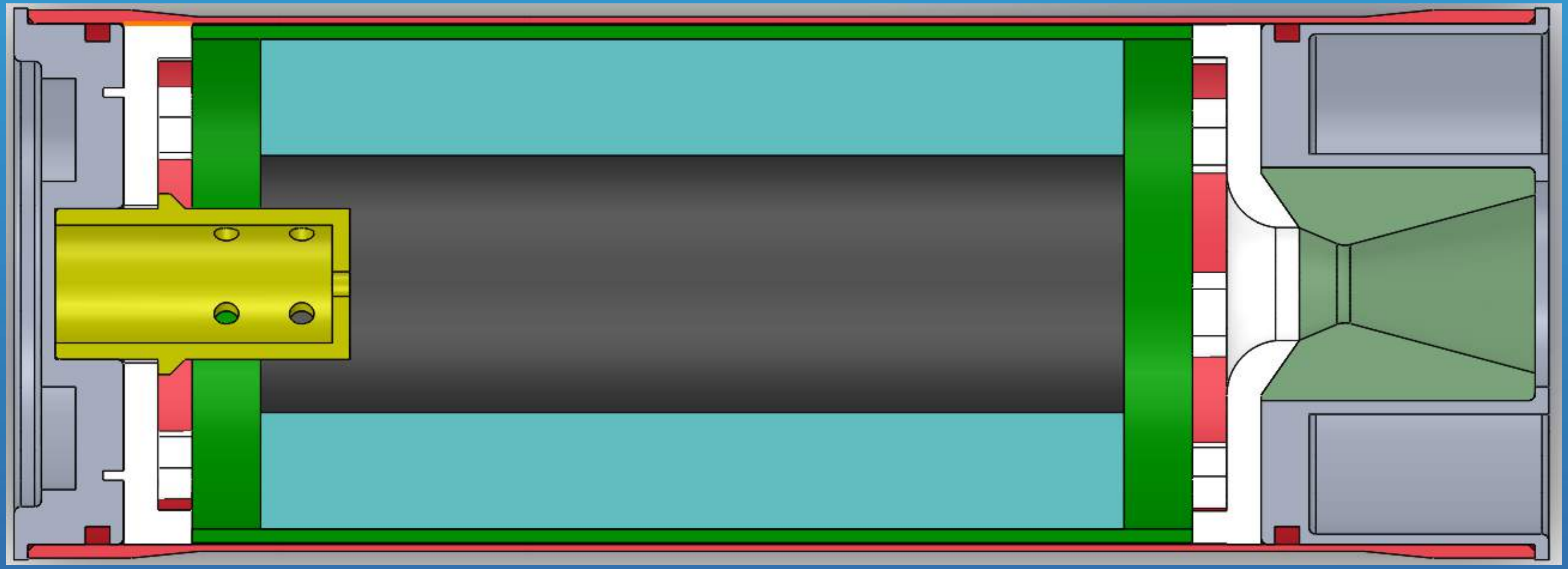
3-part motor: one tube & two lids.

Given parts from RAFAEL: isolation , ignition and propellant.

Aluminum domes and steel tube.

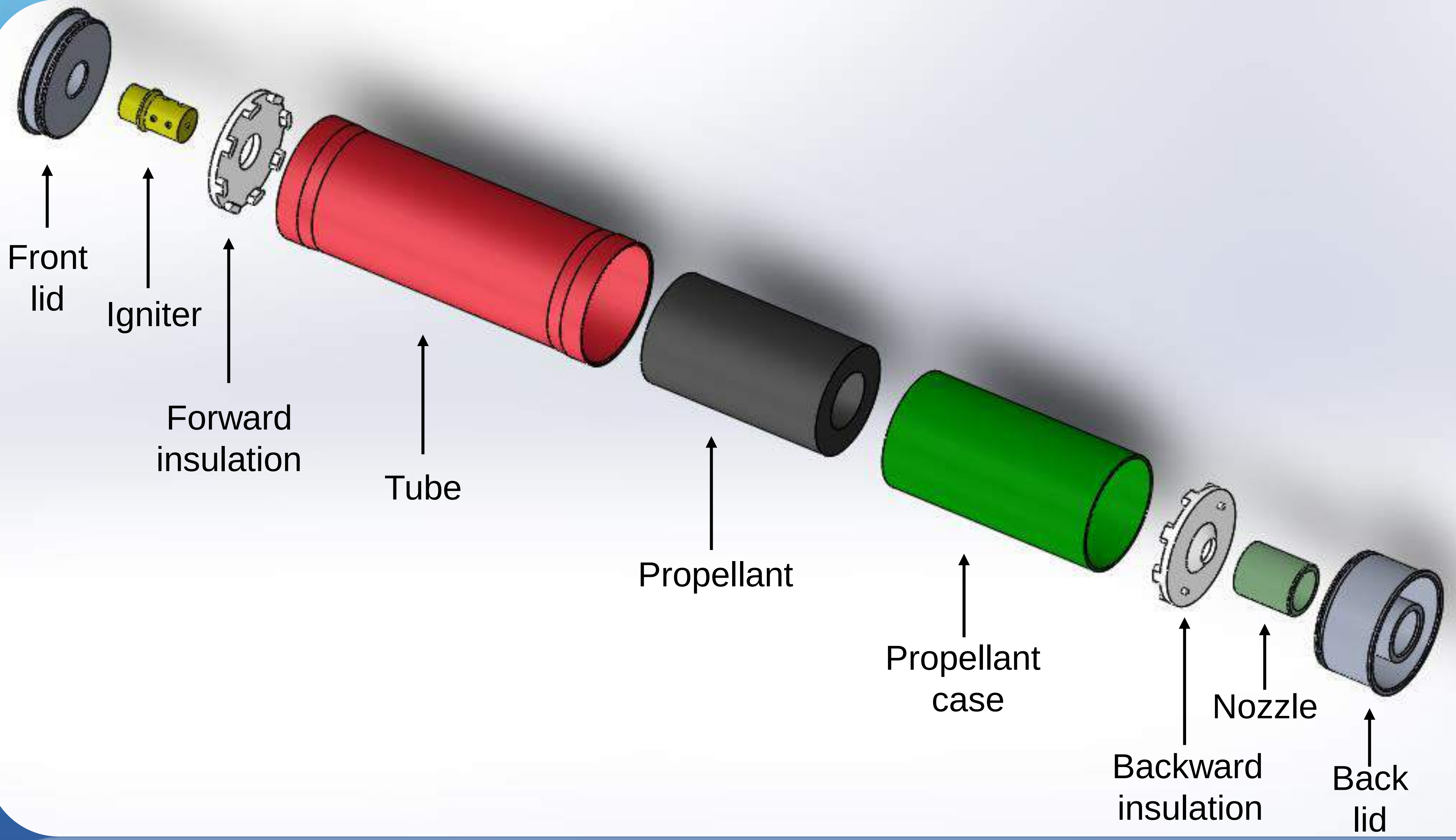
Pros:

- ✓ Endures the 75 [bar] pressure.
- ✓ Doesn't have pressure differences.
- ✓ Easy to Store in the missile's body.

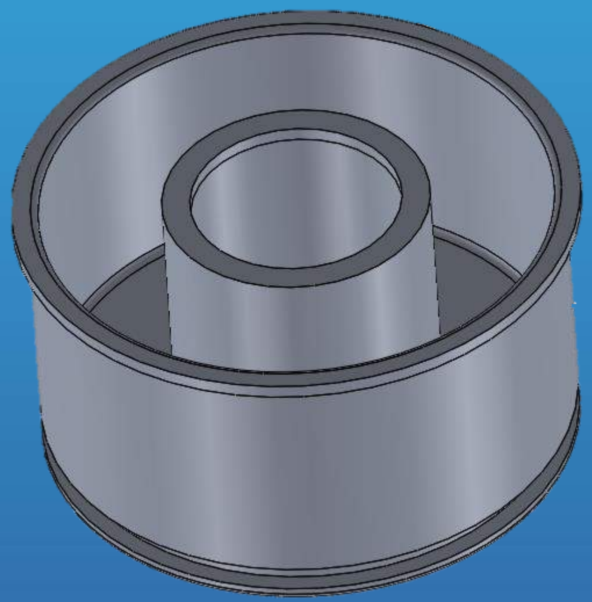


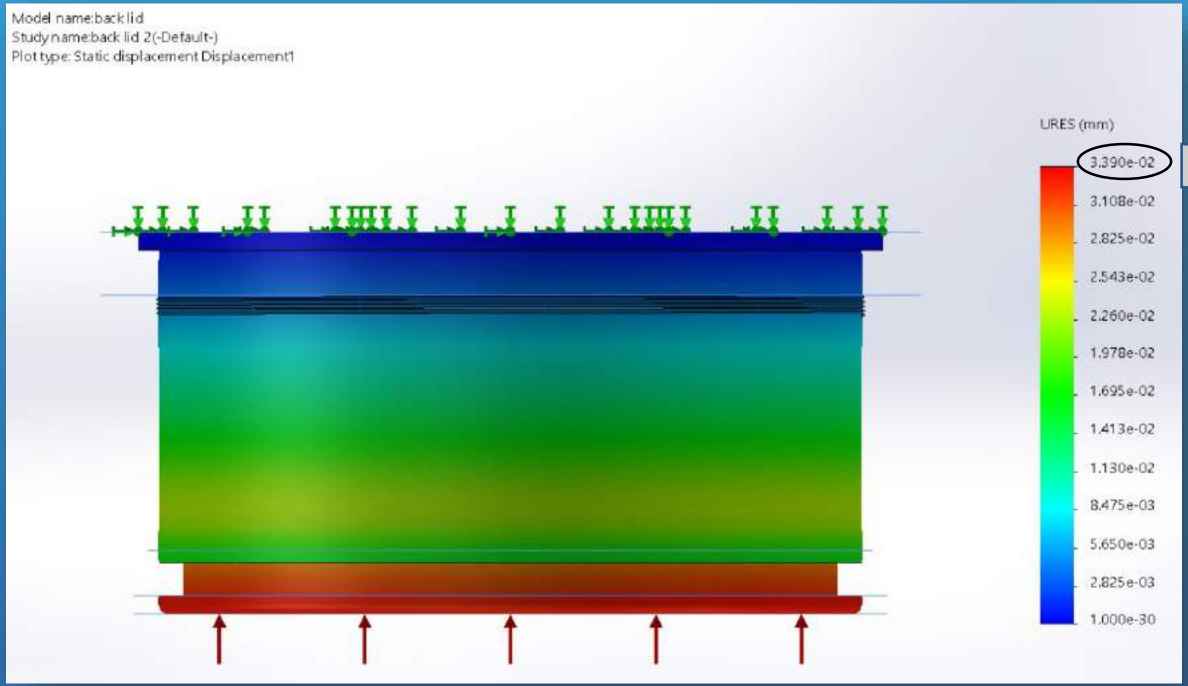
Main problems:

- ❑ Heavy tube – steel vs. aluminum.


Front lid
Igniter
Forward insulation
Tube
Propellant
Propellant case
Backward insulation
Nozzle
Back lid

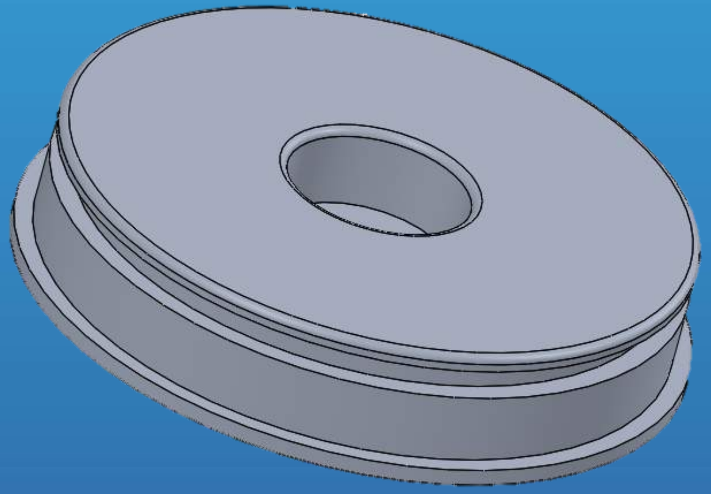
Stress analysis-75.5 bar
back lid

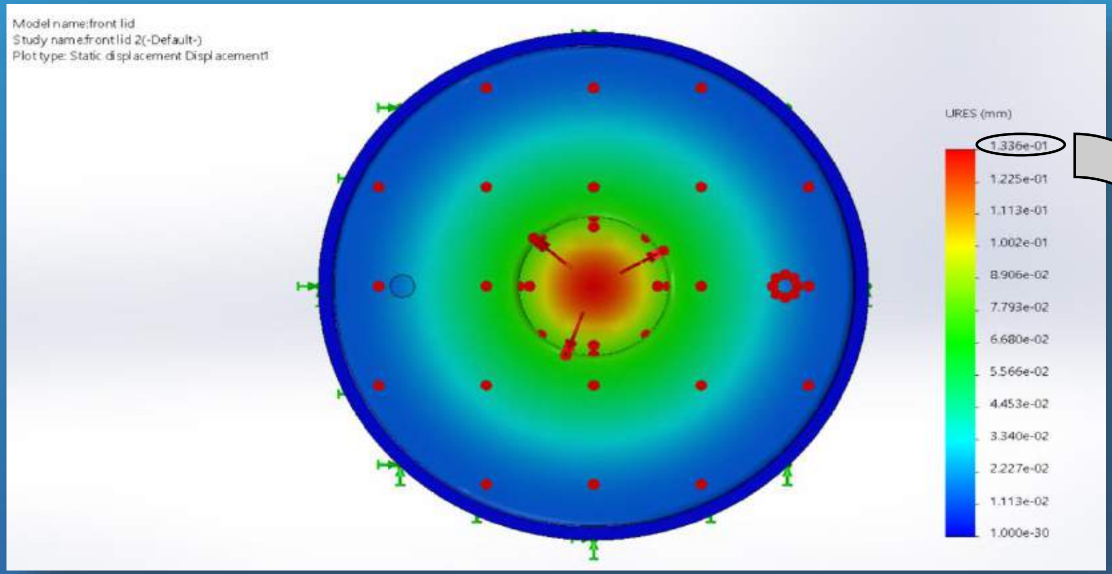




MAX DISPLACEMENT 3.39e-02 mm

Stress analysis-75.5 bar
front lid





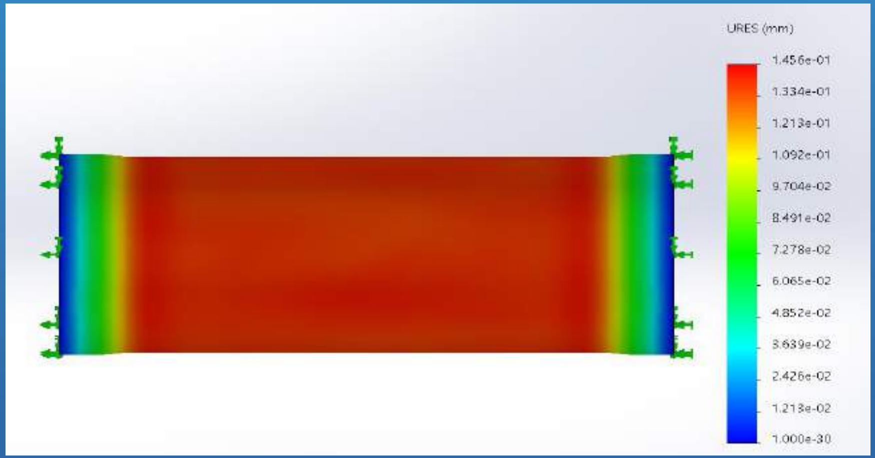
MAX DISPLACEMENT 1.36e-01 mm

Stress analysis-75.5 bar
Tube

Aluminum 7075 T6

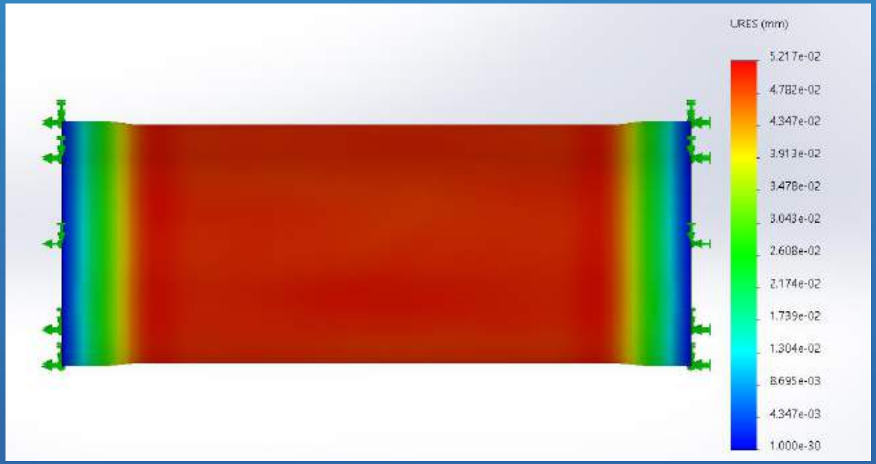
Stainless steel 4340

<u>MAX DISPLACEMENT</u>



1.456e-01 mm

5.217e-02 mm



After consulting with Natan Libis, we decided to continue with a steel Tube.
aluminum may not stand the thermal loads.

Weights

Name	Steel case(gr)	Plastic\rubber case(gr)
Propellant case	543	93
Propellant	620	620
Nozzle	55	55
Back lid	128	128
Front lid	123	123
Tube	494	494
Insulation	46	46
Igniter	58	58
Total	2067	1617

Tasks for next year

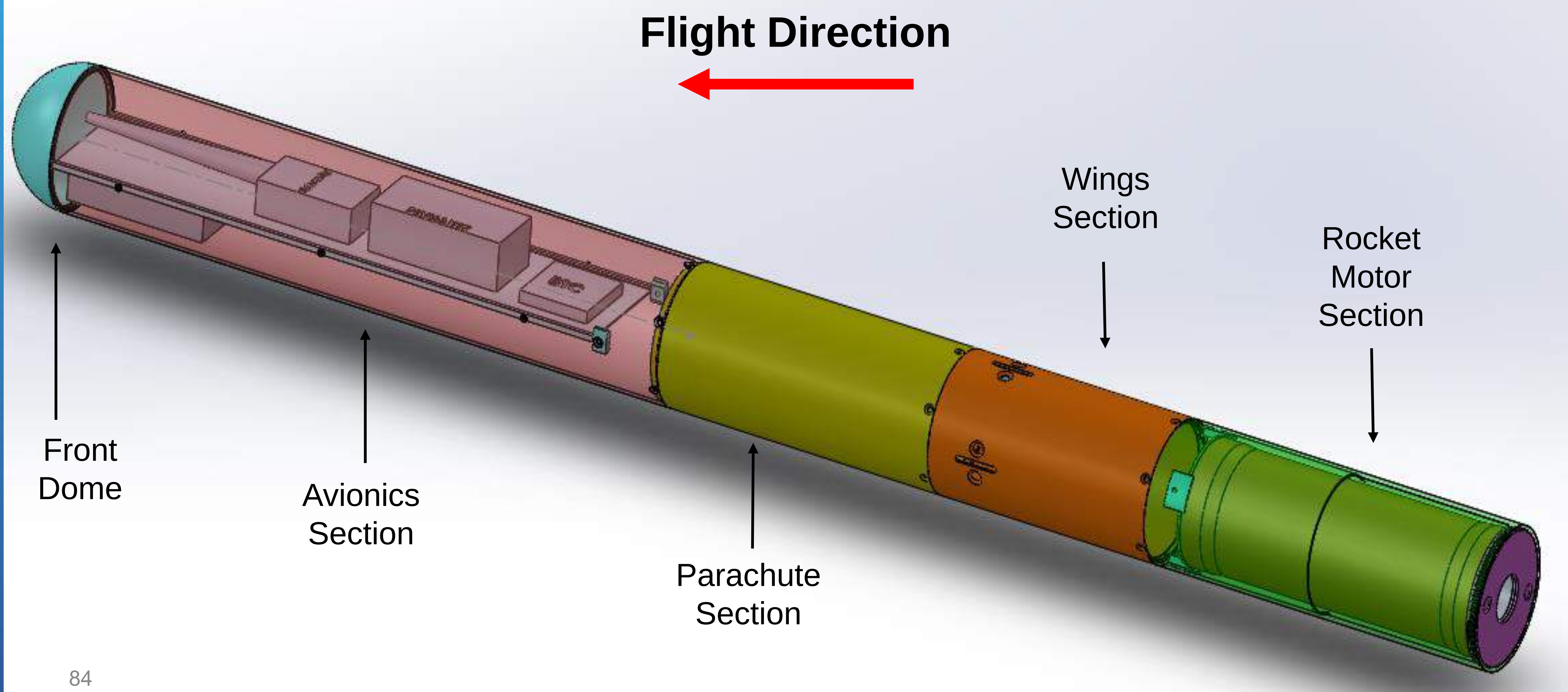
- Design threads for the motor domes.
- Manufacture the motor.
- Perform required tests.

STRUCTURE

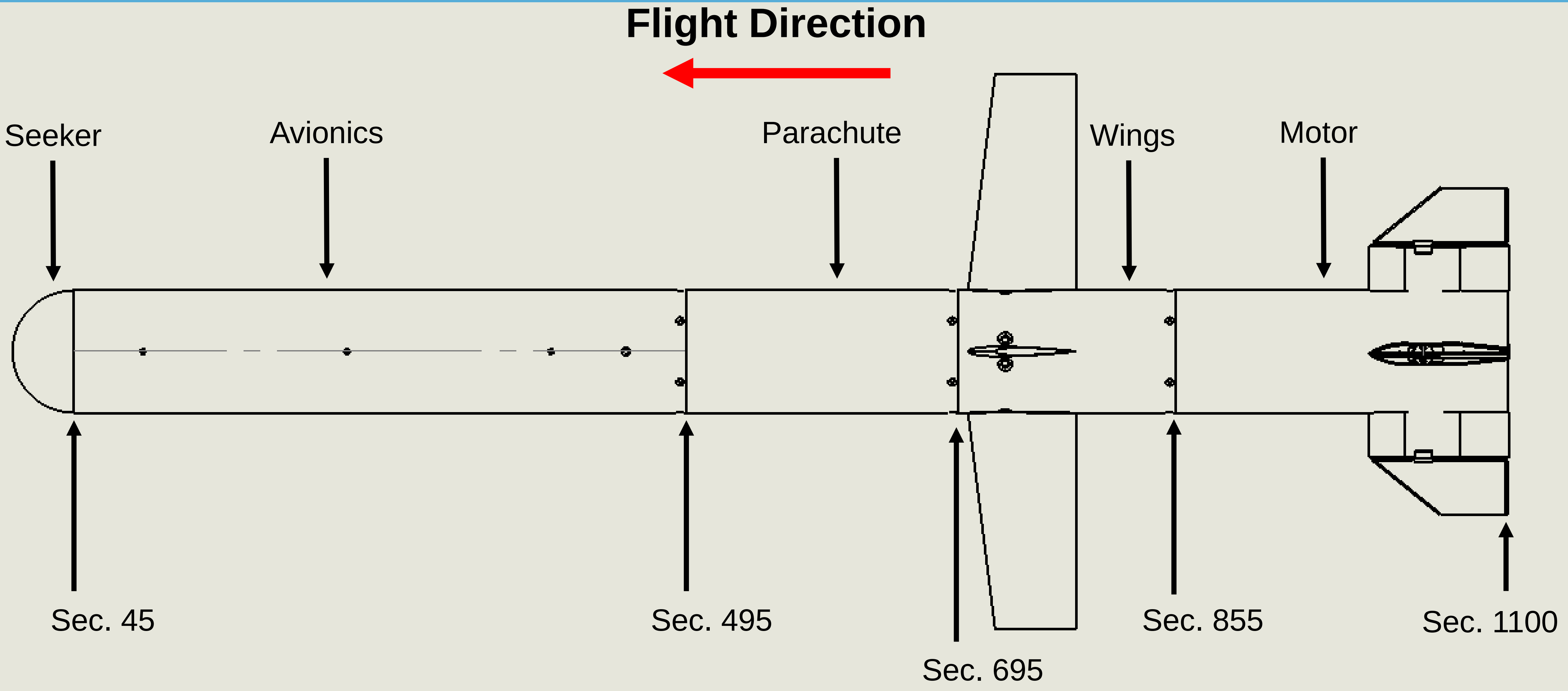
Missile Design

- Integrating work done by all groups into one model.
- What are missile parts? How do sections connect?
- What materials will be used for production?
- Stress analysis on different “force absorbing” components.
- Rocket Motor connection.
- Missile Recovery – concepts.

Missile Assembly

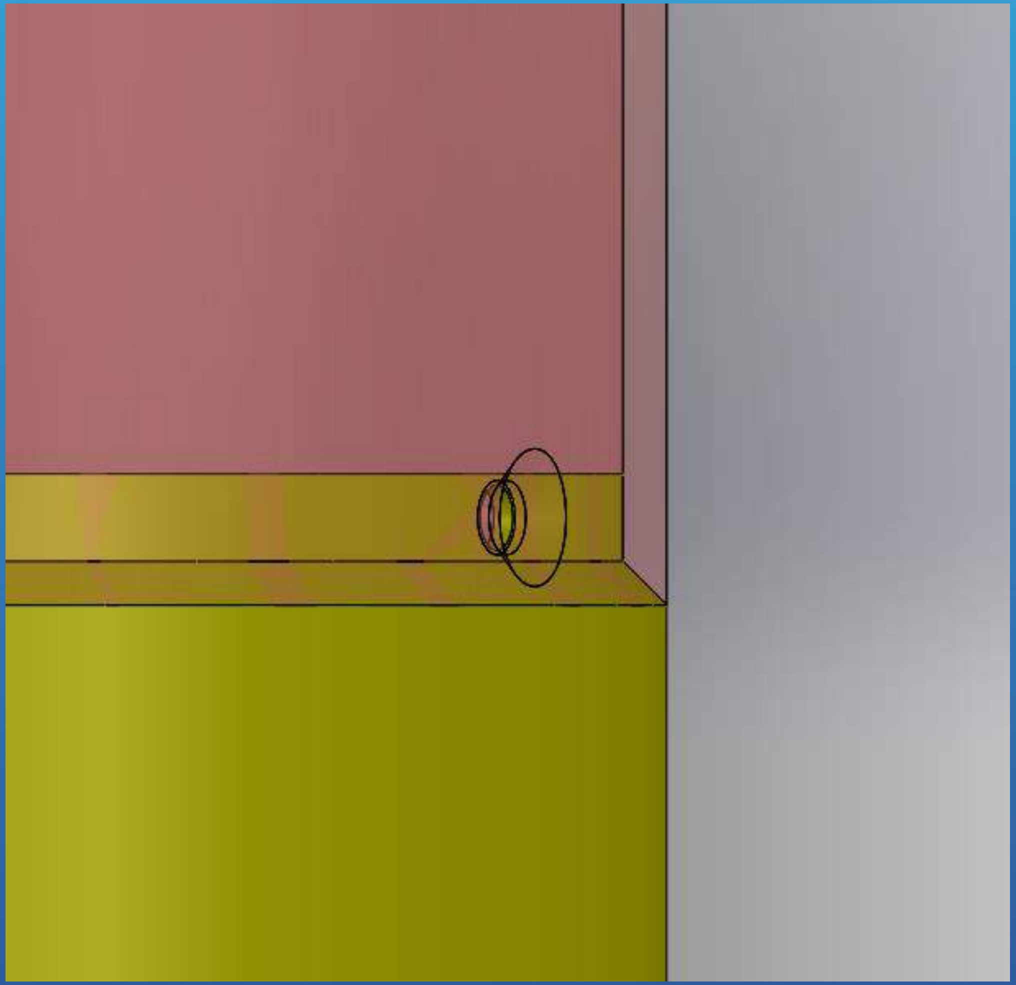


Missile Scheme



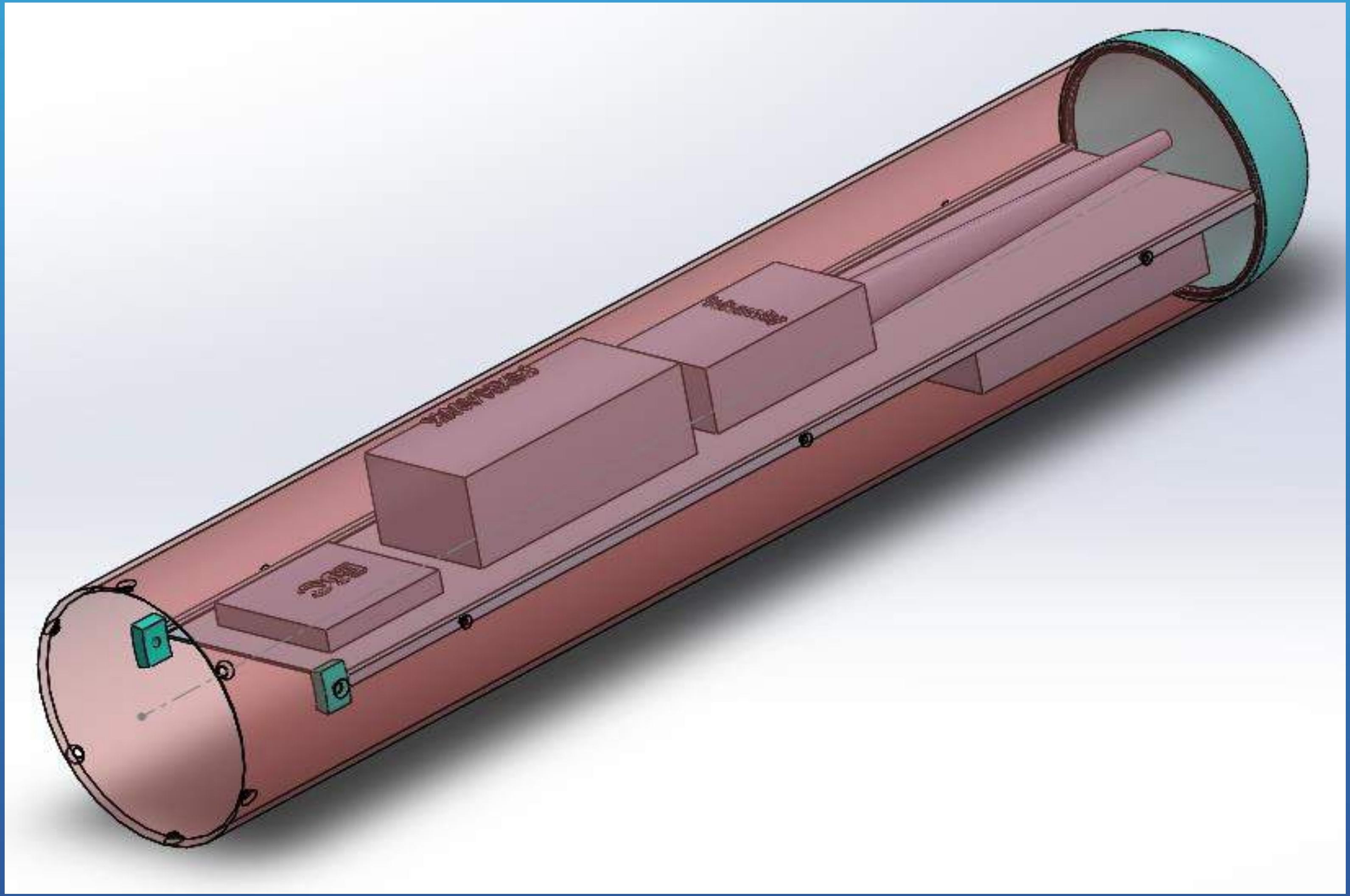
Sections Connection

- Sections are connected in a way so that they fit one inside another.
- Each section is connected to the other by 6 – M3 bolts.



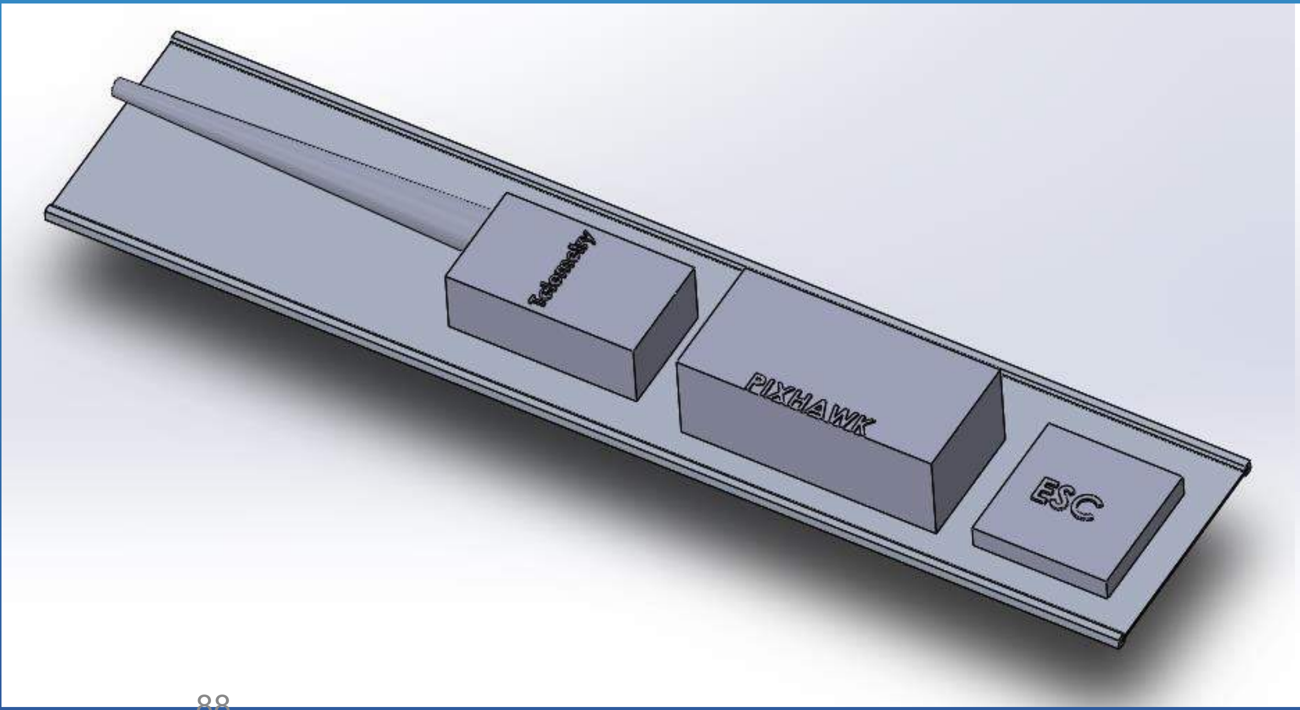
Avionics Section Assembly

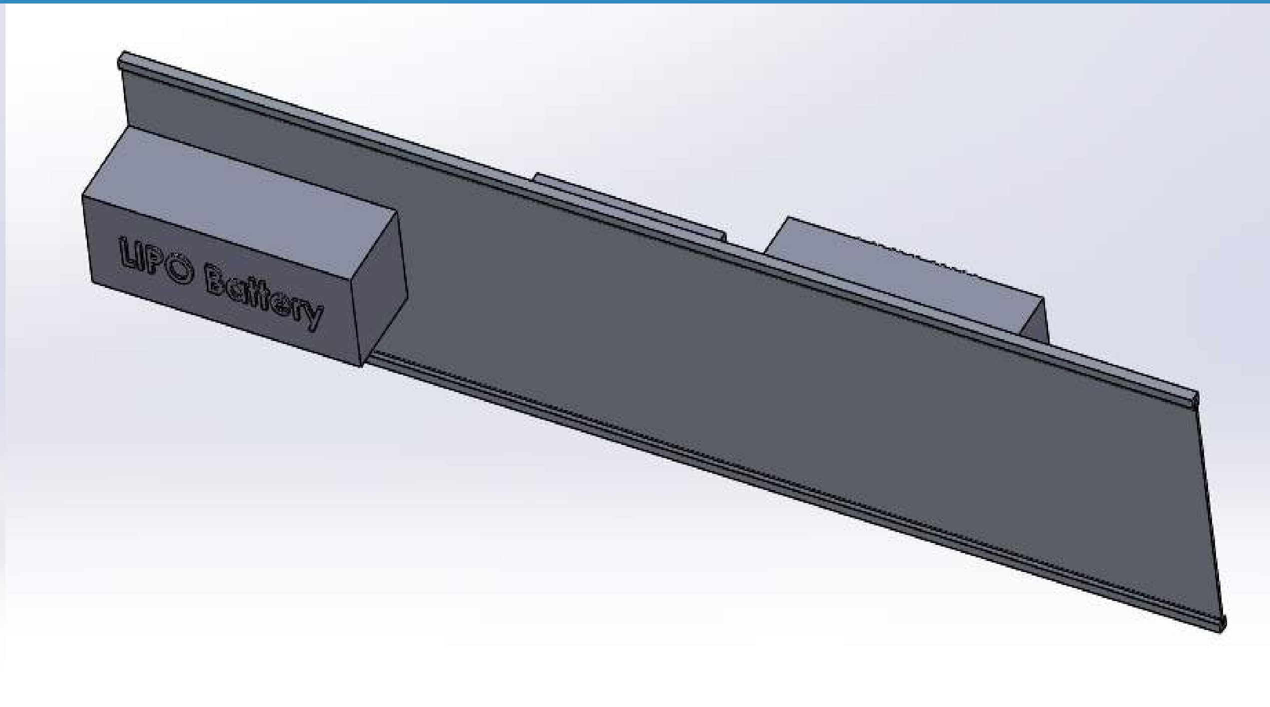
- Connected to front dome by screwing thread – not bolts.
- Contains all avionic equipment.



Avionics Section

- Layout from upper surface and bottom surface
- The section is made out of Fiberglass – for full GPS-Satellite reception

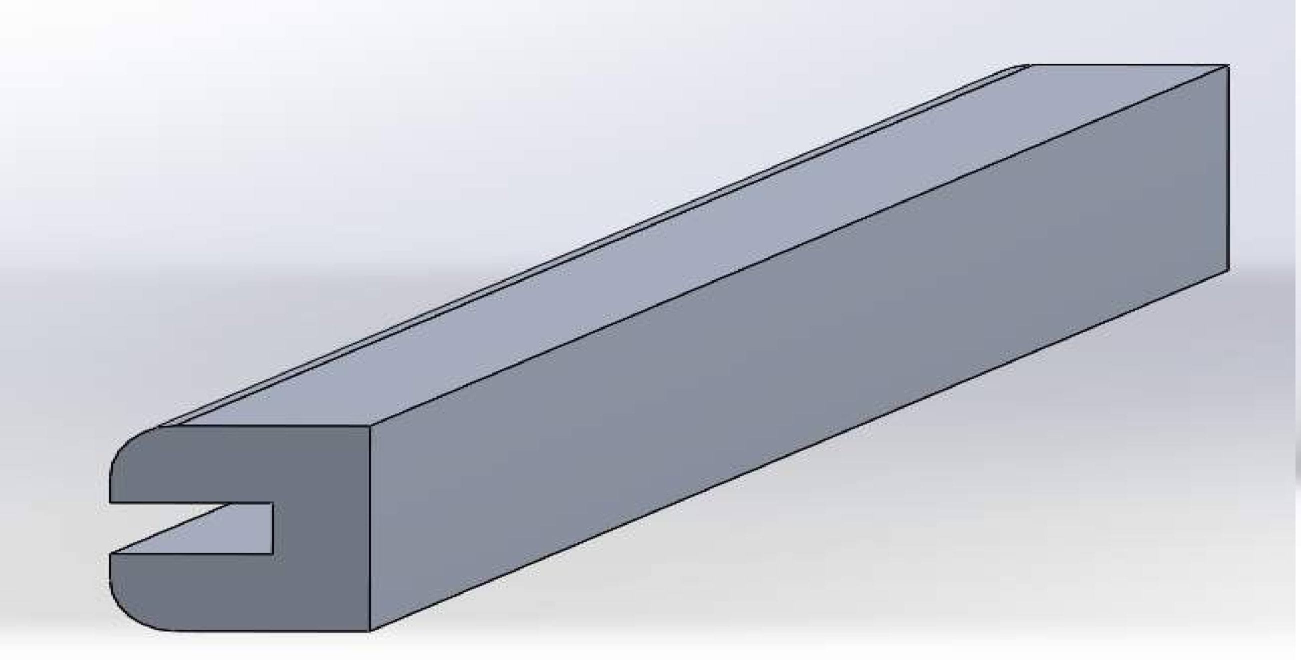




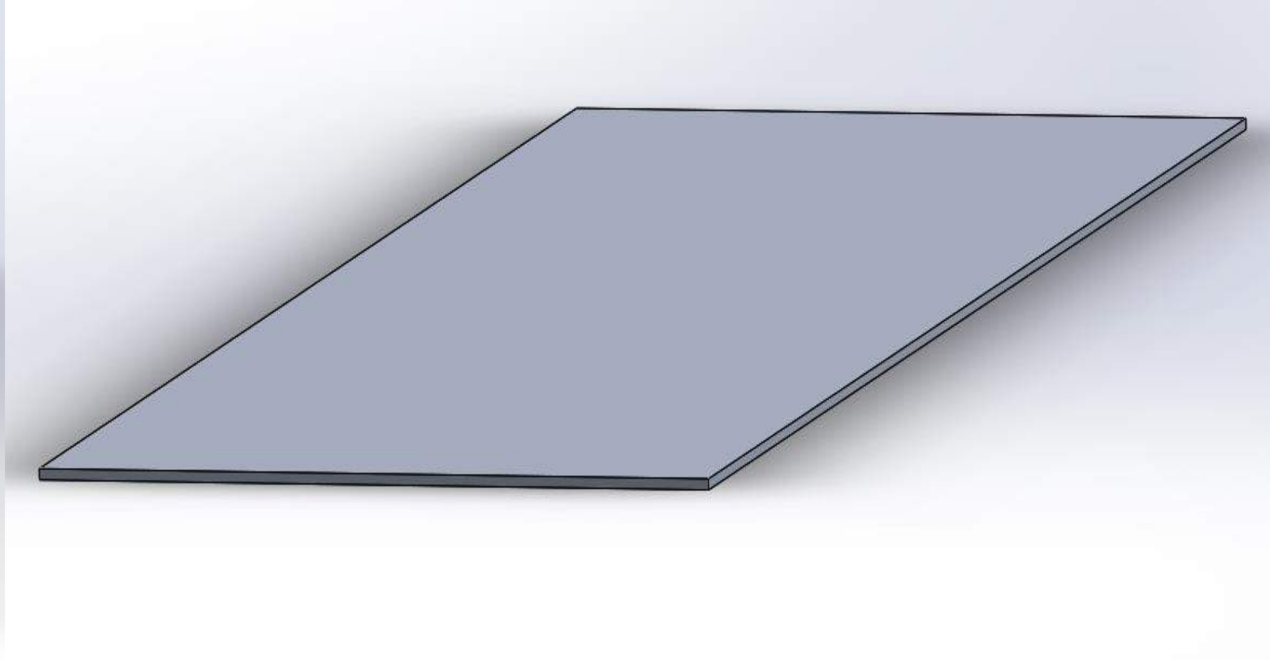
Avionics Section

- Avionic components are connected on a plate which slides in and out of a rail connected to missile body – ease of use.

Rail

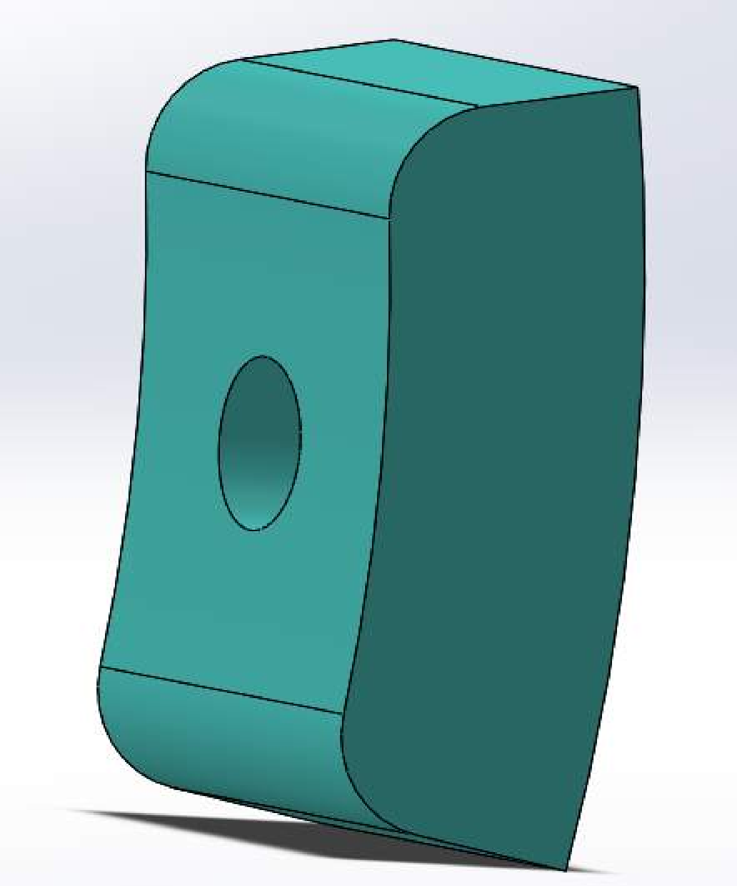


Plate



Rail Stopper

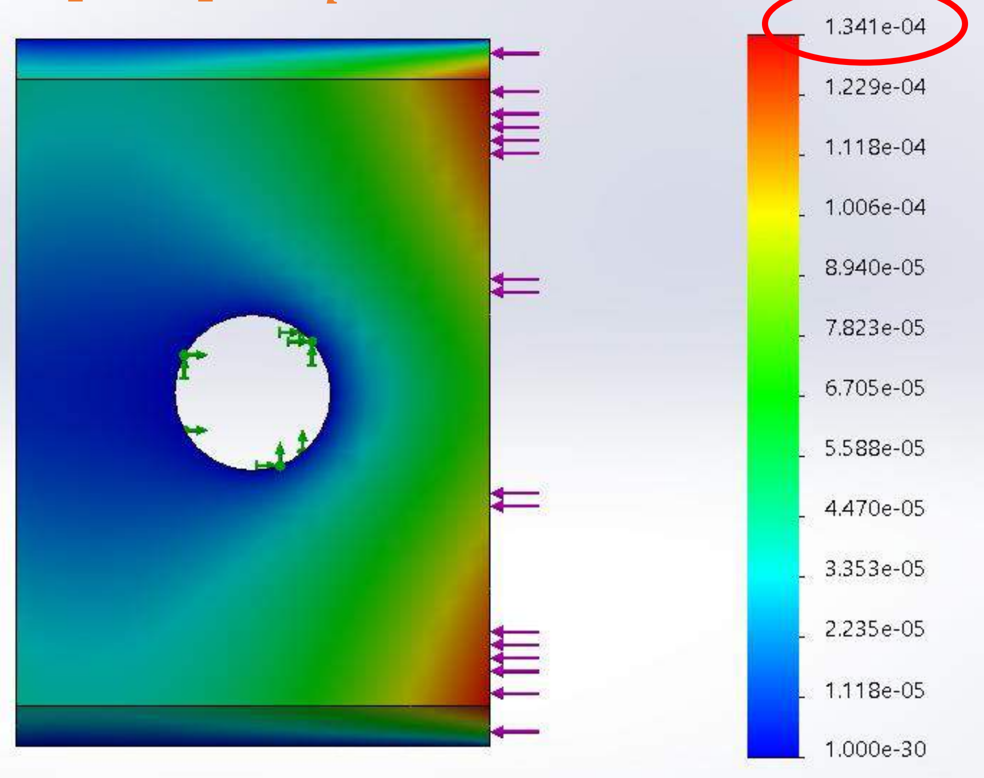
- With 15G's of force acting on avionic components = 75[N] on part



Stress

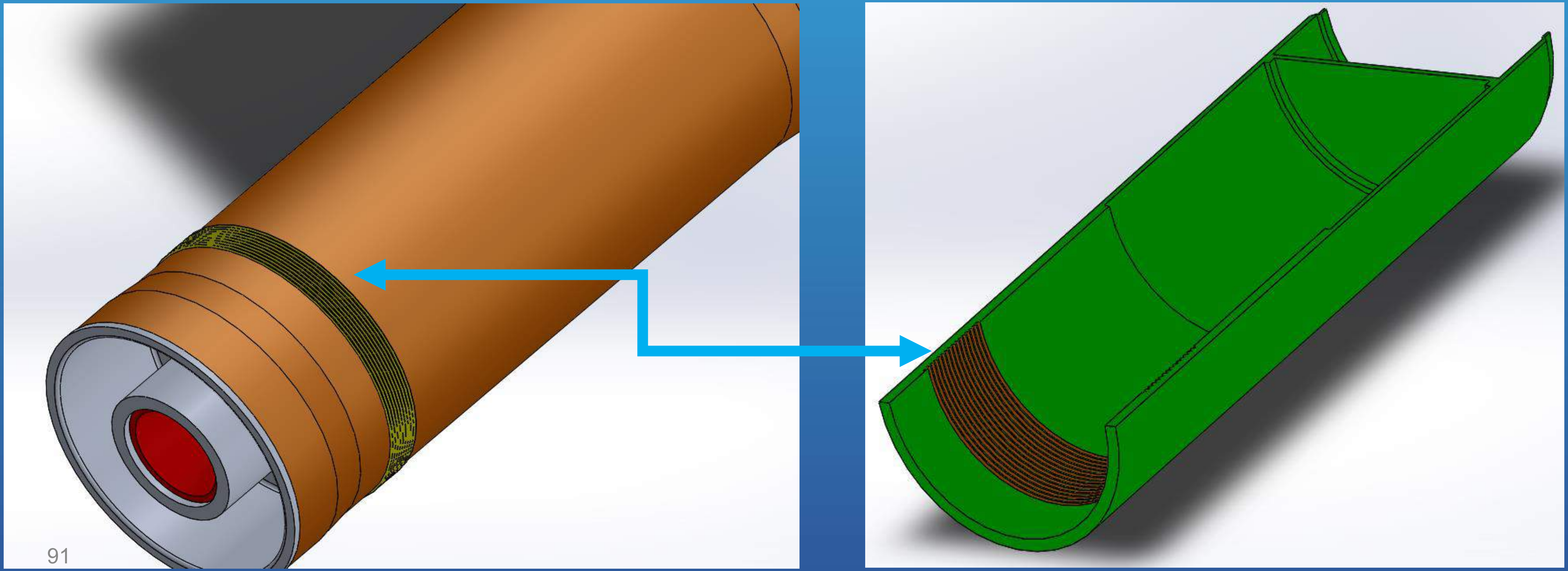
Analysis

$10^{-4}[mm]$ *displacement*



Motor Part – Screwing Concept

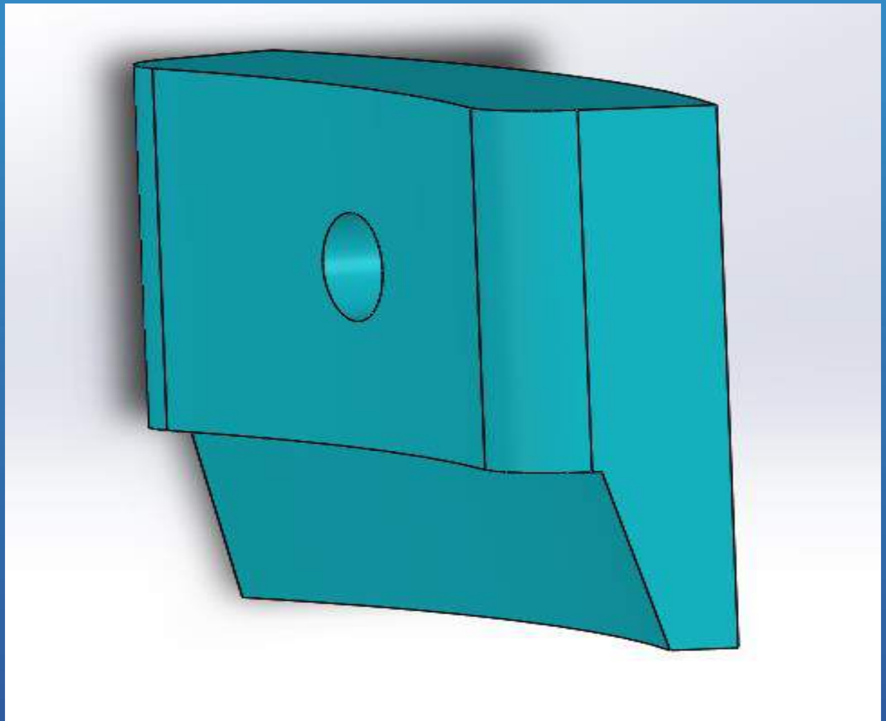
- Simple Concept
- Solid Propellant – cautious care.



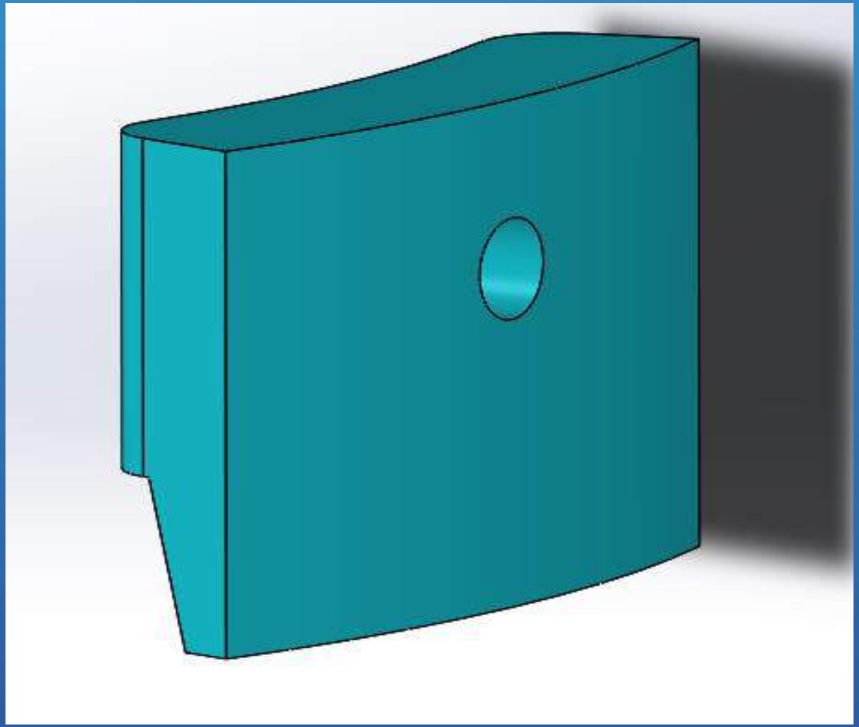
Front motor retainer

- This part supports the motor at the front of motor-missile connection.
- It also coaxially places the motor inside missile body.

Front



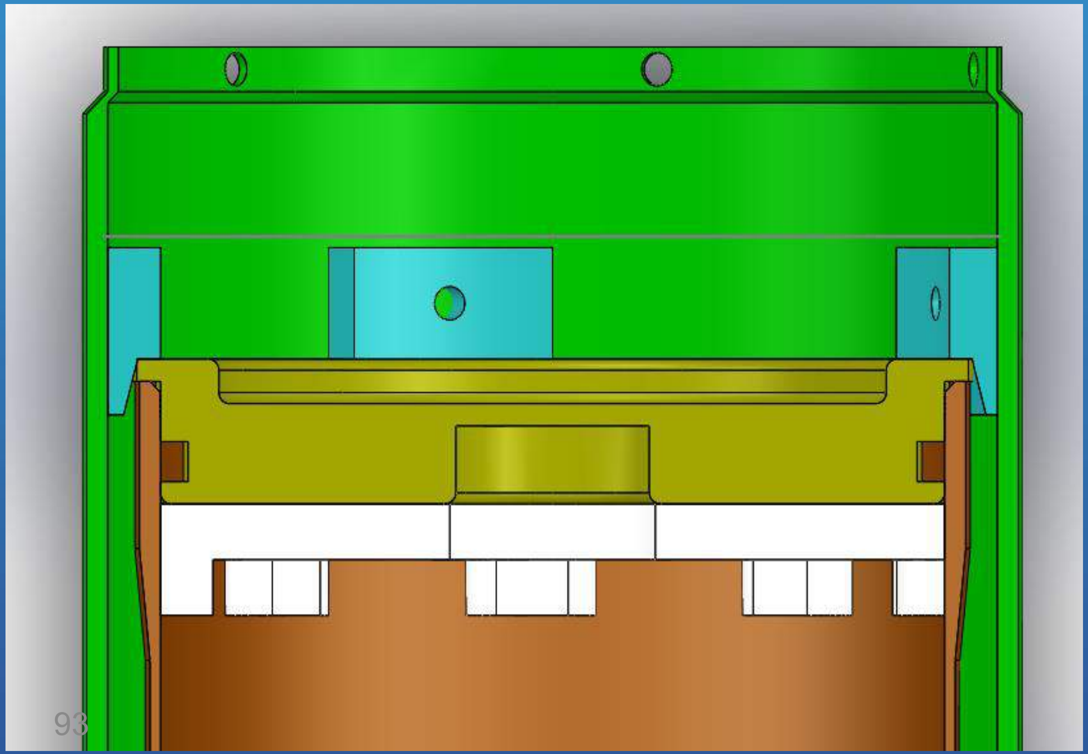
Rear



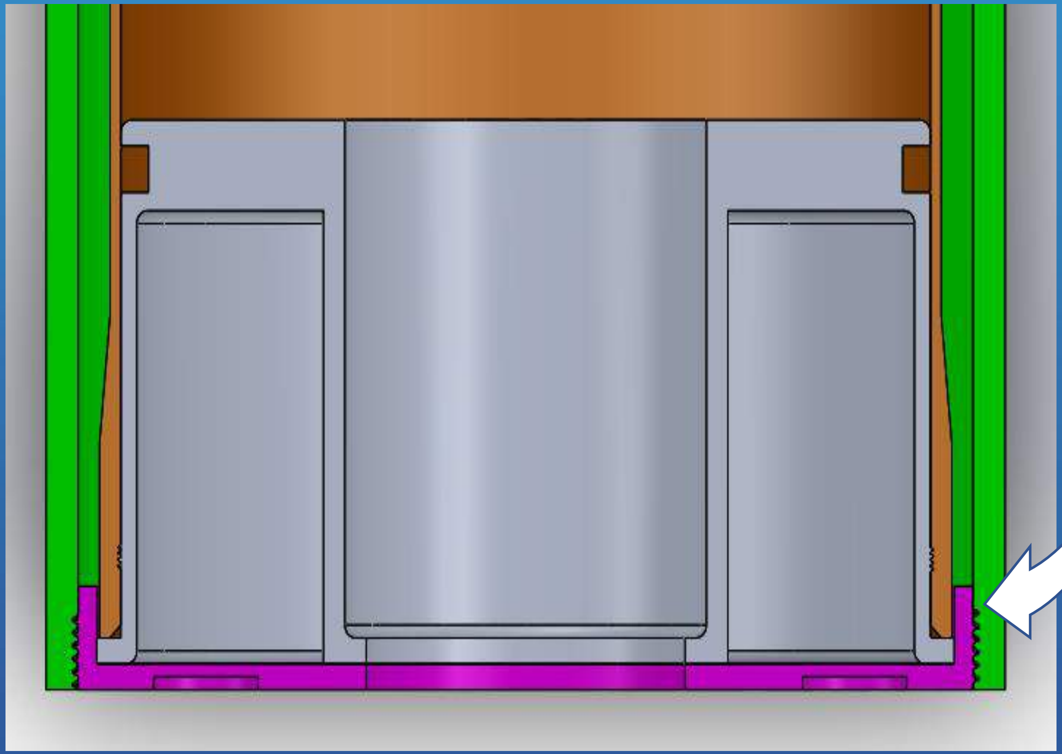
Motor - Missile Connection

- At aft motor is placed by motor retainer.
- At back motor is placed axially and coaxially by → fastener ring

Front



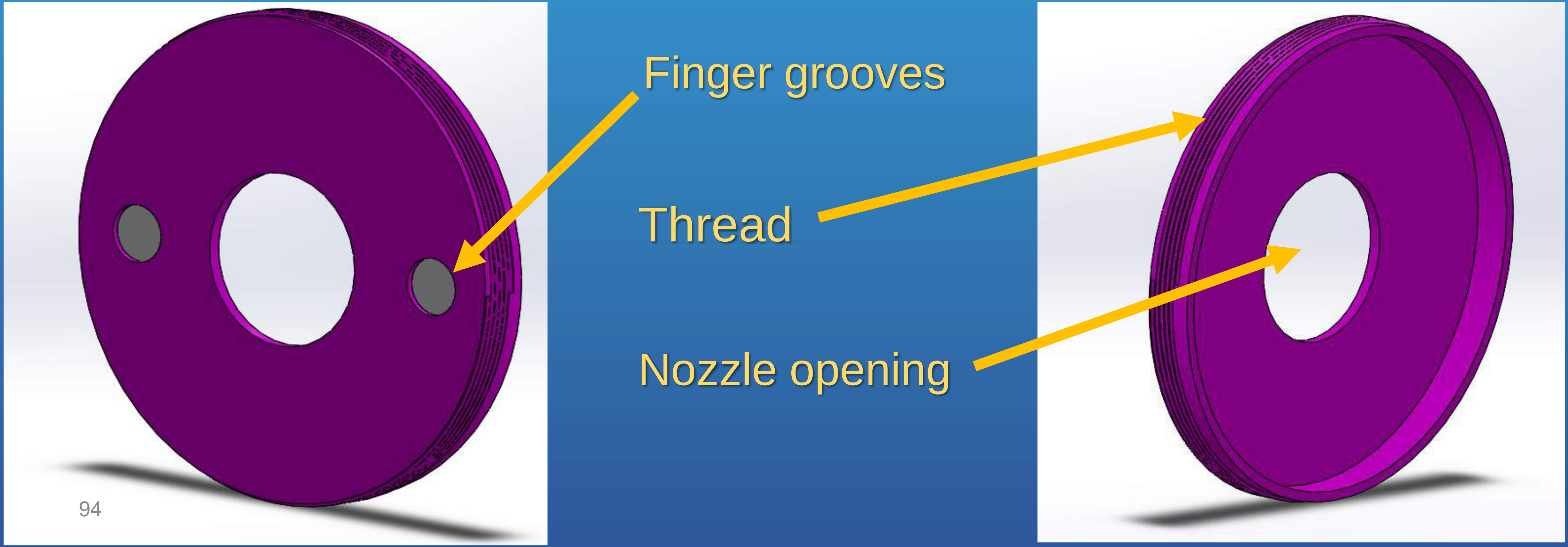
Rear



Fastener Ring

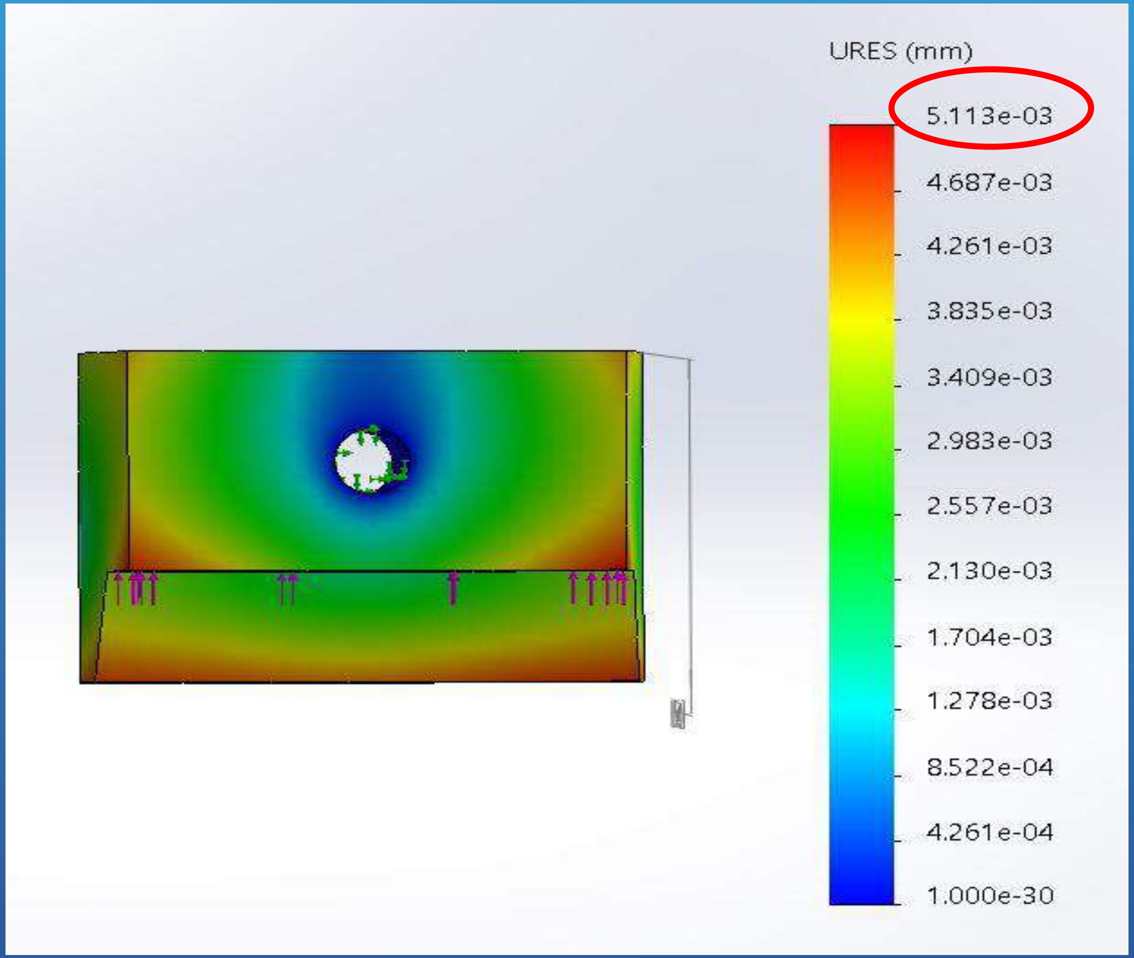
- Places the motor axially - lengthwise.
- Places the motor coaxially - aligned with the missile body.

Rear Front



Motor Retainer - Stress Analysis

$700[\mathrm{N}] \rightarrow 10^{-3}[mm]\ displacement$



Materials

Name	Thermal State	Tensile yield strength[MPa]	Ultimate tensile strength[Mpa]	Density $[\frac{g}{cm^3}]$
Aluminum 7075	T6	500	570	2.8
Aluminum Alloy 6061	T6	290	310	2.8
Aluminum Alclad 2024	T6	414	448	2.8
Stainless Steel 304	Cold Rolled	1103	1276	7.8
Stainless steel 17-4	H925	1207	1310	7.8

*Chosen is **Aluminum 6061** – For reasons of ease of manufacturing and cost.

Weight Distribution Table

Component weight

Component C.G location

Project Cornetto

Corentto - C.G LOCATION ESTIMATION

Component No.	Component weight [kg]	Component C.G location (relative to the nose) [m]	Mass X C.G location	Component Name	Additional Information / notes
1	0.6	0.7	0.42	WINGS	weight is of 4 (together)
2	0.06948	1.0607	0.073697436	CONTROL SURFACES	weight is of 4 (together)
3	0.06	1.05	0.063	SERVO HOUSINGS	weight is of 4 (together)
4	0.092	1.04	0.09568	SERVO MOTORS	weight is of 4 (together)
5	0.065	0.02255	0.06325	ROCKET HEAD\NOSE	
6	1.18	0.226	0.26668	AVIONIC SECTION	icluding avionic equipment
7	0.531	0.675	0.358425	WINGS SECTION	
8	0.498	1.17	0.58266	MOTOR SECTION	With Ring and stoppers
9	1.617	0.98027	1.58509659	ROCKET MOTOR	
10	0.5	0.03	0.015	PAYLOAD	
11	0.22	0.65	0.143	PARACHUTE (estimate)	
12					
13					
14					
TOTAL	5.43248	N/A	0.674919931		

Final Missile Properties

Property	Measure	Unit
Length	1100	[mm]
Weight with Propellant	5.43	[kg]
Weight (end of burn)	4.81	[kg]
Payload	500	[gr]
Parachute	220	[gr]
Wings	600	[gr]
Rocket motor	1617	[gr]

Parachute requirements

- After end of propellant burn and during the missile's second mission (max. gliding range)- we will want a parachute to open so we can control the missile's landing.
- The equation of forces acting on the missile during free-fall:

$$W = D = \frac{1}{2}\rho v^2 S C_D$$

- he value for the parachute's drag coefficient is about 1.75. Also, we will use standard sea level density which is $1.225\frac{kg}{m^3}$. The weight of the rocket is set to $W = 5 \cdot g \approx 49[N]$.
- After putting the data into the equation and setting terminal velocity to be $v = 7\frac{m}{sec}$:

$$S = \frac{2W}{\rho v^2 C_D} = \frac{98}{1.225 \cdot 49 \cdot 1.75} = 0.933m^2$$

Parachute requirements

- We chose a parachute with an area : $1.161m^2$, And also a drag coefficient : $C_D = 1.5 - 1.6$.
- A re-calculation will give us :

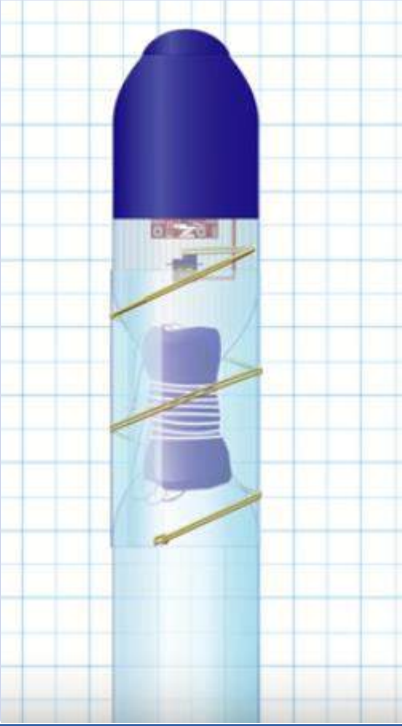
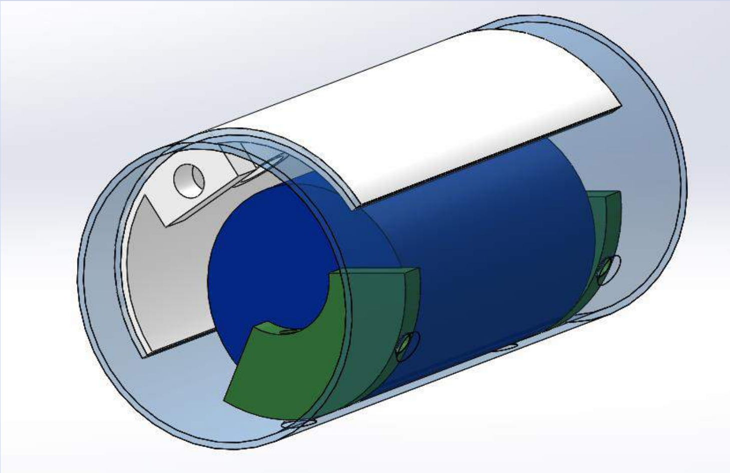
$$\frac{2W}{\rho S C_{D,max}} < v^2 < \frac{2W}{\rho S C_{D,max}}$$
$$\Rightarrow 43.11 < v^2 < 45.9$$
$$\Rightarrow 6.56\frac{m}{sec} < v < 6.78\frac{m}{sec}$$

- Velocity range is good for us (minimal terminal speed is $5\frac{m}{sec}$).

Parachute Concepts

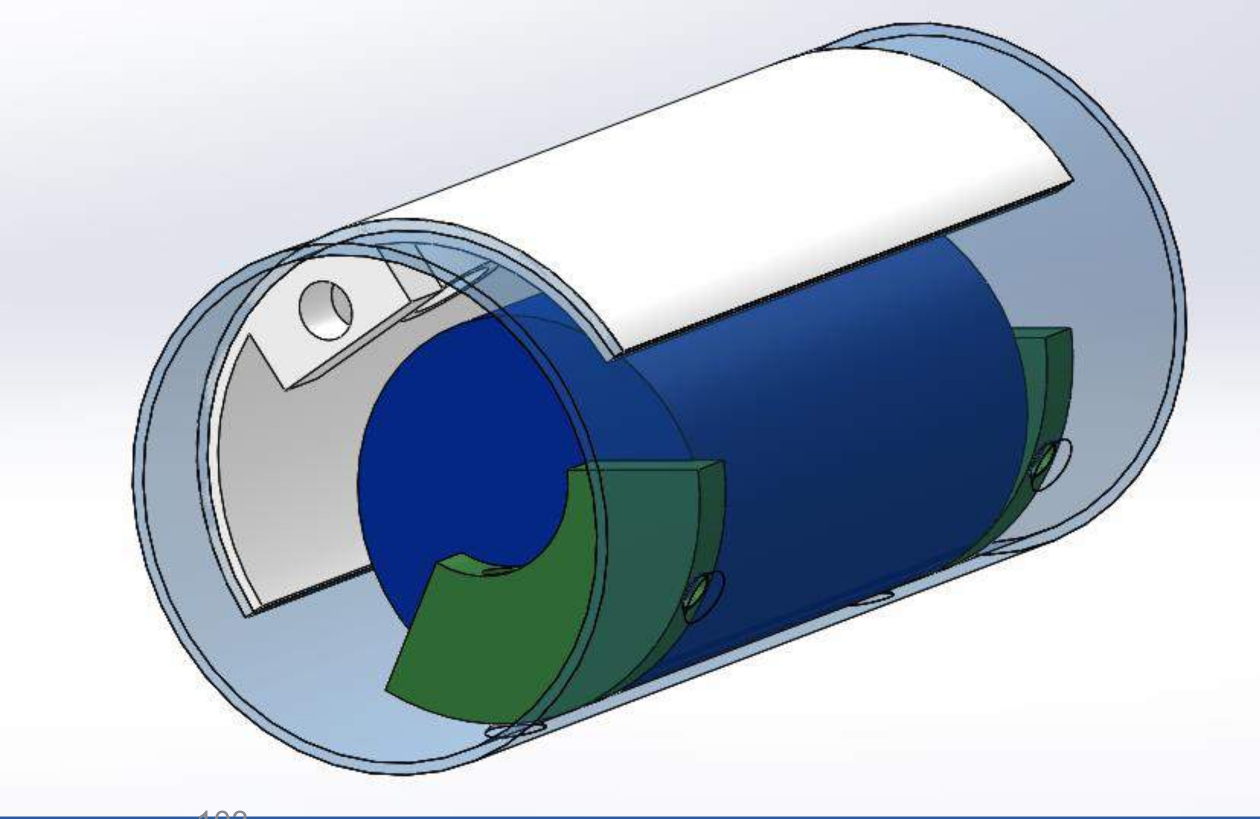
First Concept – 2 piece missile	Second Concpet – Body narrowing, parachute enwarping	Third concept- removable door
• Popular concept with a lot of online information	• Simple and modular mechanism • Easy to assemble and disassemble	• Simple design (relatively to the other solutions) • Easy to maintenance • Fitting with COTS
• Could harm missile structure • Could harm avionic wiring along the missile • Problem with using GPS • Problem with section screwing • Exposure sensitive parts at dangerous environment	• Problem with weight wrapping on body • Parachute deployment is hard to engineer • Problem with section screwing • Possible stress concentration on the narrow part	• Release timing problems

Parachute Concepts

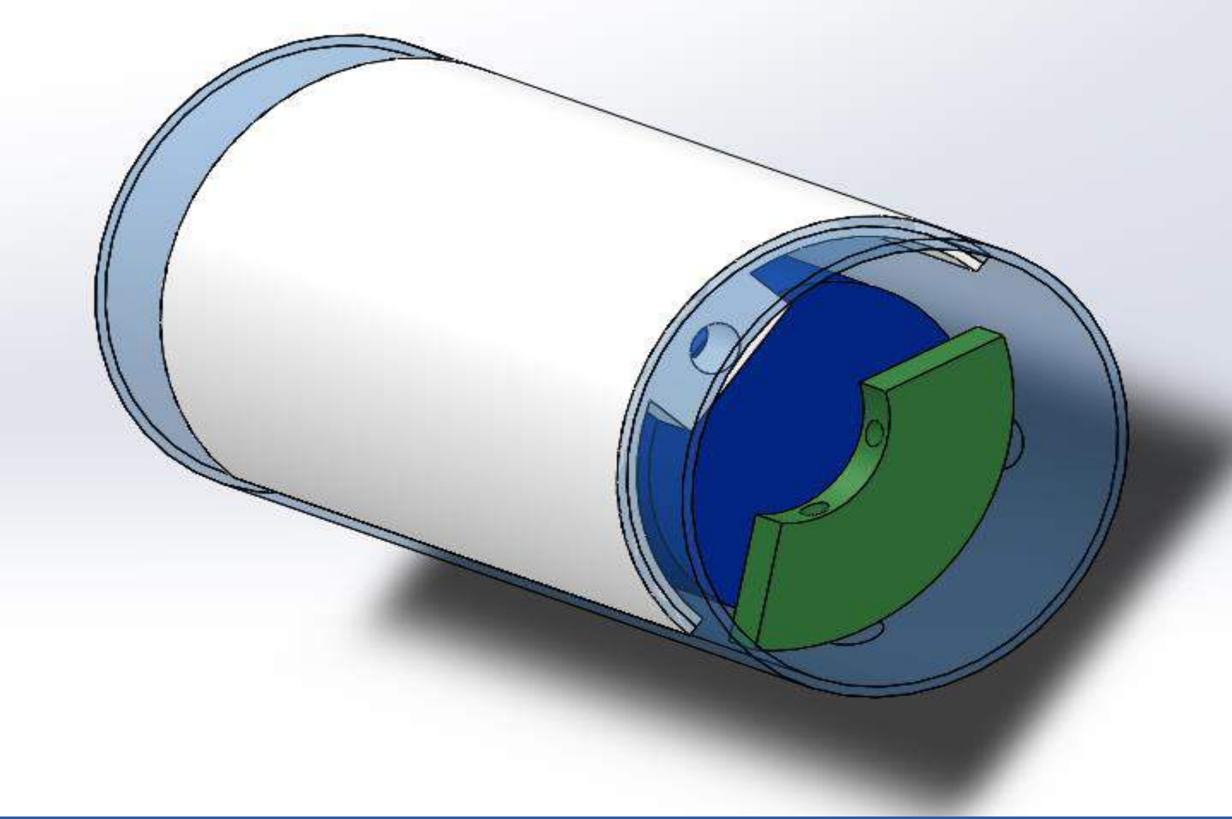
First Concept – 2 piece missile	Second Concpet – Body narrowing, parachute enwarping	Third concept- removable door
		

Parachute

Front



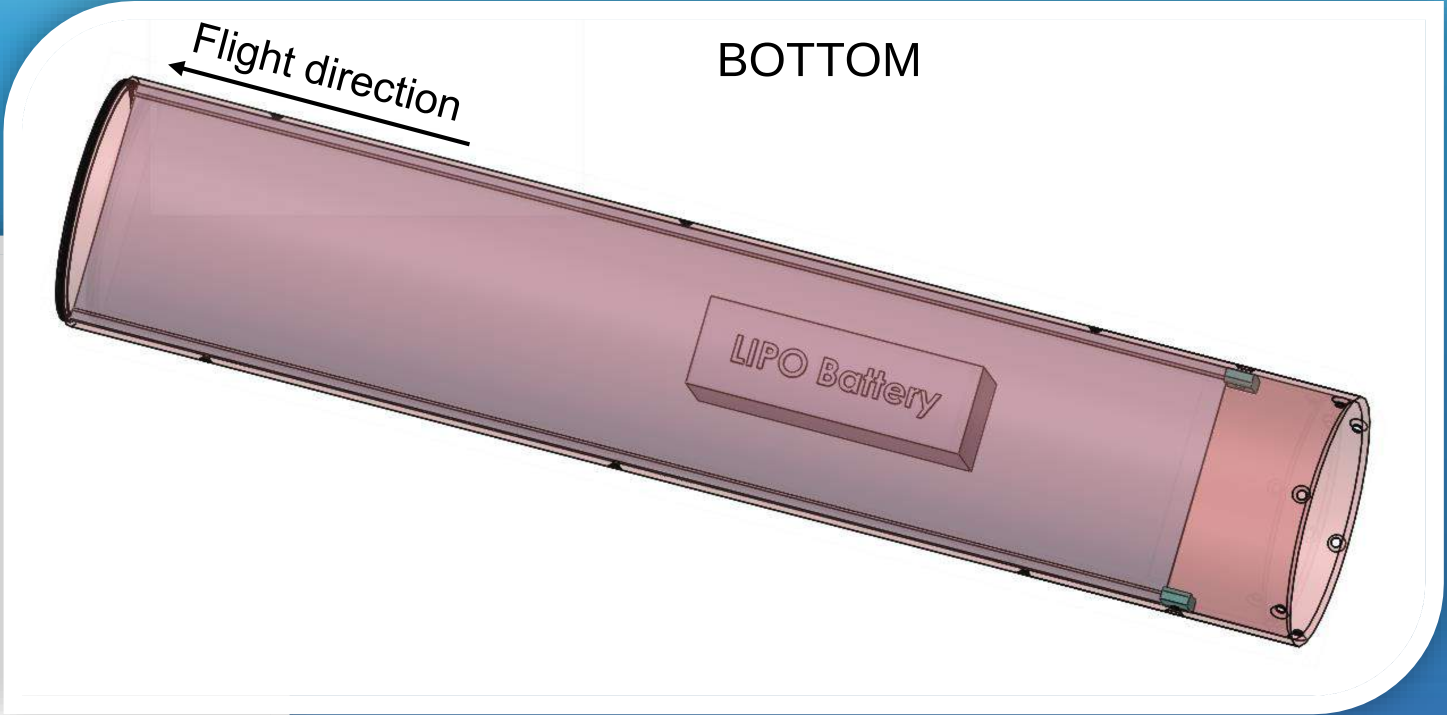
Rear

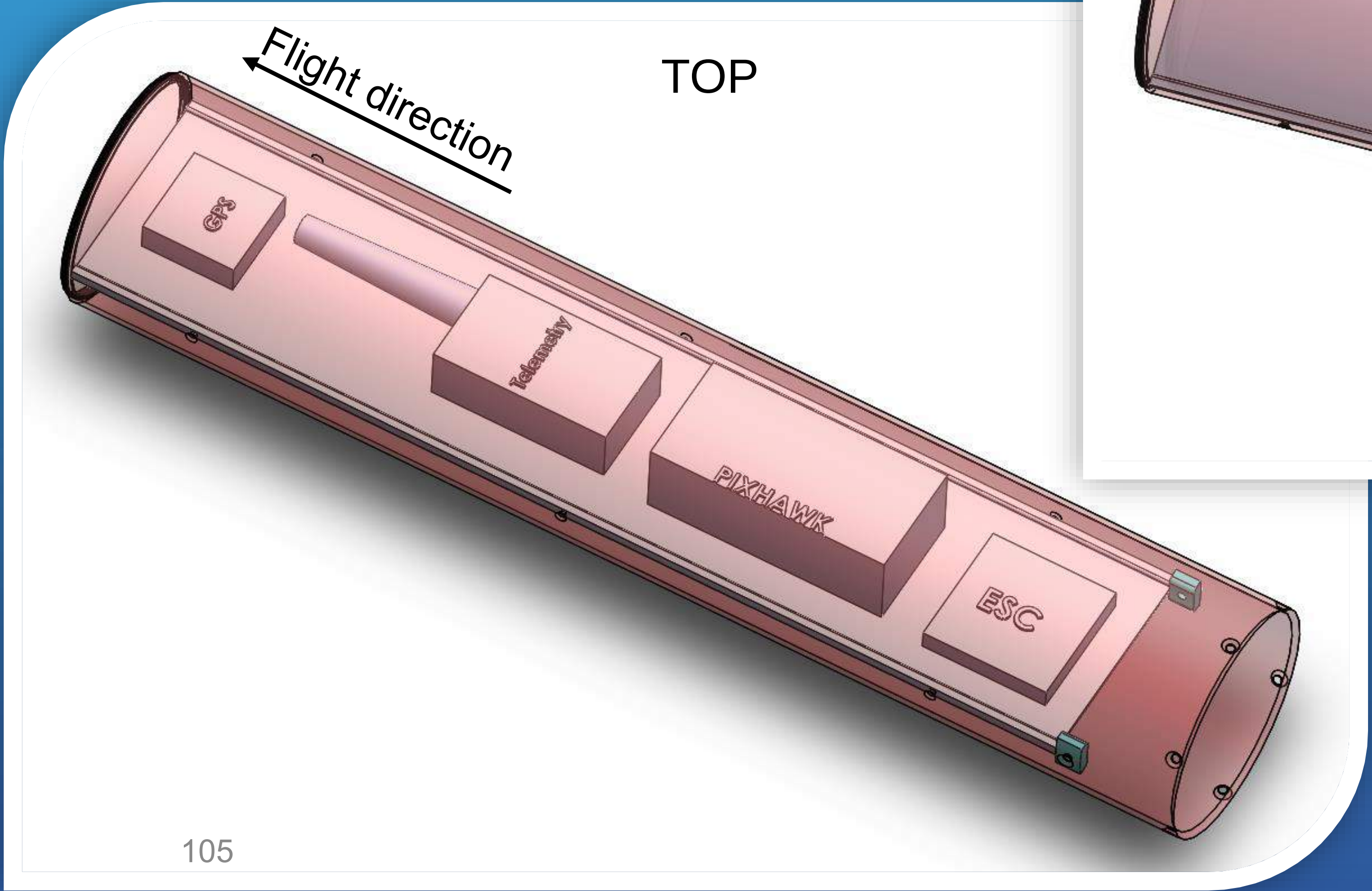


AVIONICS

Avionics

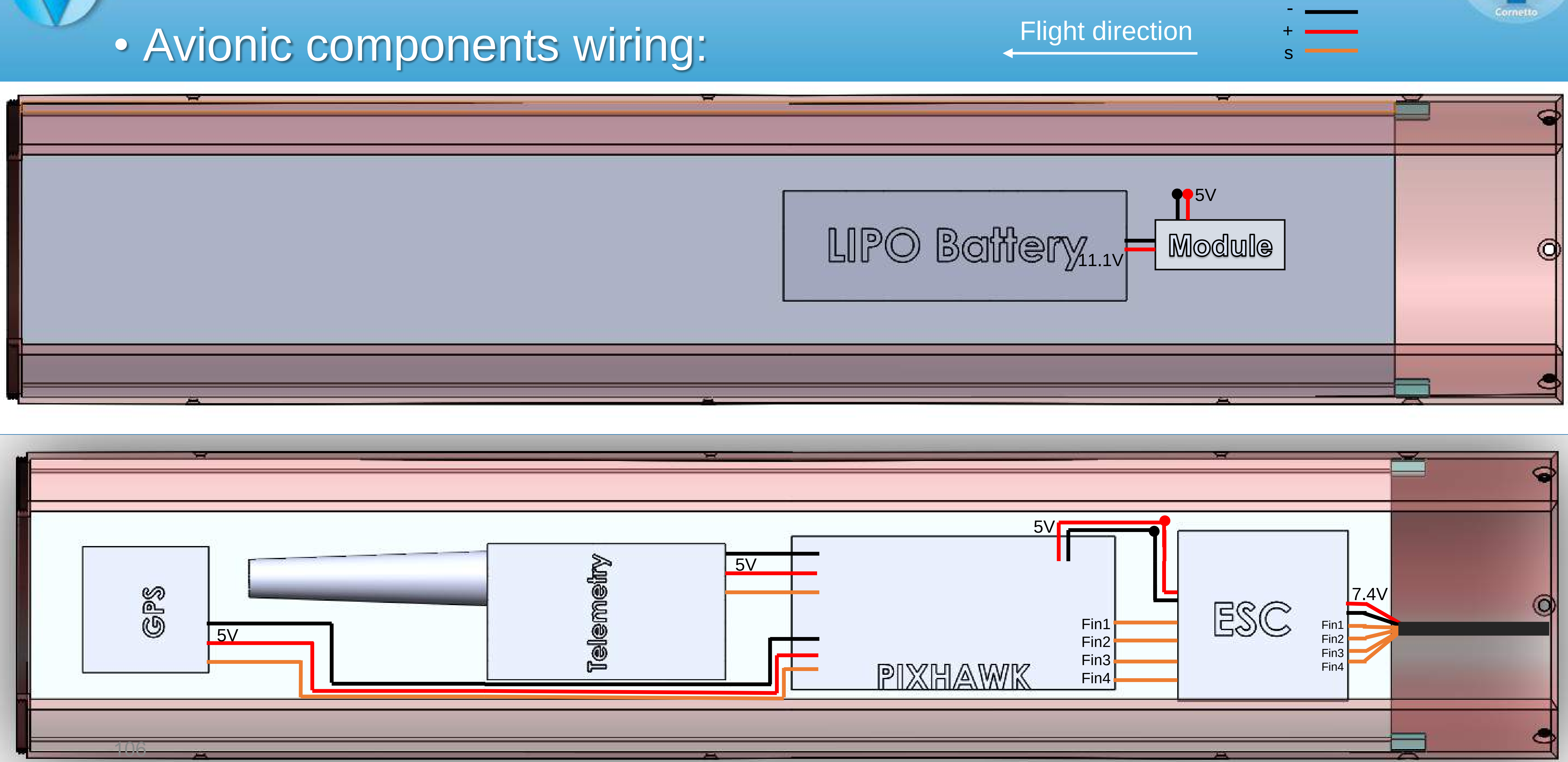
- Avionic components section:





Avionics

- Avionic components wiring:



ESC – Electronic Speed Controller

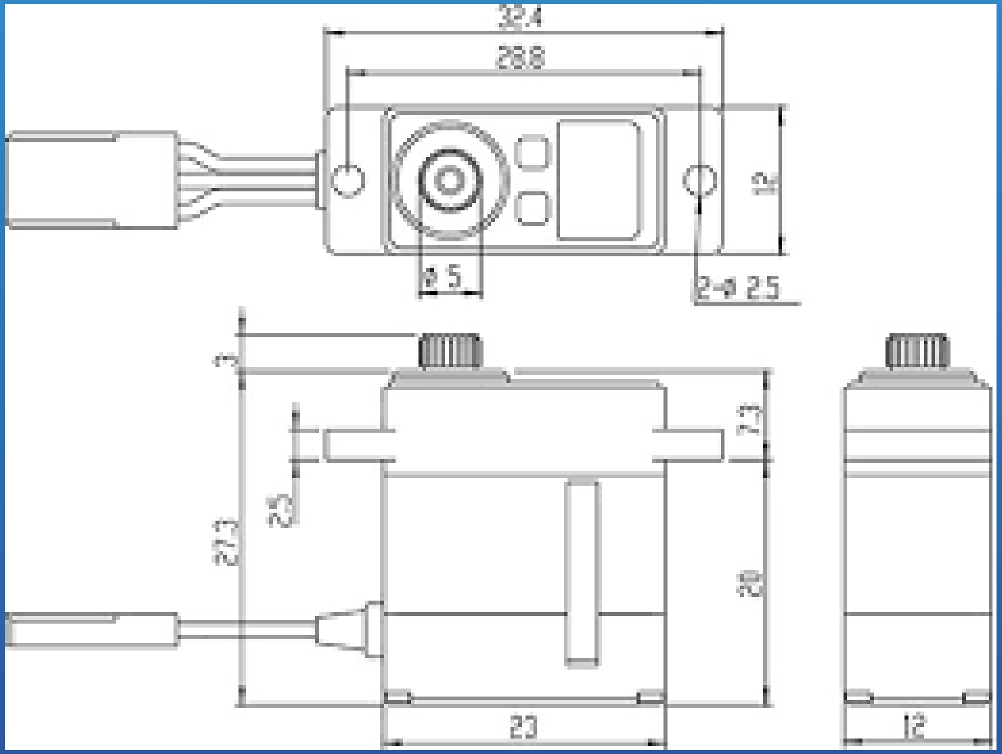
Avionics Power Consumption

- This analysis is from last year's work.
- Battery of 11.1v 1800mAh is used. This power source should be sufficient to power all avionic components.
- Maximum Time of flight is around 2 minutes.
- The current that needs to be supplied is around 4250mA.
- The calculation of the avionics current usage gives: $\frac{1800[mAh]}{4250[mA]} \approx 25[min]$

New Servo Specifications

The new servos are Savox model 1232MG

- Servo Technology: Digital High Voltage
- Input Voltage (V): 6.0V – 7.4V
- Motor Type: Coreless Motor
- Gear Material: Metal Gears
- Servo Case: Aluminium – Composite
- Servo Power – Torque kg·cm : 5 – 10 kg·cm
- Servo Speed 60°/sec: 0.05 – 0.10 Sec/60°
- Weight (g): 23 g

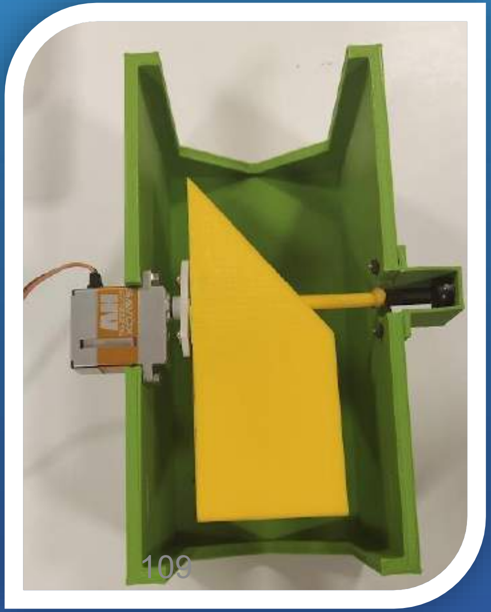


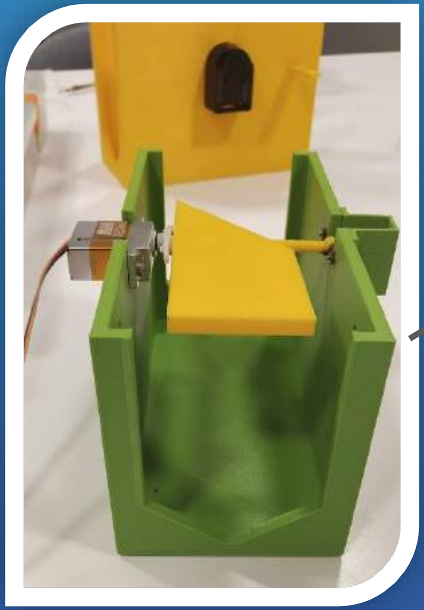
New Servo Identification

Servo transfer function identified with the use of:

1. A robust device was designed and 3D printed.
2. Control surface inertial and mass properties are 1:1.
3. Servo axis is on the Center of Pressure calculated by aerodynamics team using CFD, loads were not tested yet.
4. Potentiometer and Optical rotary encoder were used to test the servo.
5. On board the missile the possibility of closing a loop on the servos output by its own servo has been discussed but not yet implemented.

Potentiometer:
High Voltage
1kOhm



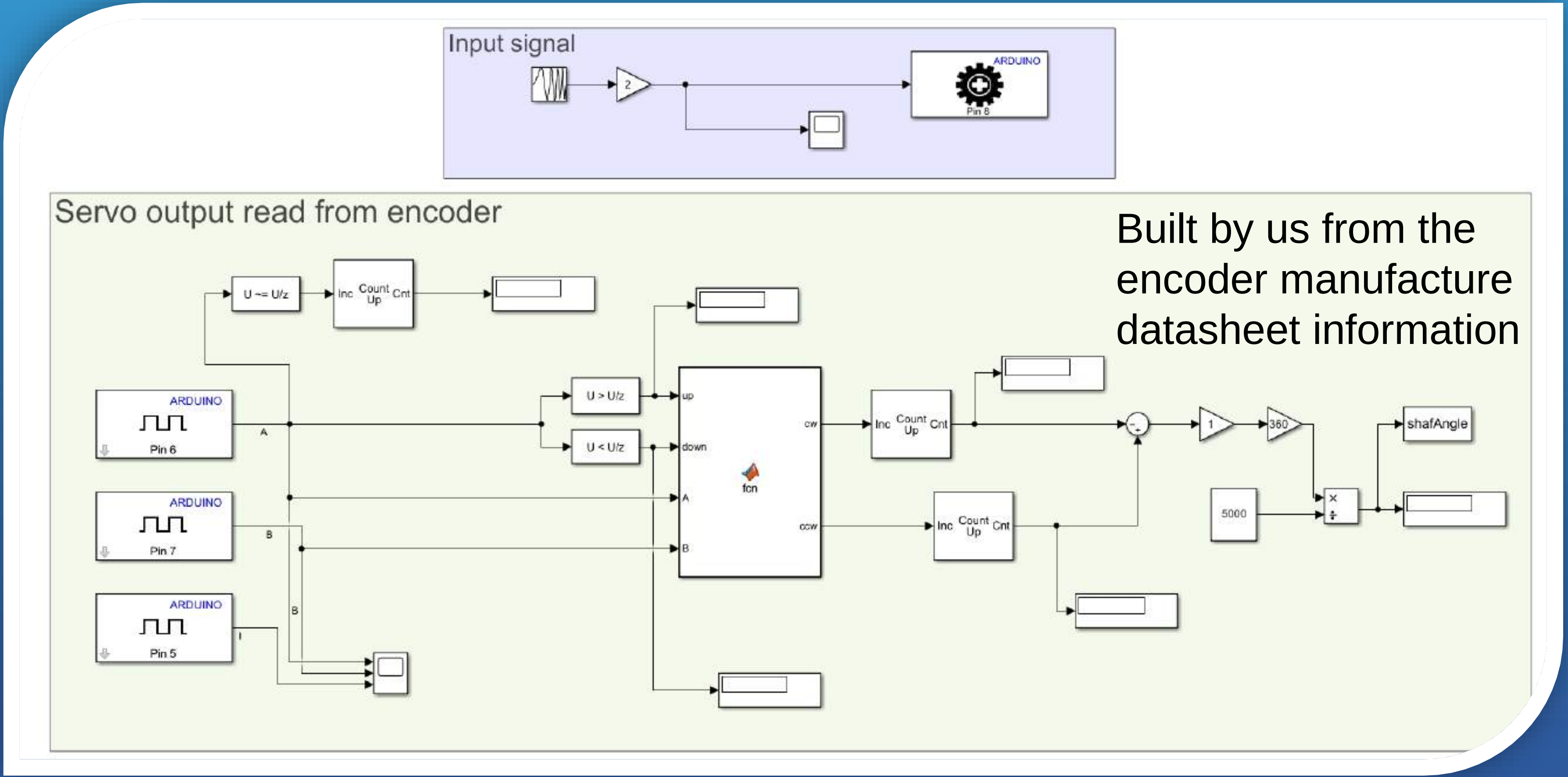


Optical Rotary Encoder:
AEDM-5810-Z12
5000 PPR, 20000 CPR

Identification with Optical Encoder

- Block diagram, Chirp signal input:

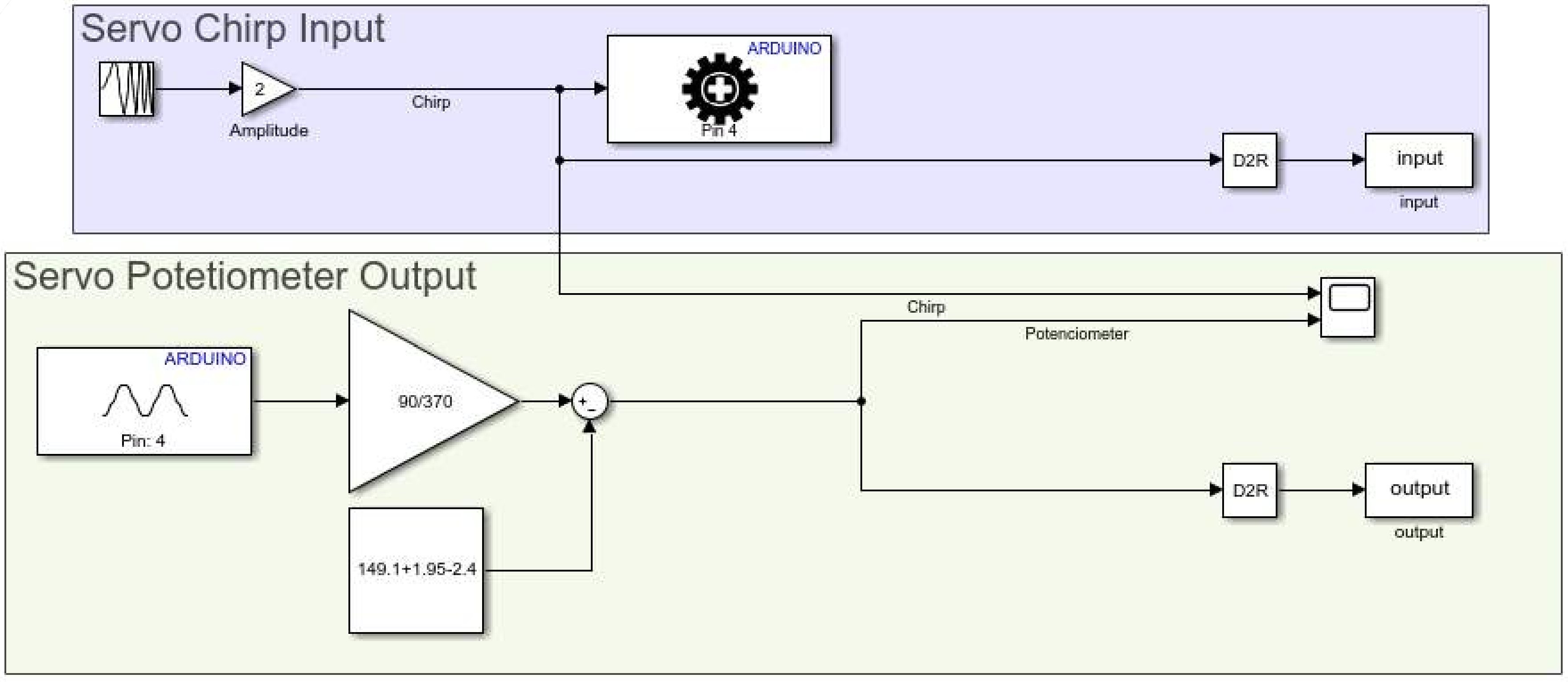
$$A = 2°,\ t_0 = 0[s],\ t_f = 100[s],\ f_0 = 0.1[\mathrm{Hz}],\ f_f = 30[Hz]$$



Identification with Potentiometer

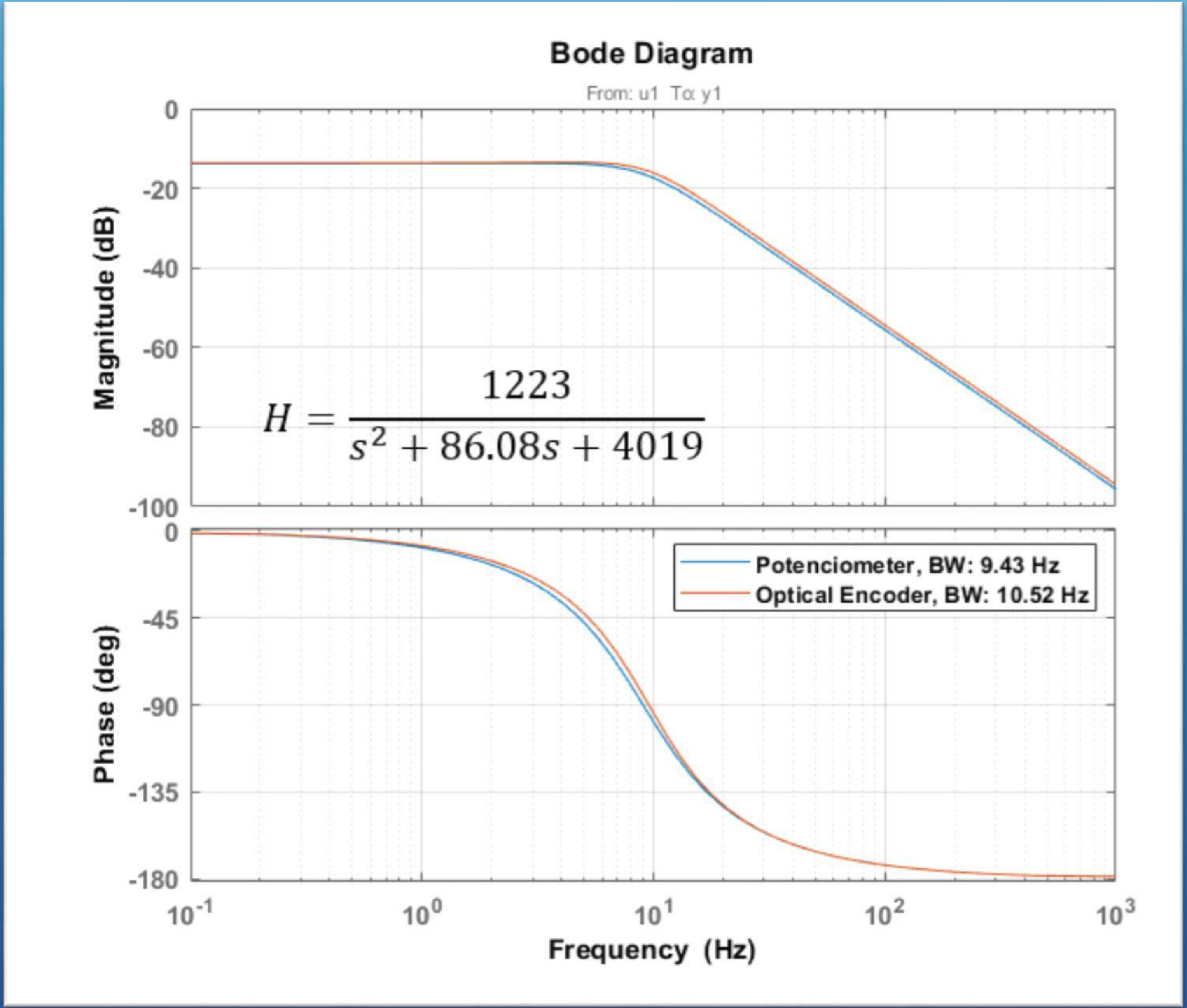
- Block diagram, Chirp signal input:

$$A = 2°,\ t_0 = 0[s],\ t_f = 100[s], f_0 = 0.1[\text{Hz}], f_f = 30[Hz]$$



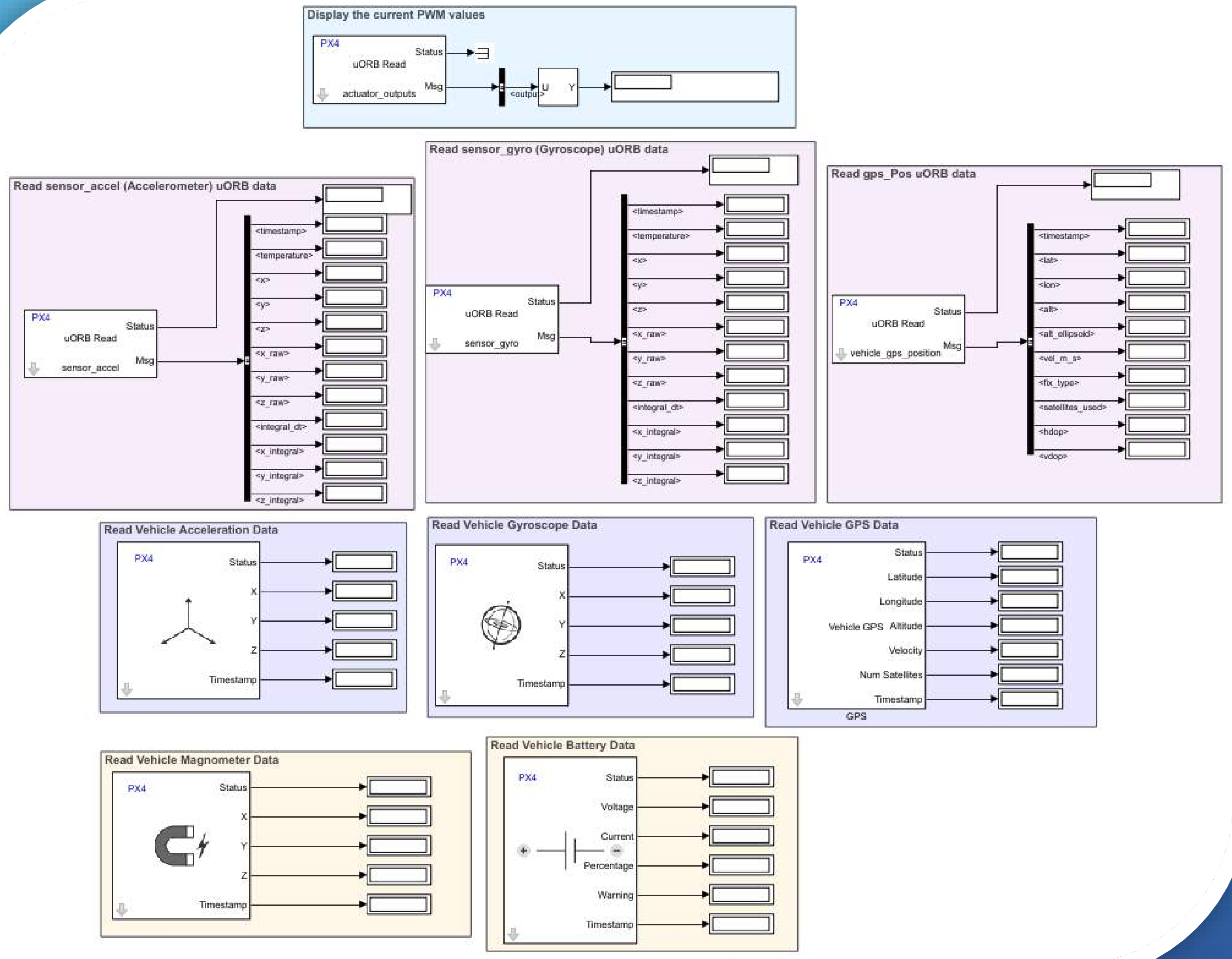
Identification Results

- Bode was made using Chirp continues signal and identification was made by FFT and a filter on the output to damp noise using MATLAB System Identification Toolbox.
- High Voltage Potentiometer was used in order to decrease the SNR.
- In our previous work with the old servo we did the test both with Chirp signal and Sine wave with incremental frequencies and got the same results so we chose to work with chirp.
- The bode diagram represents the closed loop response of the servo itself.



Pixhawk Sensors Data Acquirement

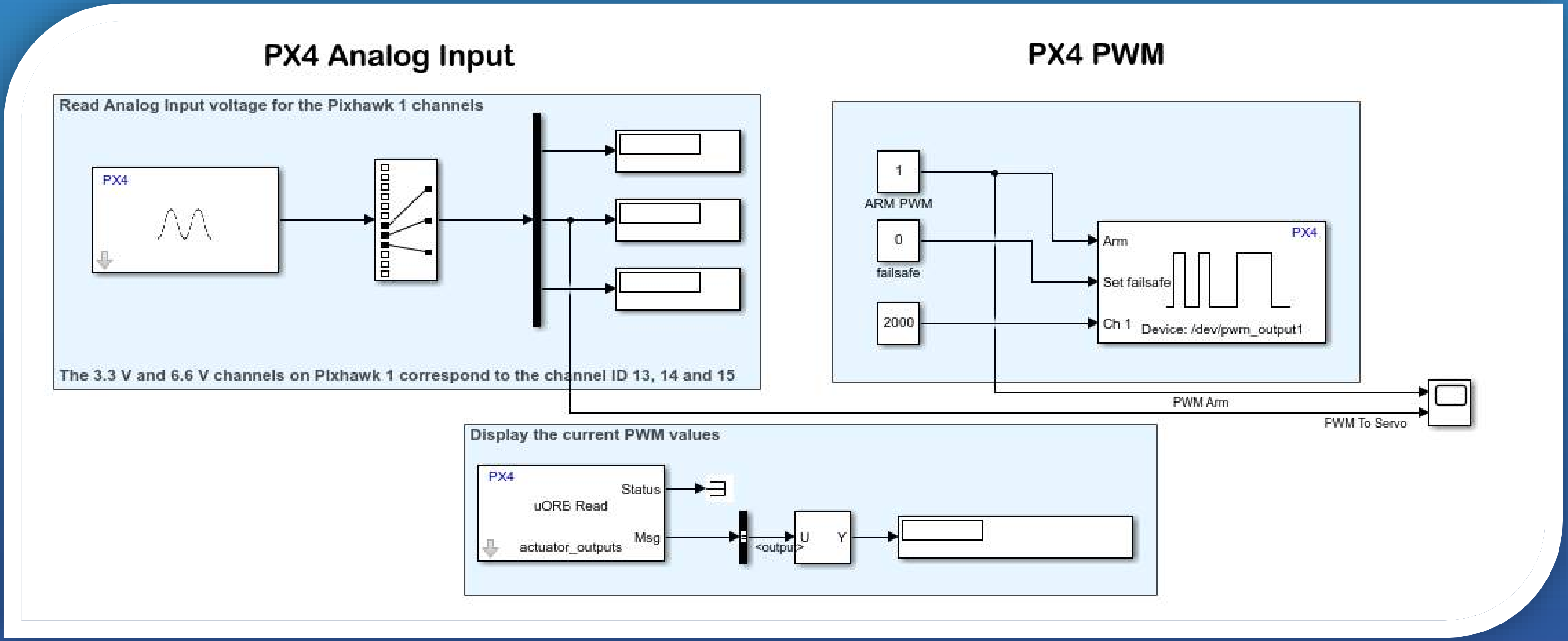
Pixhawk flight computer **Real Time** data acquirement has been achieved with the support of MATLAB 2019a.



Pixhawk Delay

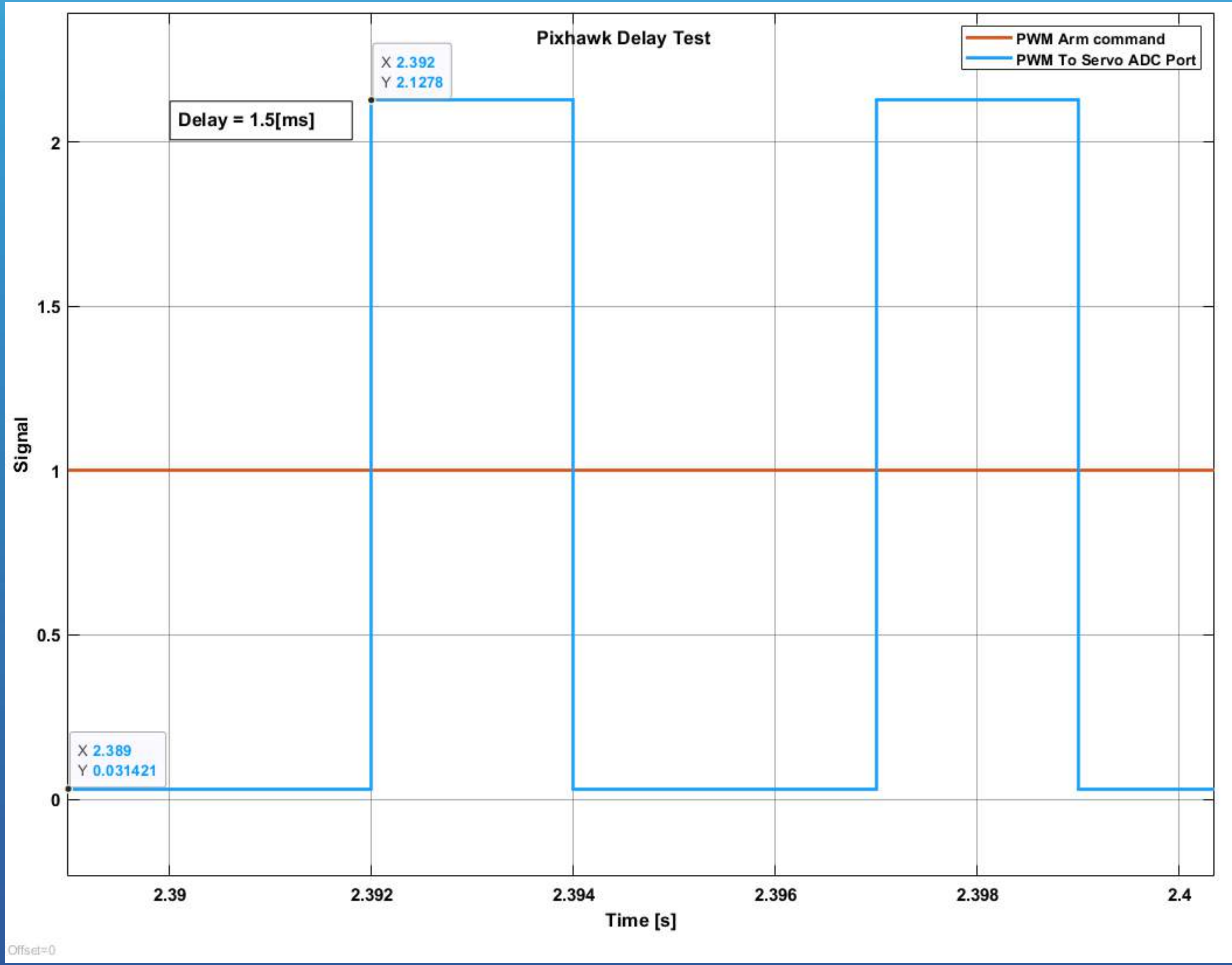
Pixhawk flight computer delay was found with an experiment:

1. Pixhawk is connected to the computer and showing real time data.
2. Input signal to the servo at t_0 is written.
3. The signal to the servo is connected both to the servo and the Pixhawk ADC (Analog to Digital Converter) Port.
4. Results are shown in a scope and the time delay was measured.



Results

$$\Delta t = \frac{2.392 - 2.389}{2} = 1.5[ms]$$



Fin Deflection Algorithm

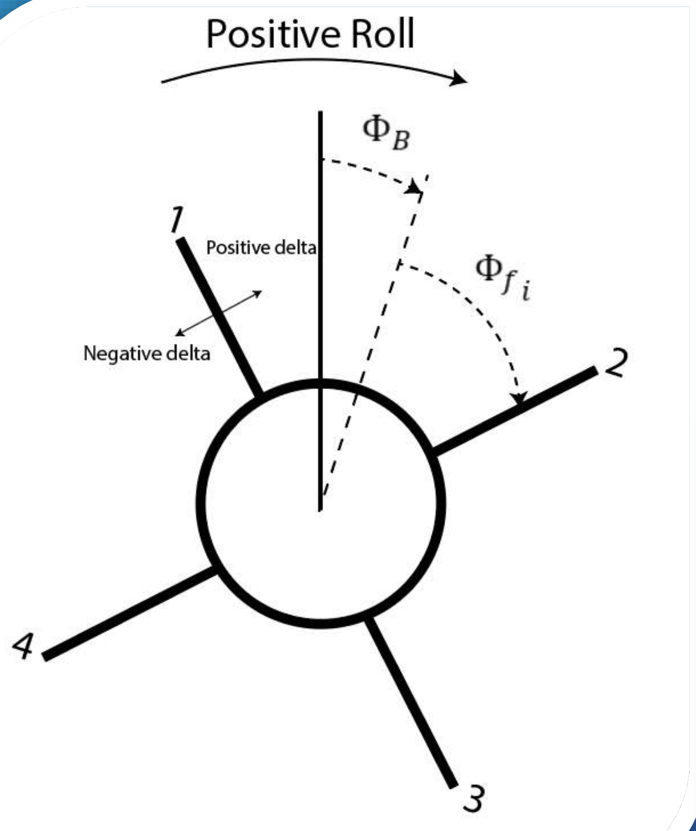
Fin deflection algorithm with highest priority to Roll using the current roll angle Φ_B was developed for **X** flight mode:

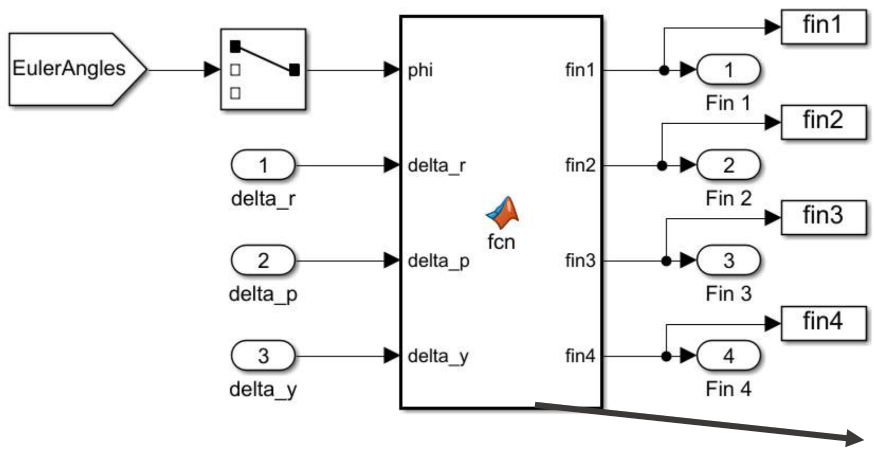
$$\delta_i = \delta_r - \delta_y \cos\left(\Phi_{f\,i} + \Phi_B\right) + \delta_p \sin\left(\Phi_{f\,i} + \Phi_B\right), \qquad i = 1,2,3,4$$

$$Where:$$

$$\Phi_{f_1} = -45^\circ, \qquad \Phi_{f_2} = \Phi_{f_1} + 90^\circ$$

$$\Phi_{f_3} = \Phi_{f_2} + 90^\circ, \qquad \Phi_{f_4} = \Phi_{f_3} + 90^\circ$$






```
function [fin1,fin2,fin3,fin4] = fcn(phi, delta_r, delta_p, delta_y)

% For X flight mode
phi_1 = -pi/4;
phi_2 = phi_1 + pi/2;
phi_3 = phi_2 + pi/2;
phi_4 = phi_3 + pi/2;

% Budgeting
fin1 = delta_r - delta_y*cos(phi_1 + phi) + delta_p*sin(phi_1 + phi);
fin2 = delta_r - delta_y*cos(phi_2 + phi) + delta_p*sin(phi_2 + phi);
fin3 = delta_r - delta_y*cos(phi_3 + phi) + delta_p*sin(phi_3 + phi);
fin4 = delta_r - delta_y*cos(phi_4 + phi) + delta_p*sin(phi_4 + phi);
end
```

CONTROL

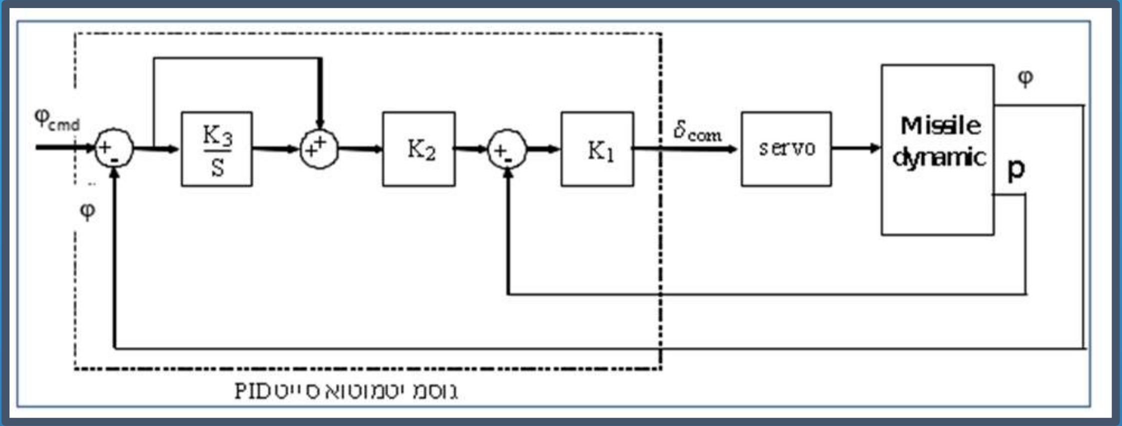
Controllers Requirements

- **For each Controller, the following design requirements are needed:**

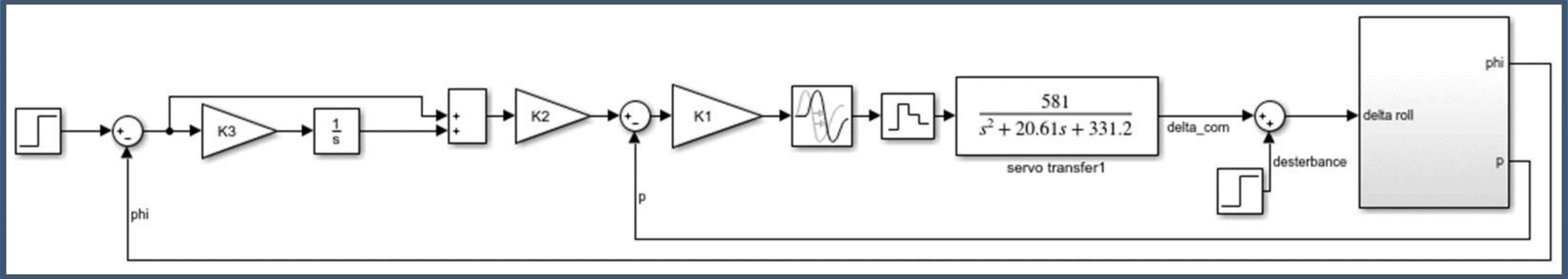
1. Overshoot for Yaw and Pitch will not exceed 10%, and for the Roll it will not exceed 20%.
2. Gain margin is up to 9 dB and minimum Phase margin of 45 degrees for Pitch and Yaw and 4dB and 30 degrees for Roll.
3. Consider delays.
4. High bandwidth for autopilot and servo. (ratio of 1:6)
5. Consider rudder's limits.

Roll Control Loop

Theoretical



Practical



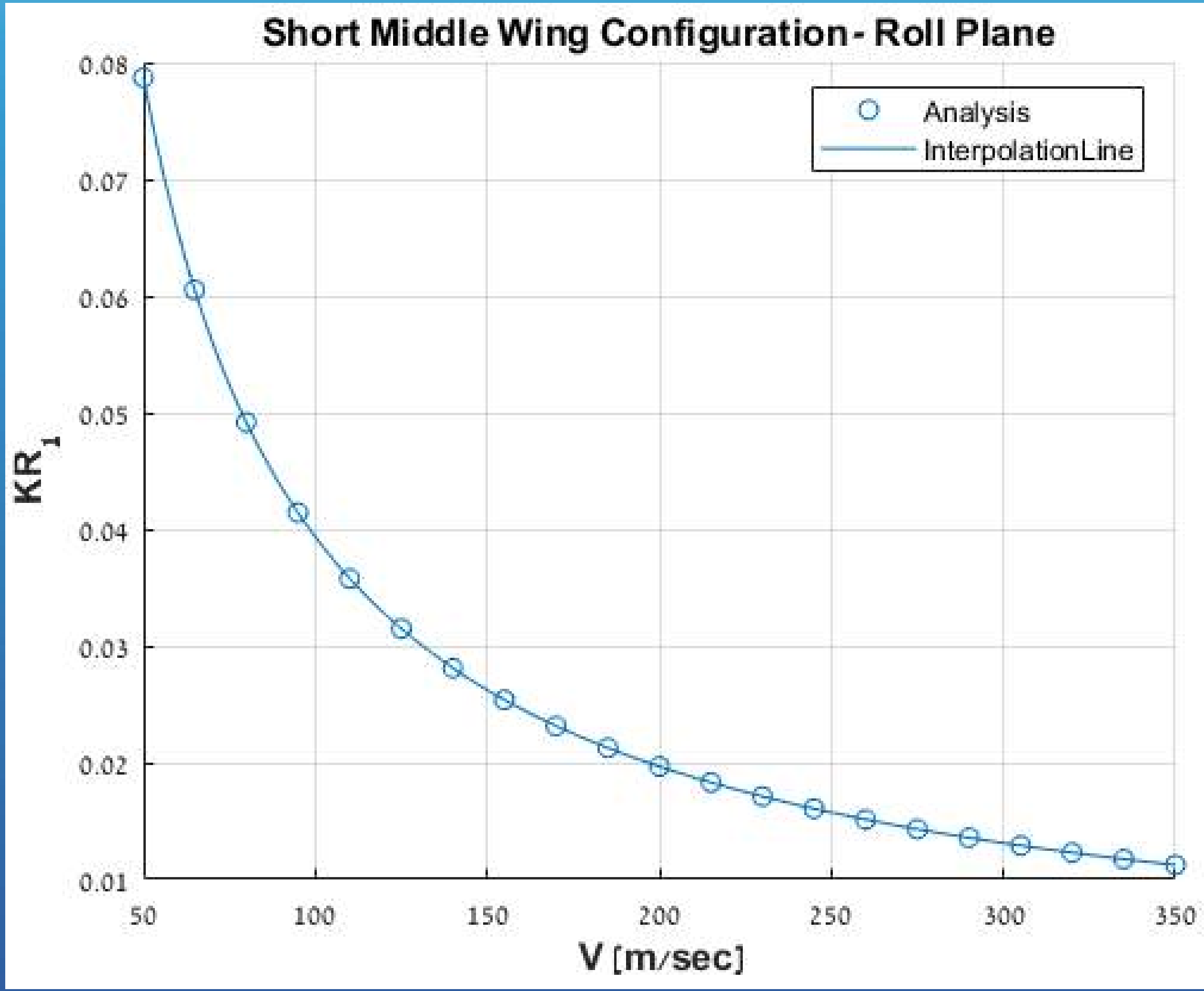
- The roll angel is calculated from Navigation in the simulation. This is an external loop.

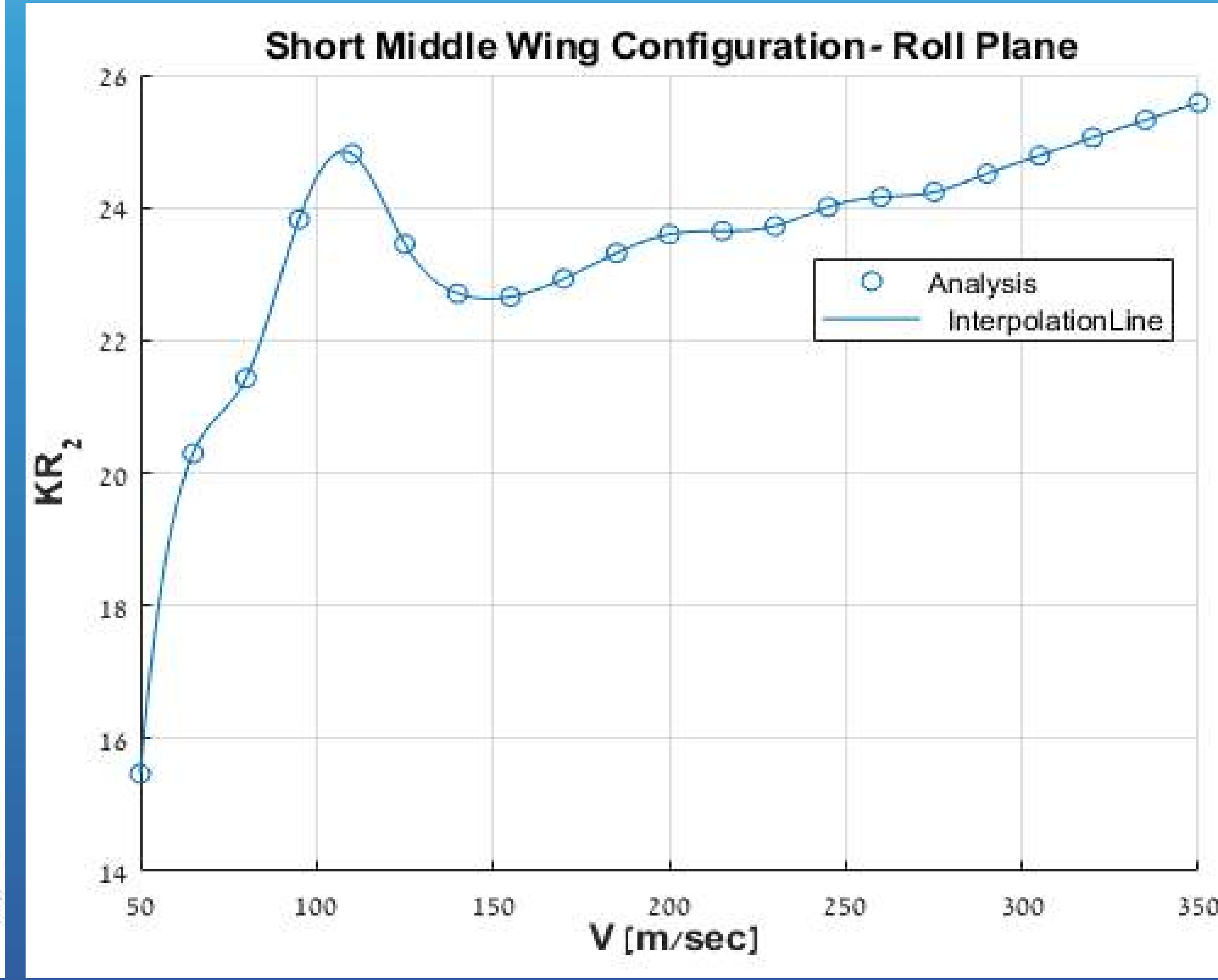
Analysis Process

- For 13 different velocities between 20 and 340 meters per seconds we found controllers as follows:

1. K1 was found using Simulink Control Designer considering the loop requirements.
2. K2 and K3 were found using Simulink Control Designer considering the loop requirements.
3. Conduct another iterations using the control app to check the requirements achievement.
4. Validation was made using Nichols diagram and Pole Placement analysis.
5. For the other velocities , we used interpolation.

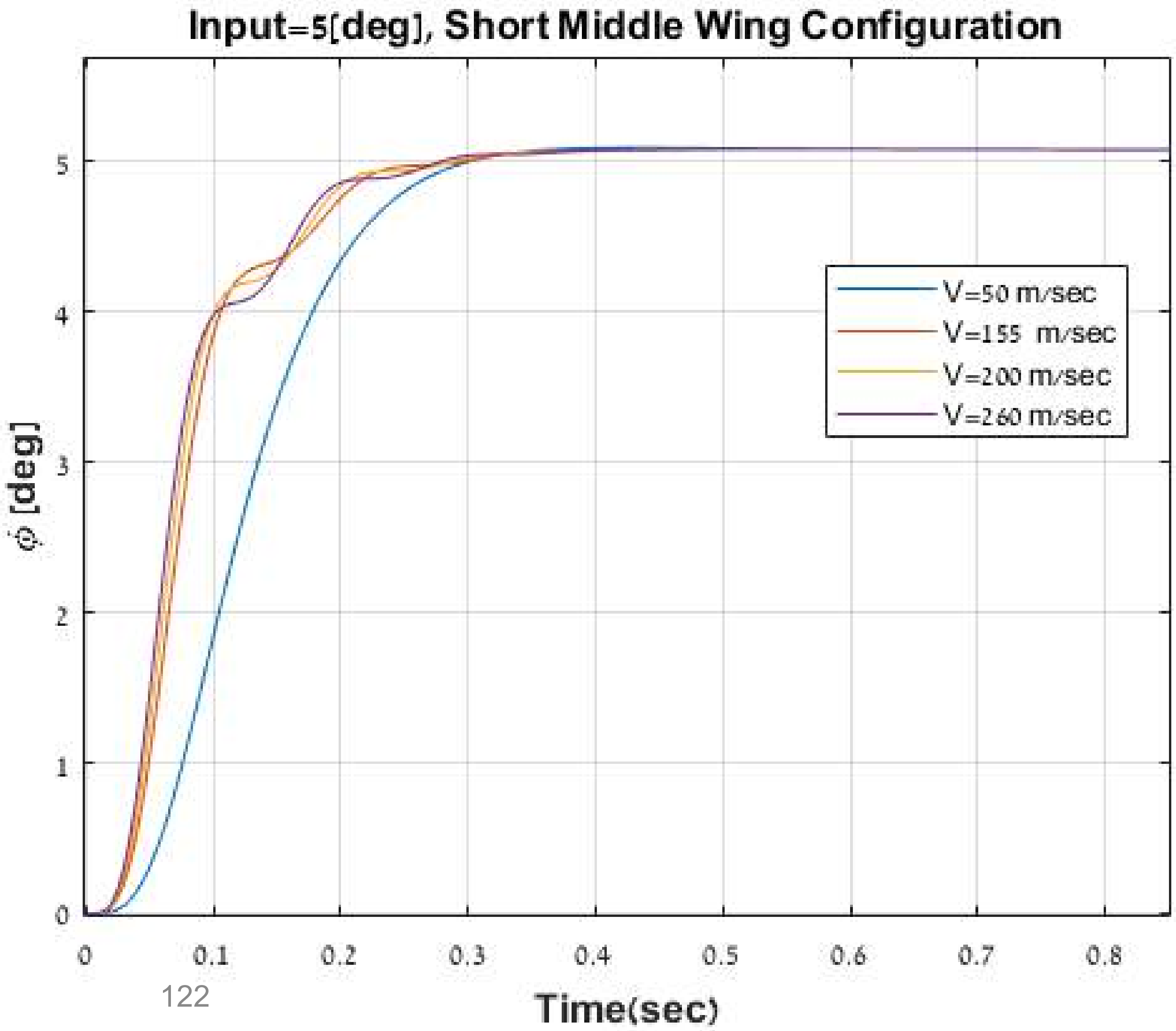
Roll Controller’s Interpolation

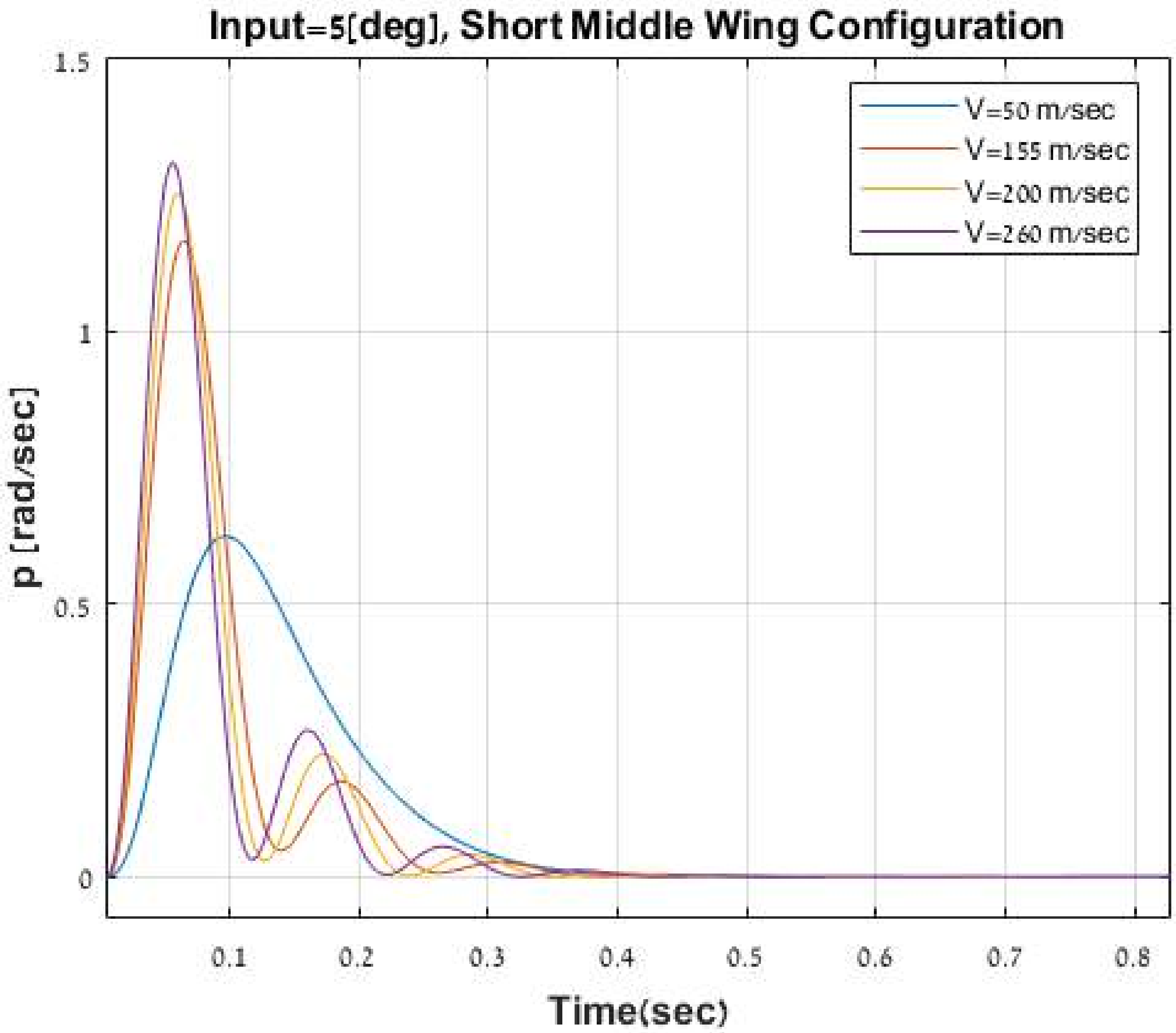




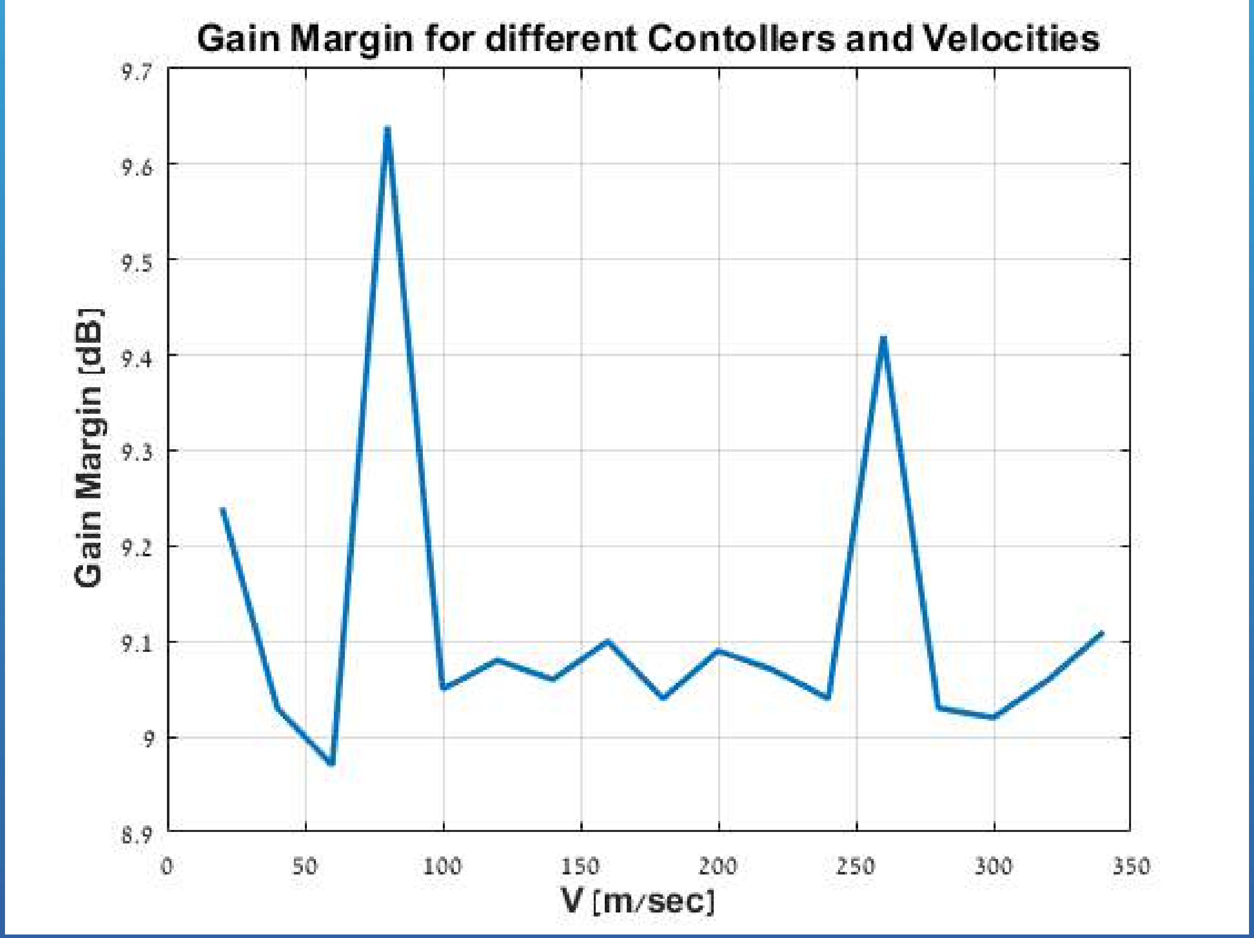
Note: The Same thing was done for KR_3, and the values against Velocity were almost Constants.

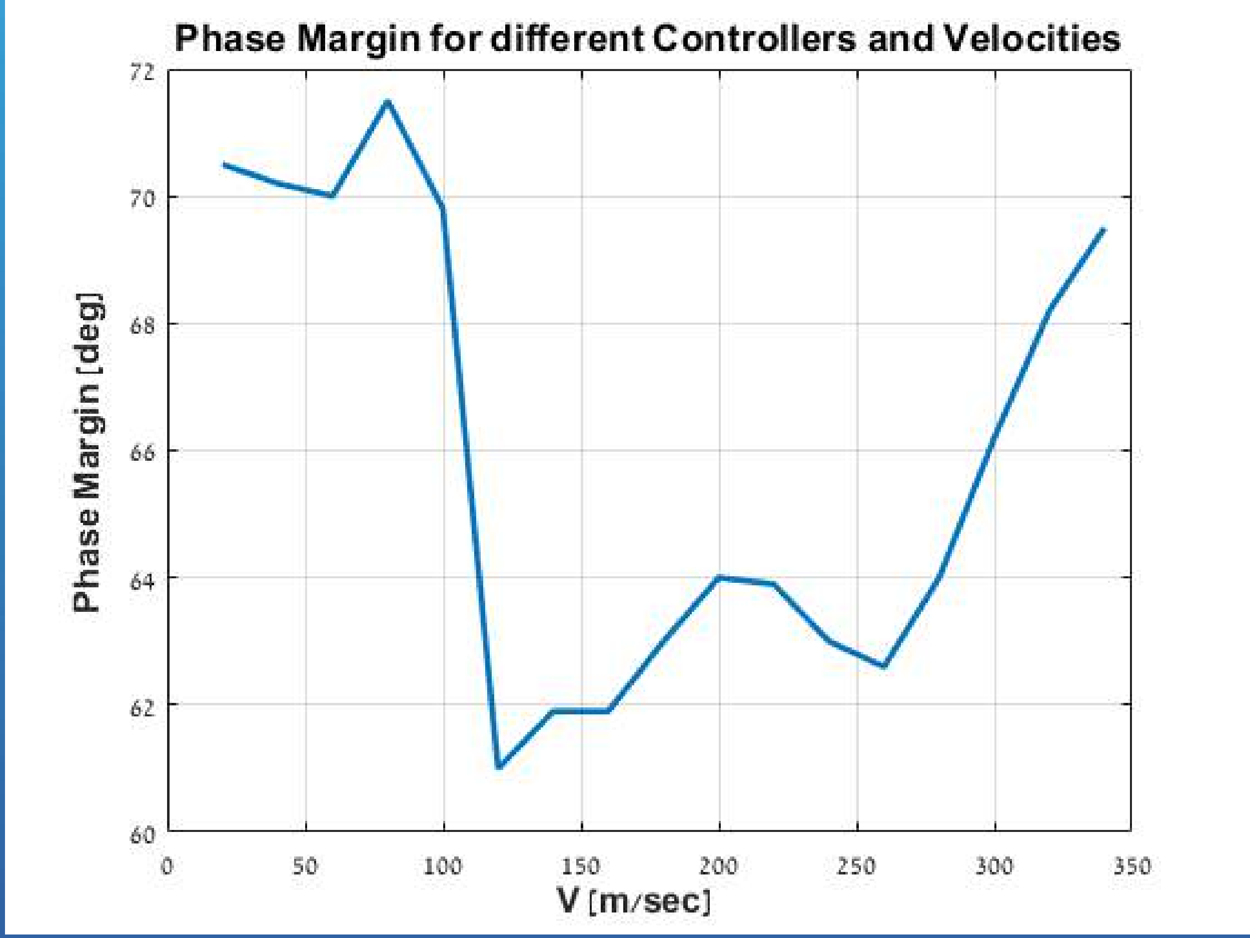
Roll Control Loop Simulation Results



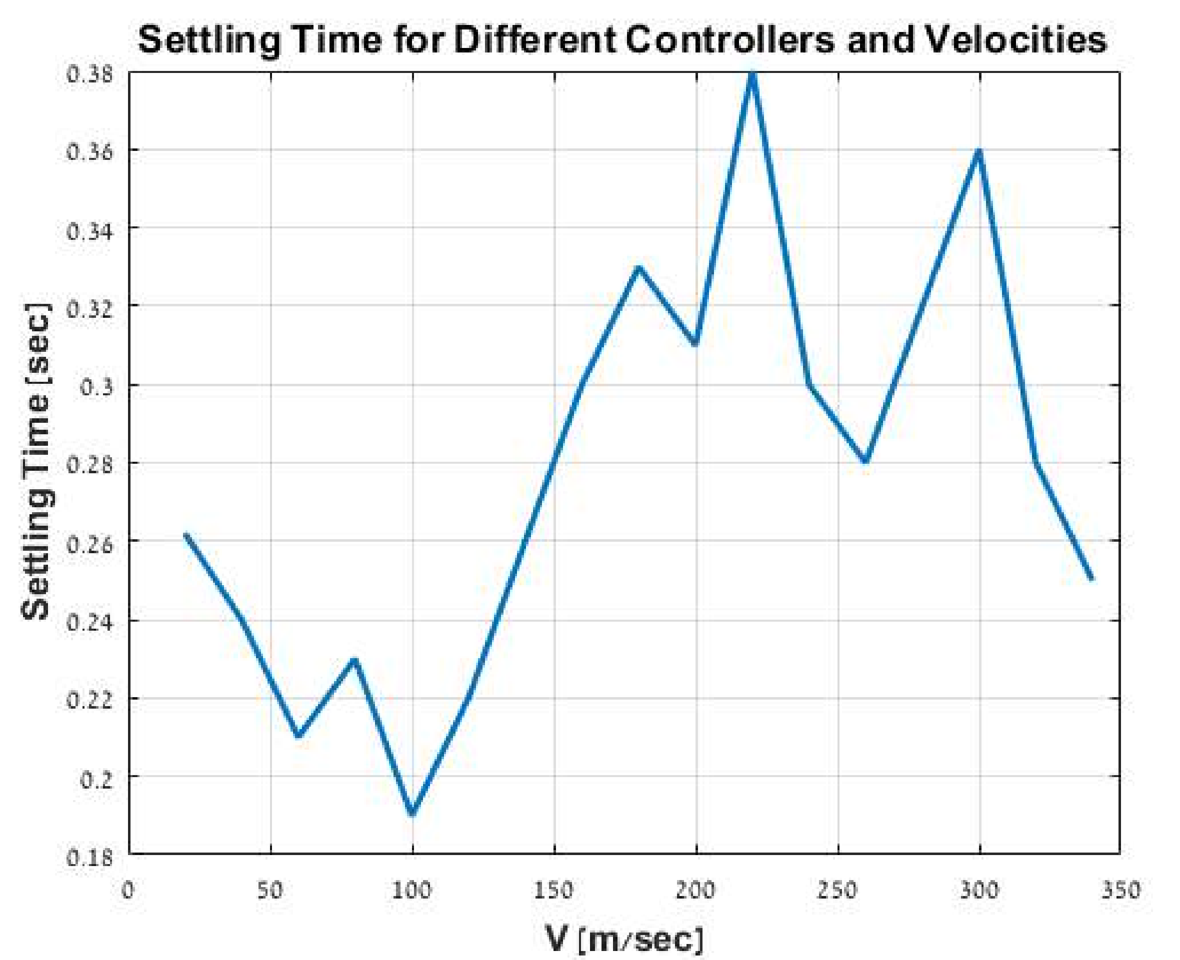


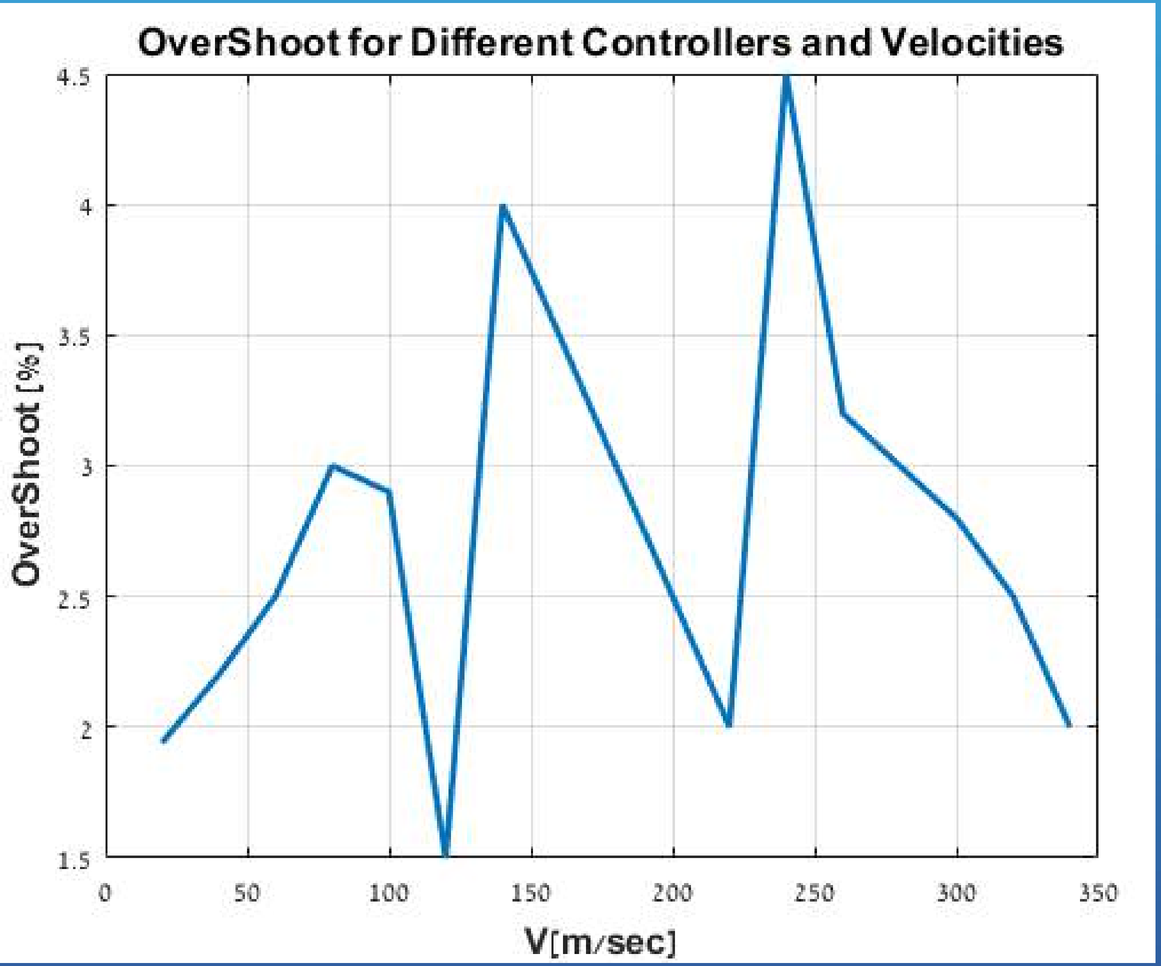
Roll Control Loop Simulation Results





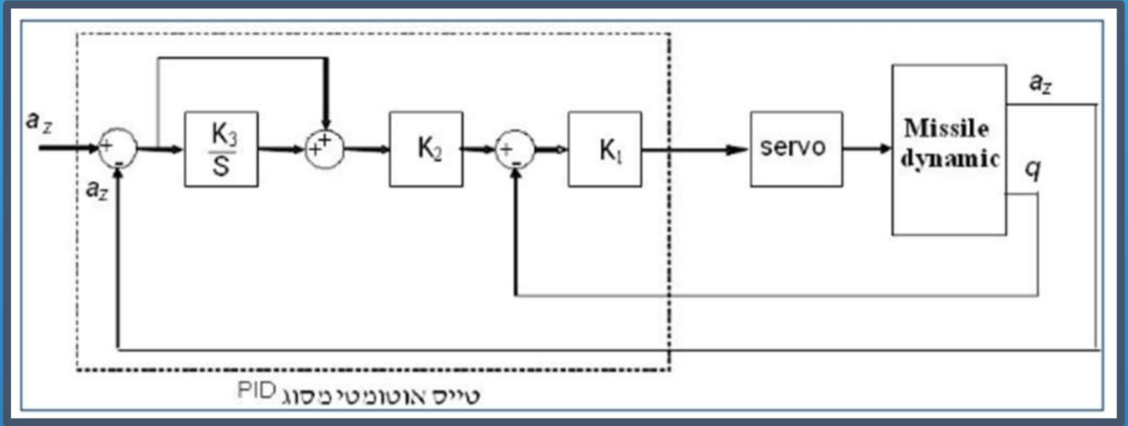
Roll Control Loop Simulation Results



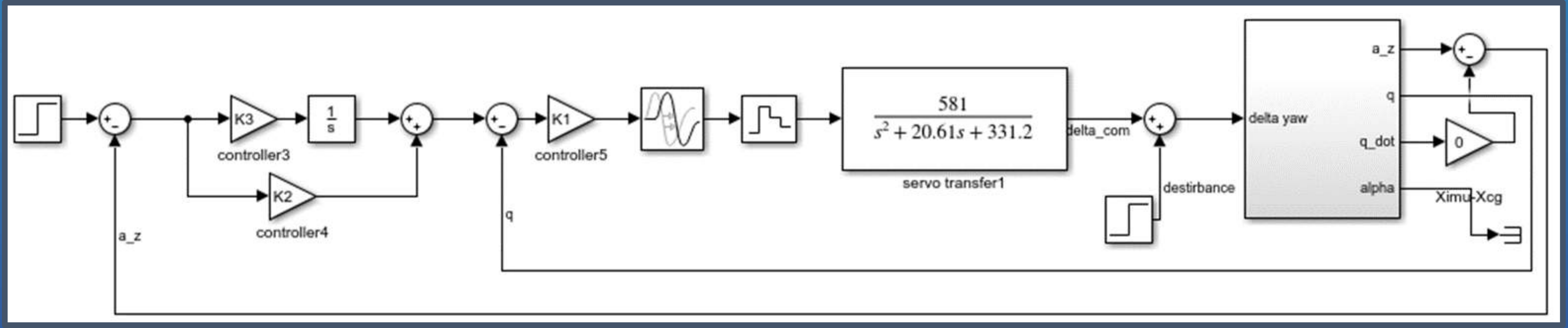


Pitch Control Loop

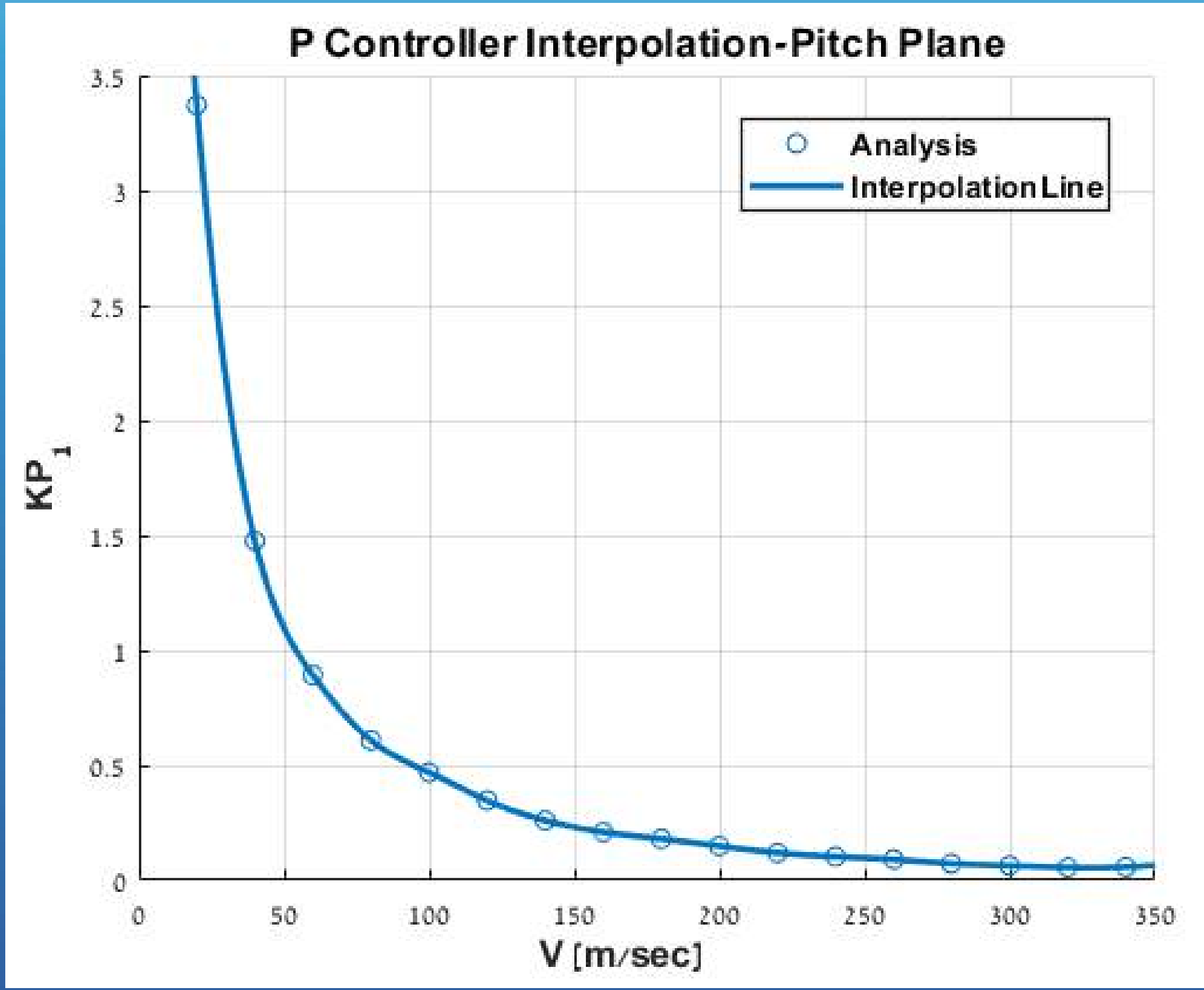
Theoretical

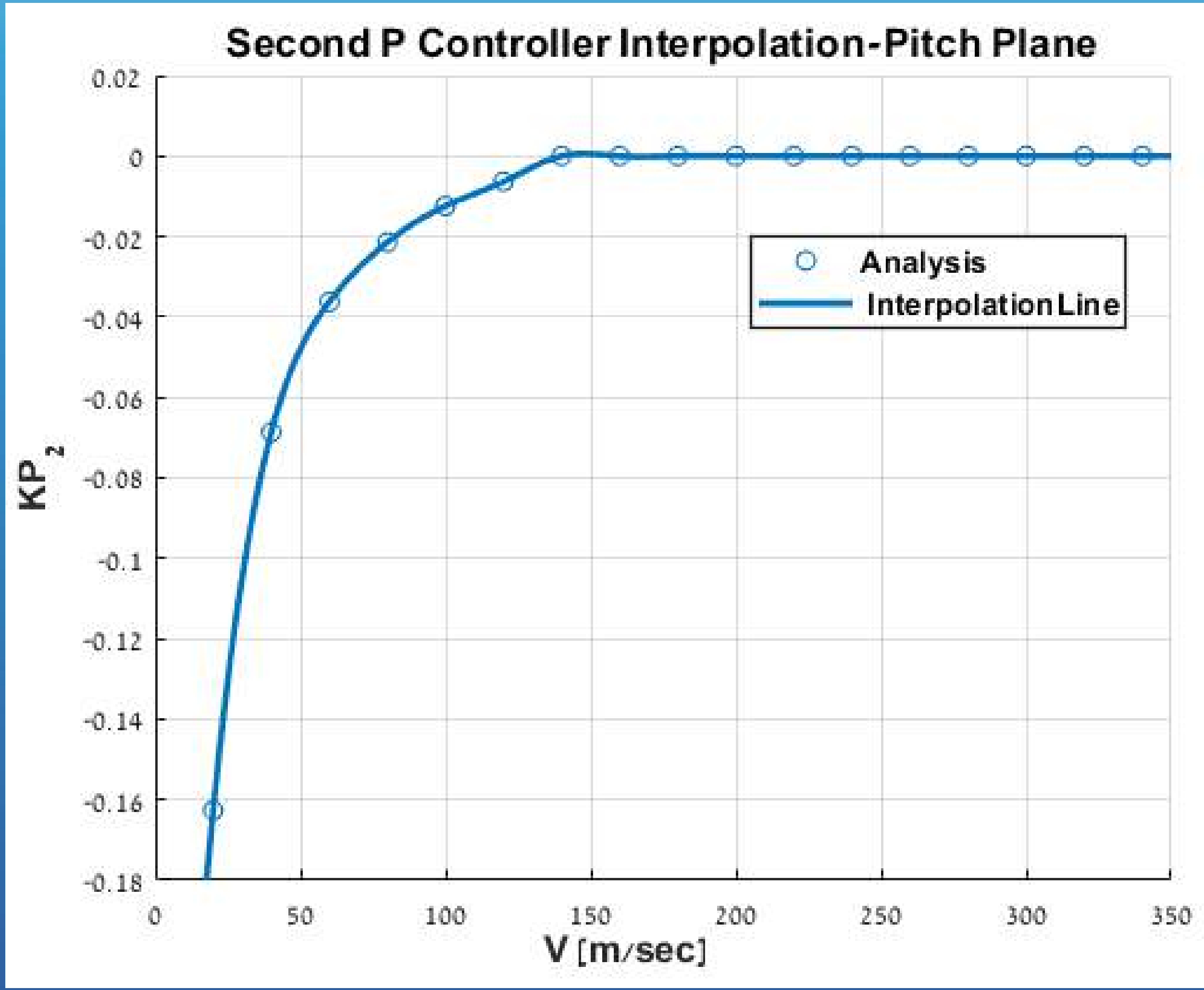


Practical



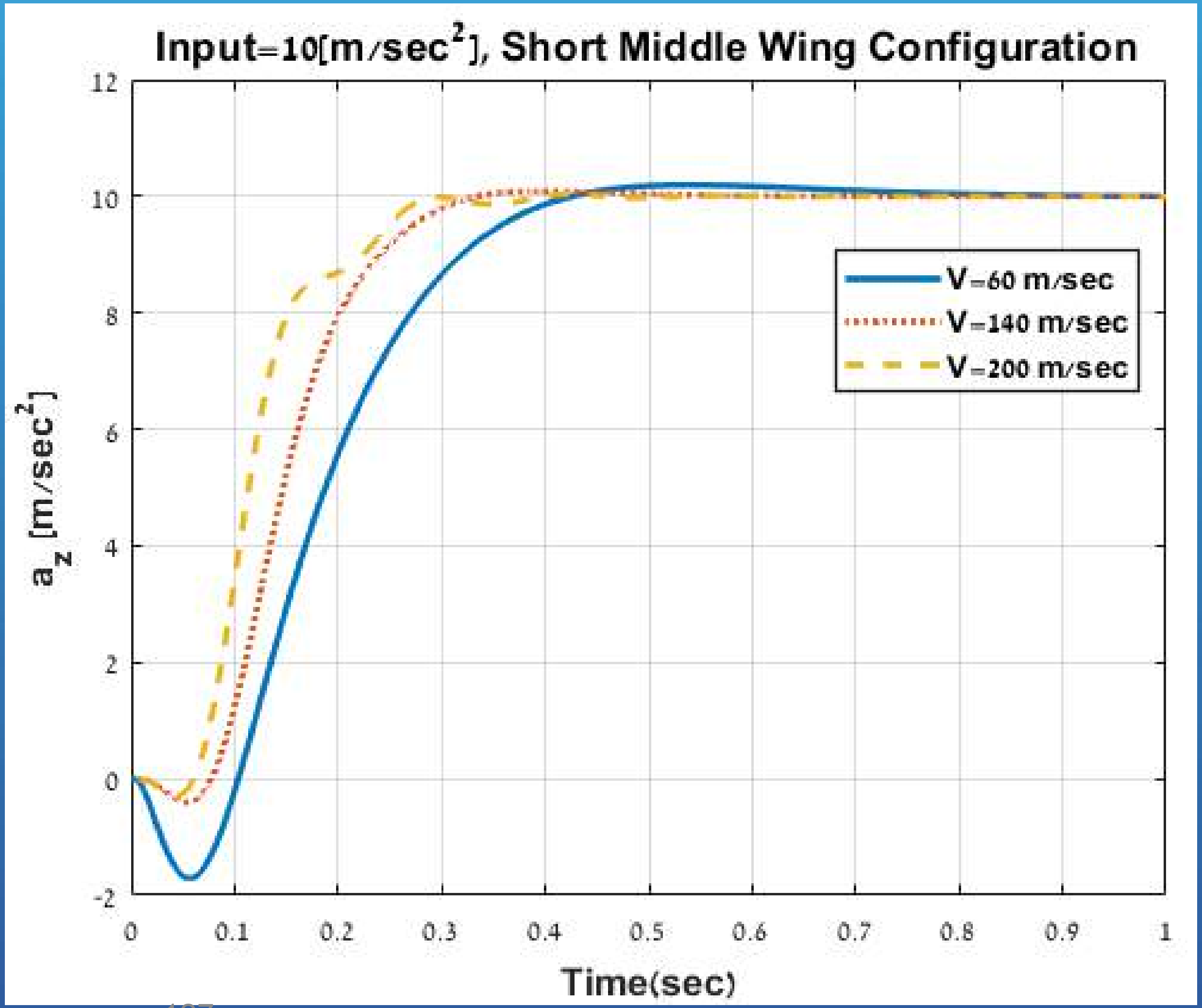
Pitch Controller’s Interpolation

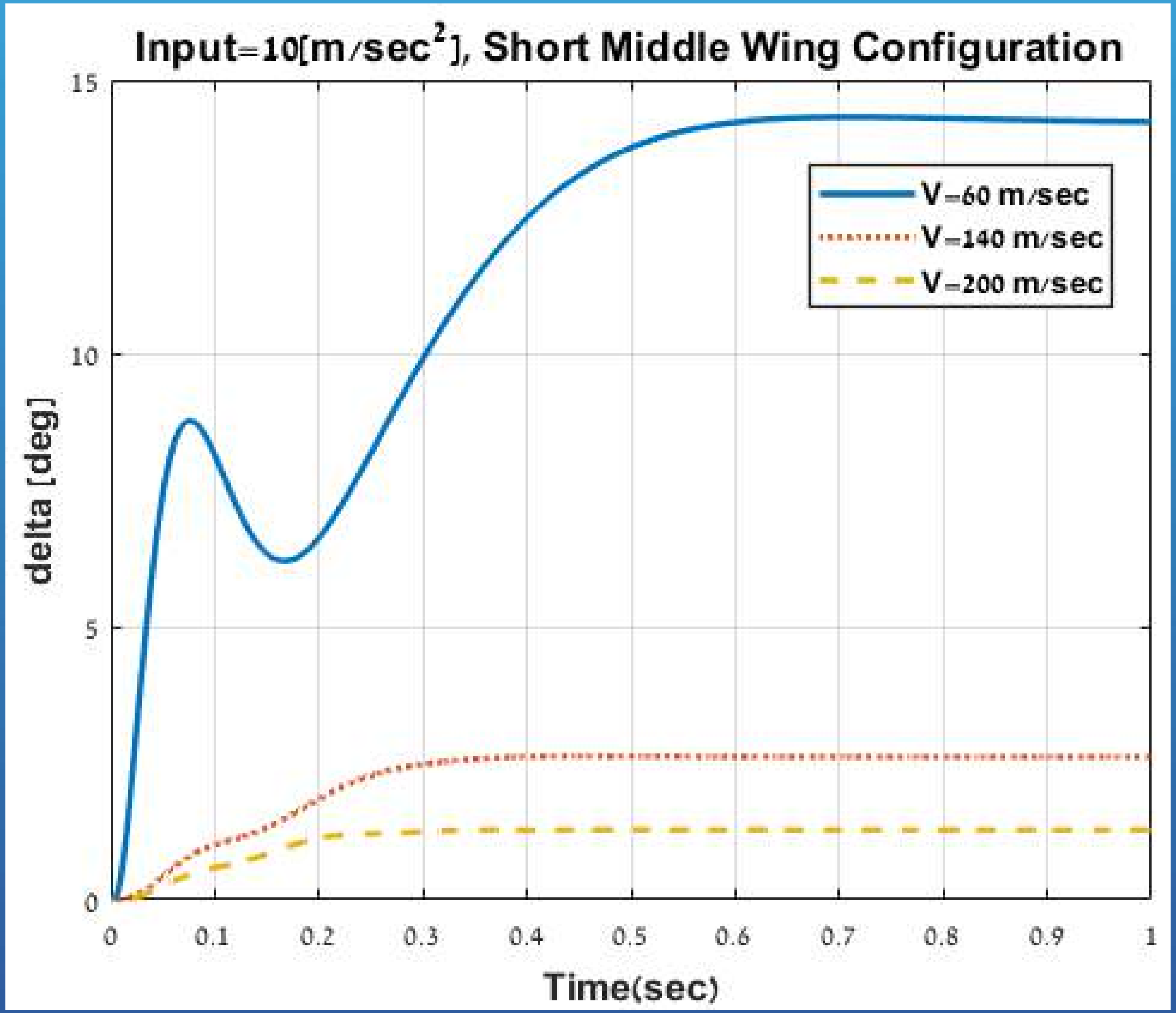




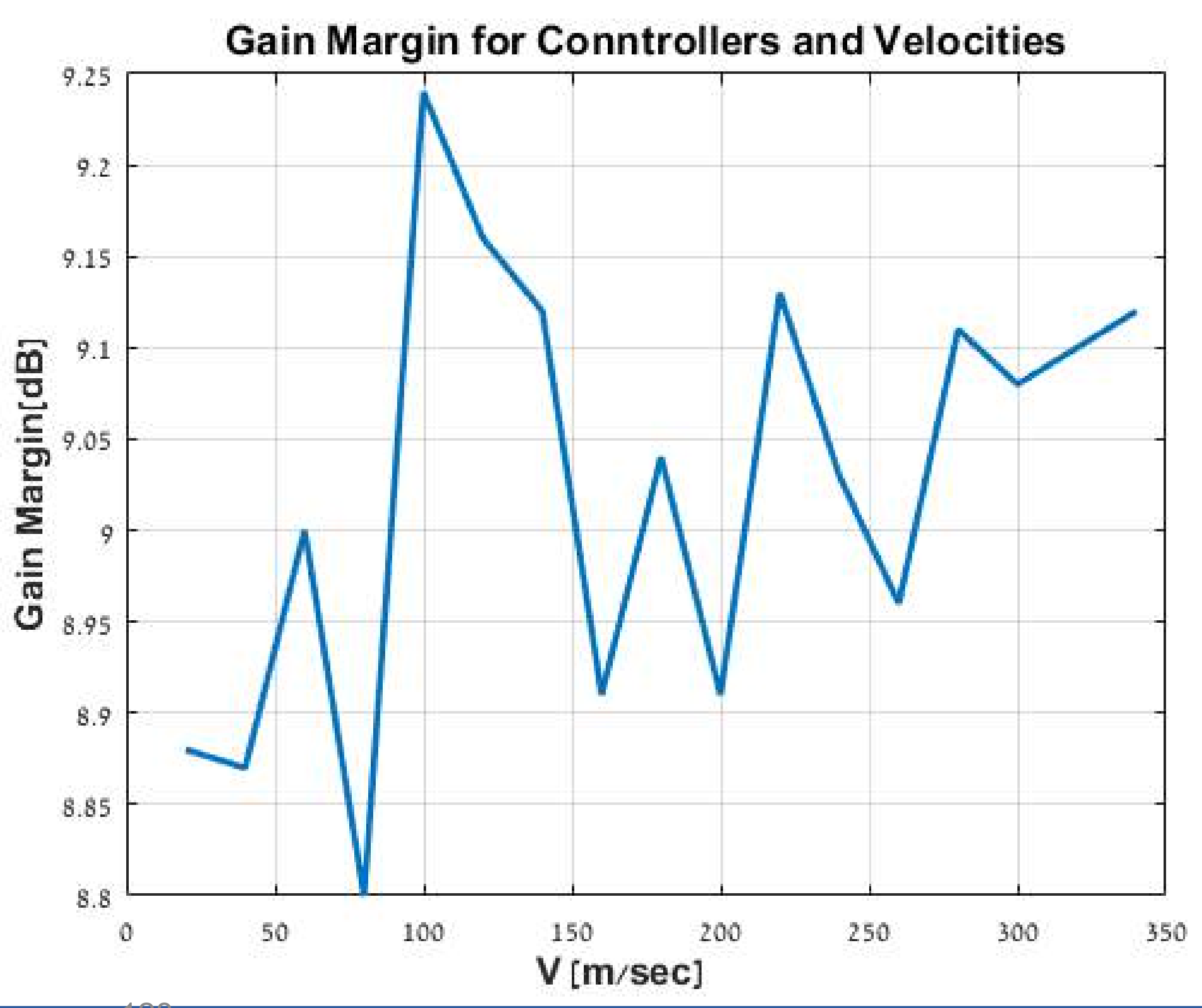
Note: The Same thing was done for KP_3, and the values against Velocity were almost Constants.

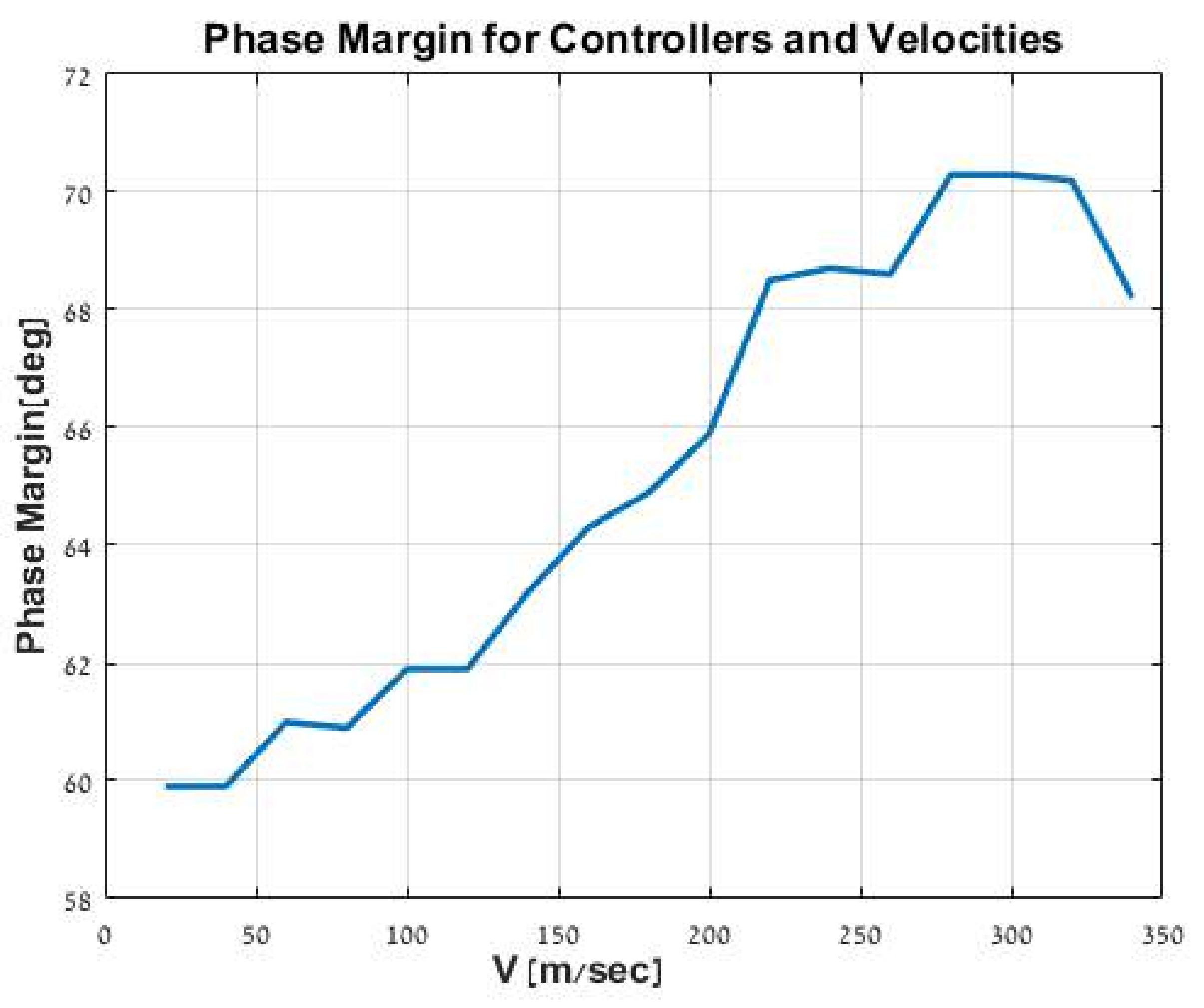
Pitch Control Loop Simulation Results



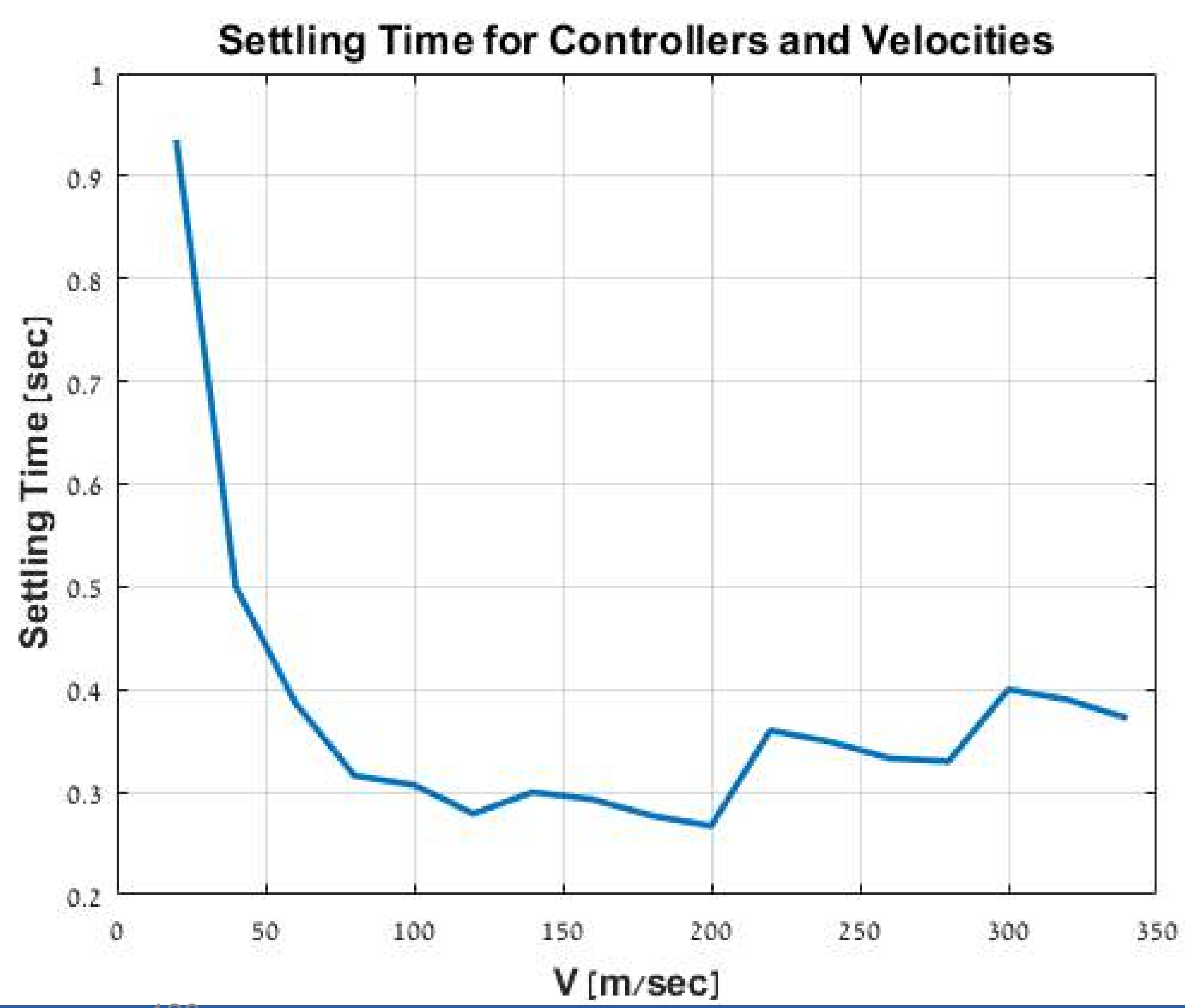


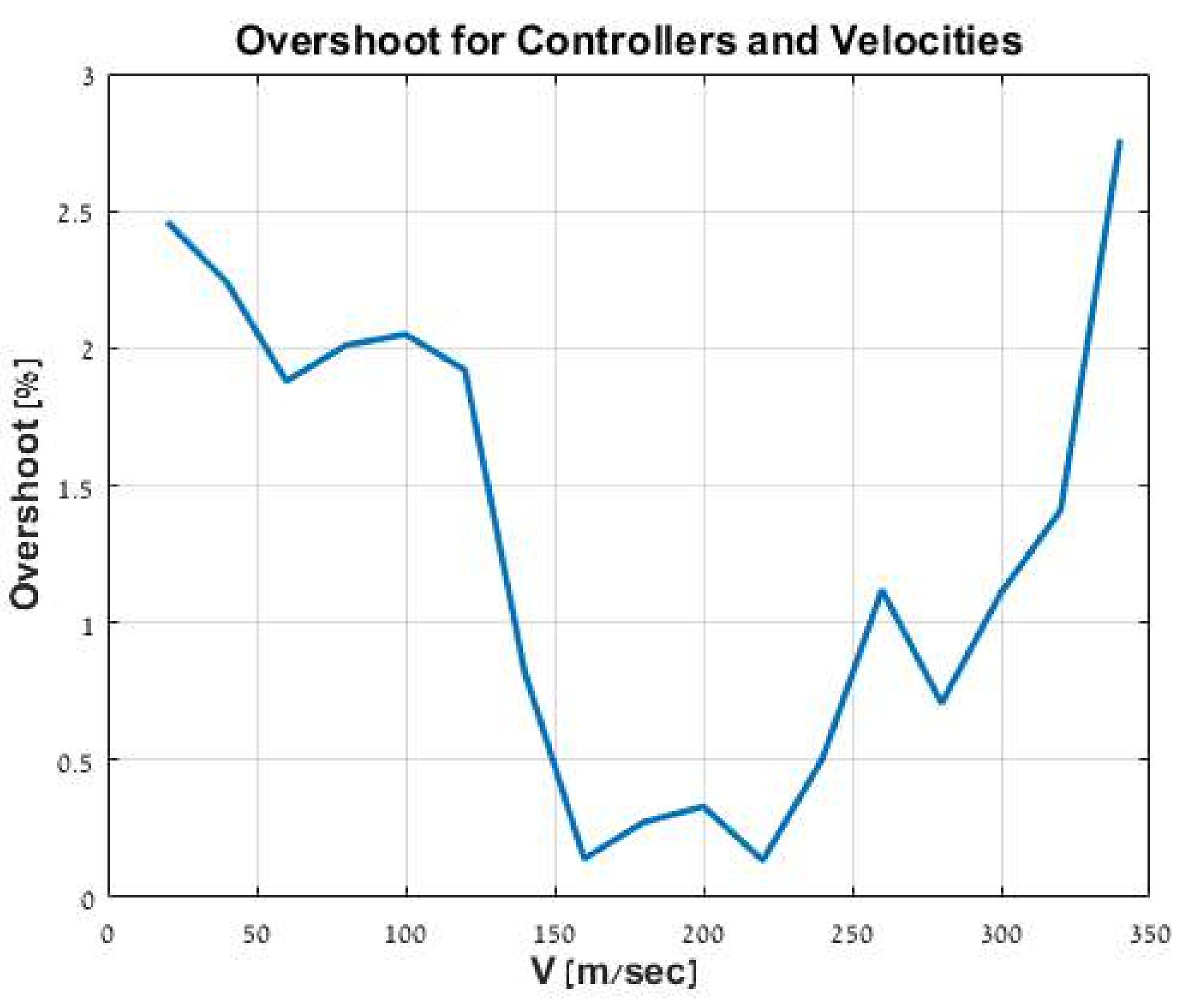
Pitch Control Loop Simulation Results





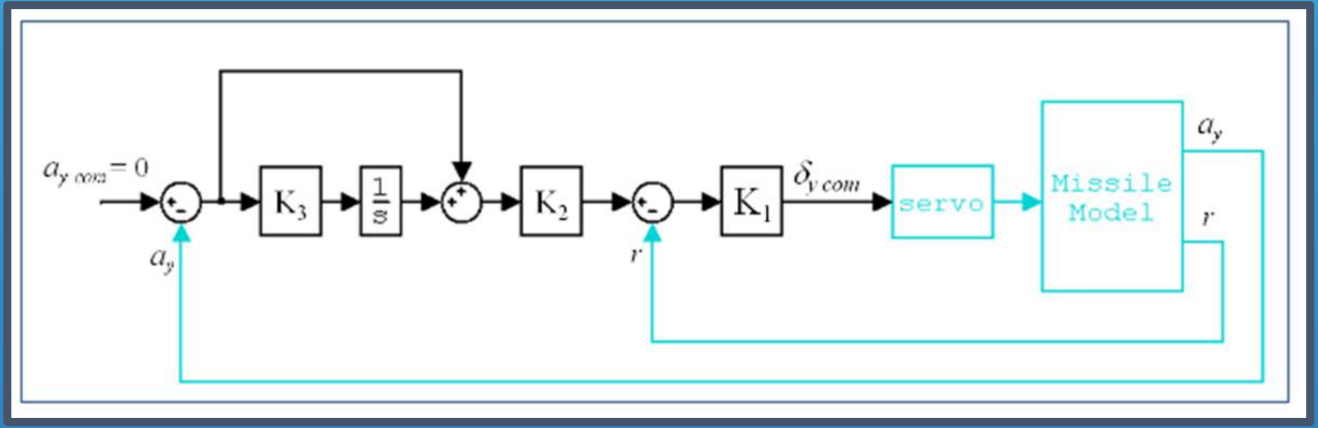
Pitch Control Loop Simulation Results



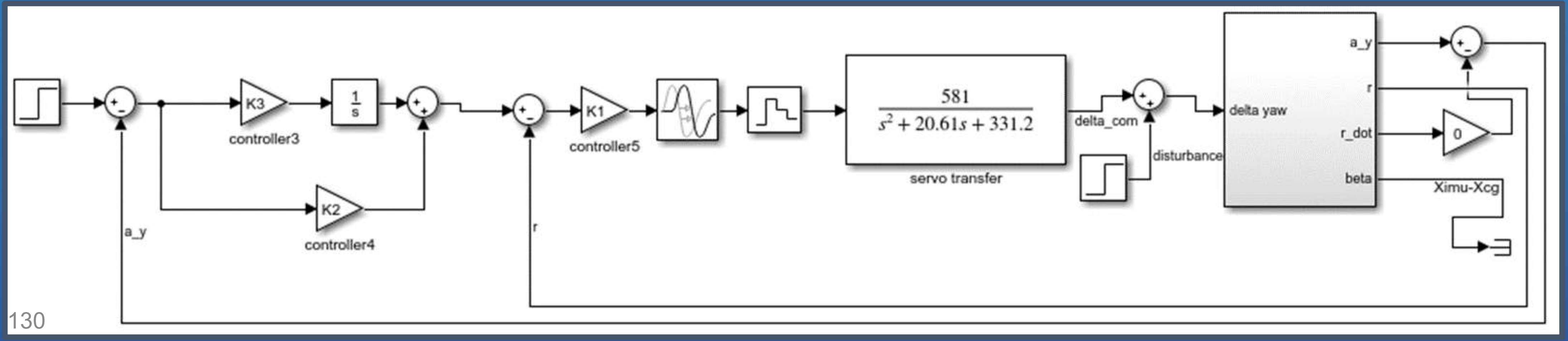


Yaw Control Loop

Theoretical

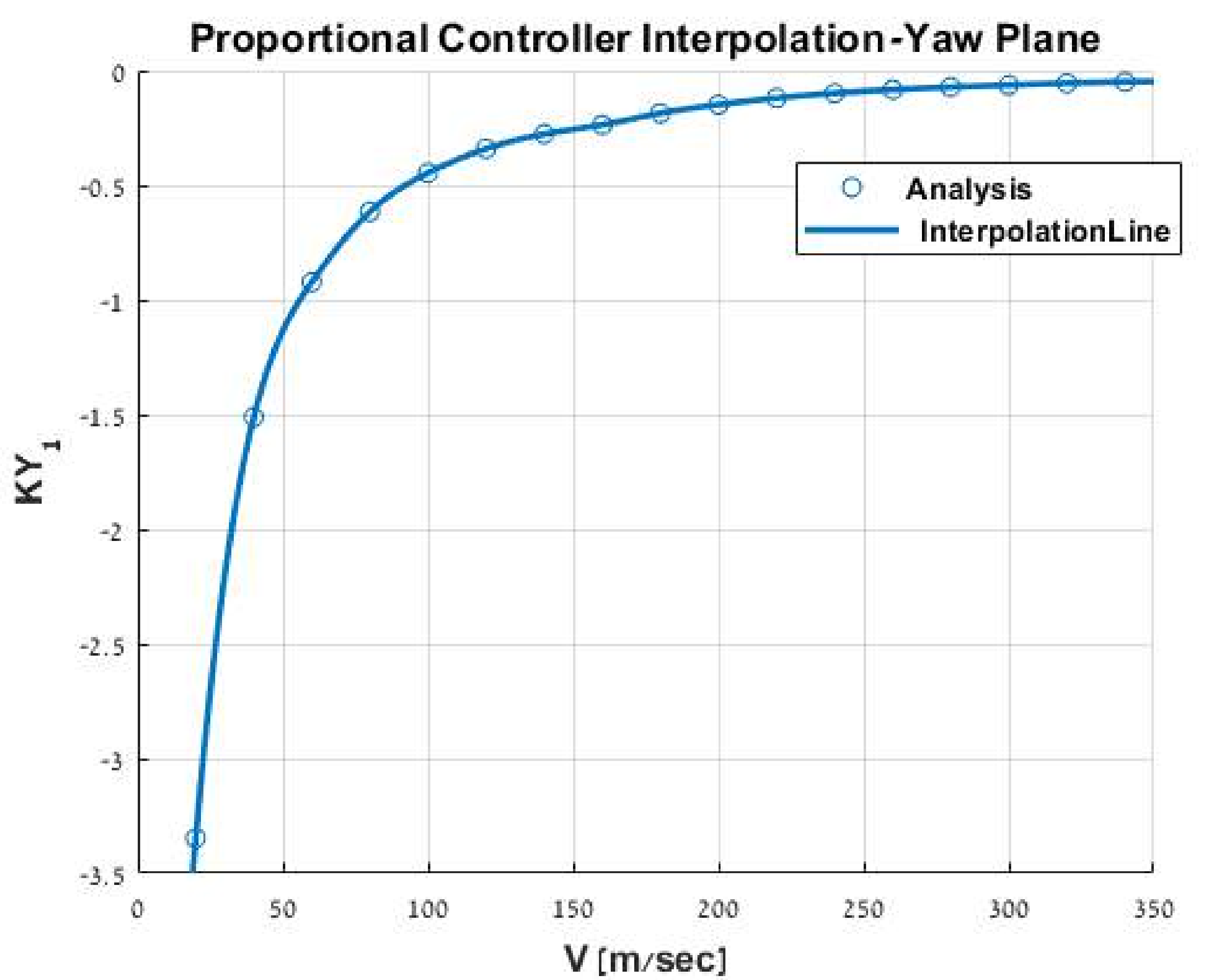


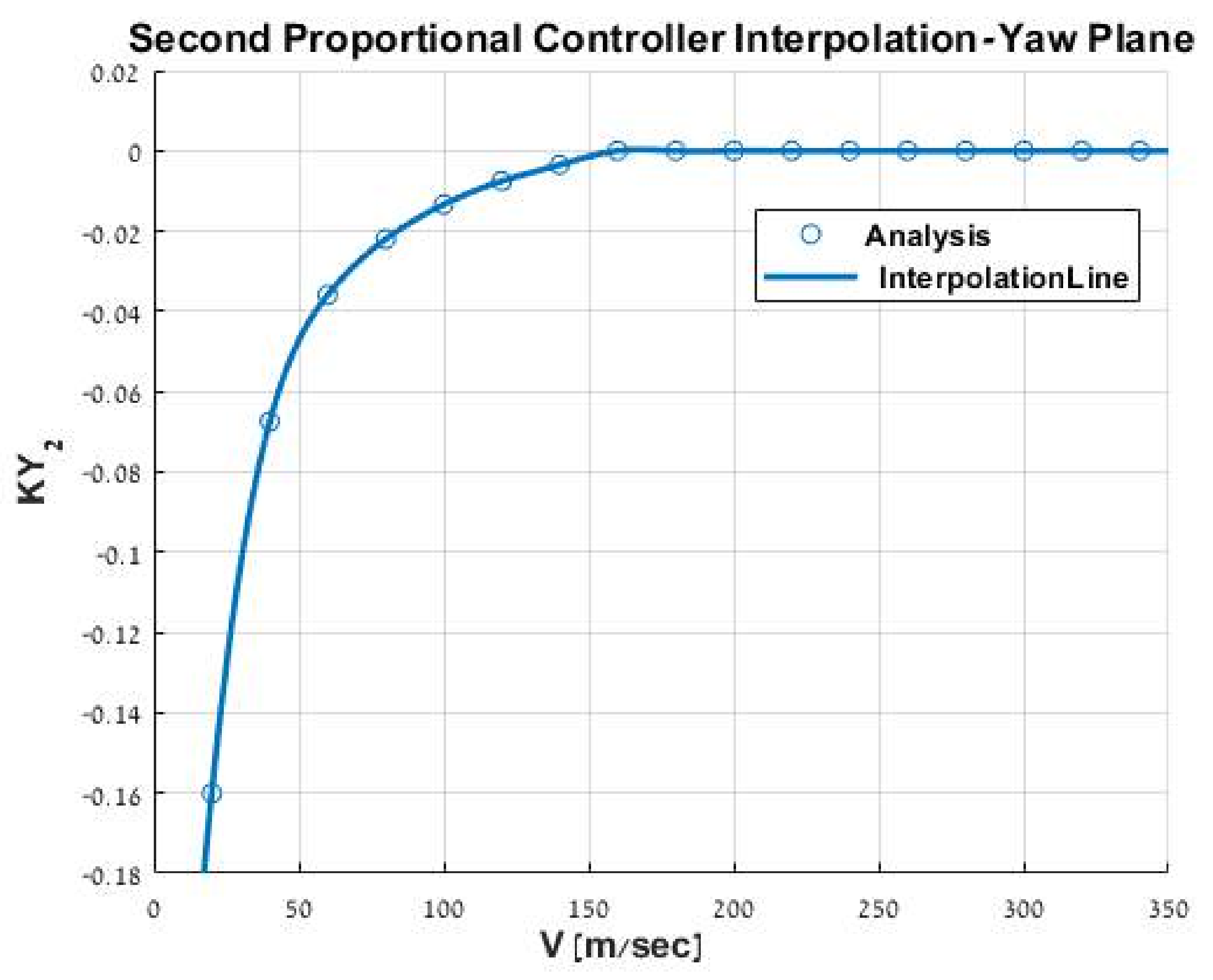
Practical



- As a result of finding different controllers for yaw and pitch, we had to analyze both planes.

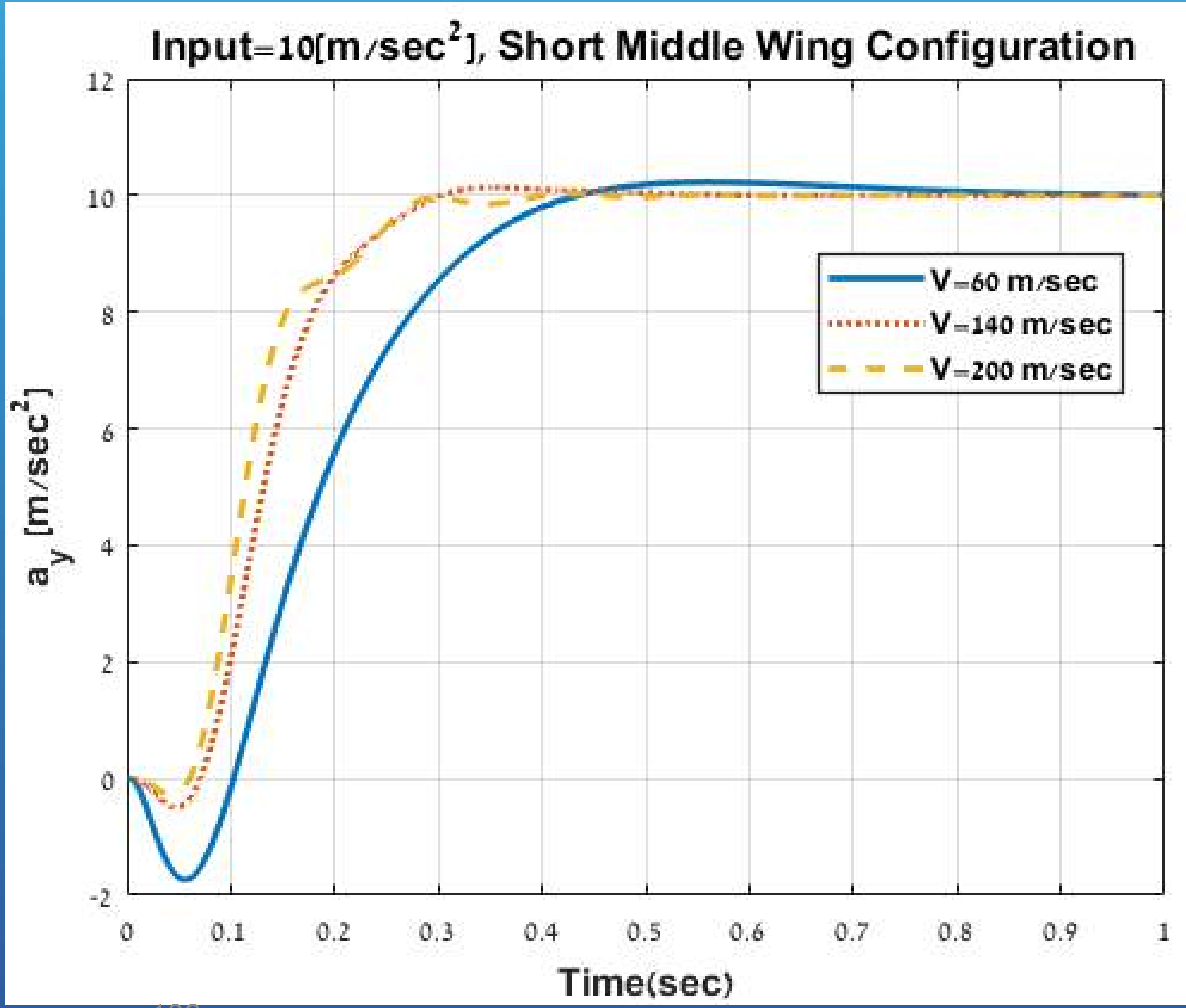
Yaw Controller’s Interpolation

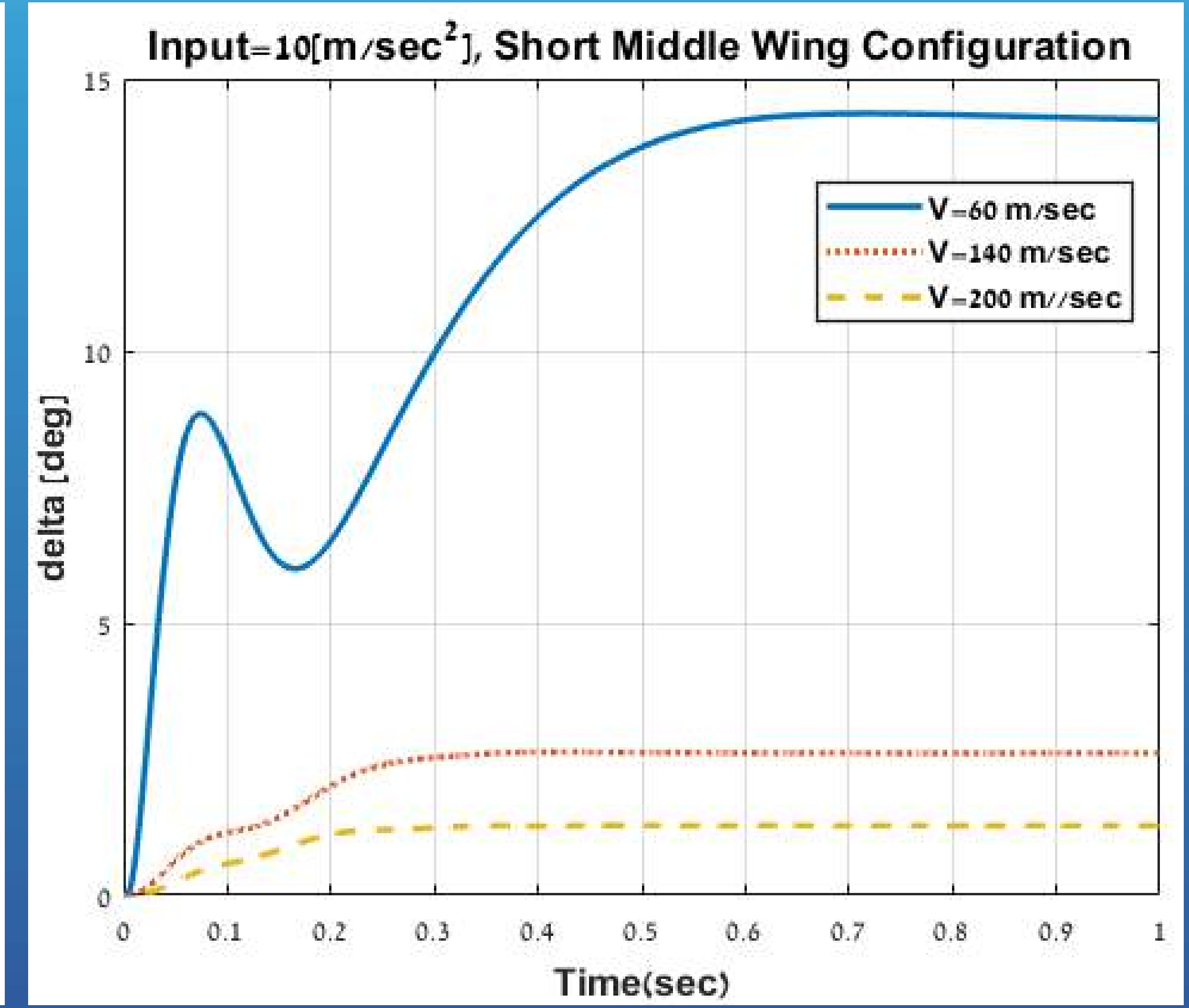




Note: The Same thing was done for KY_3, and the values against Velocity were almost Constants.

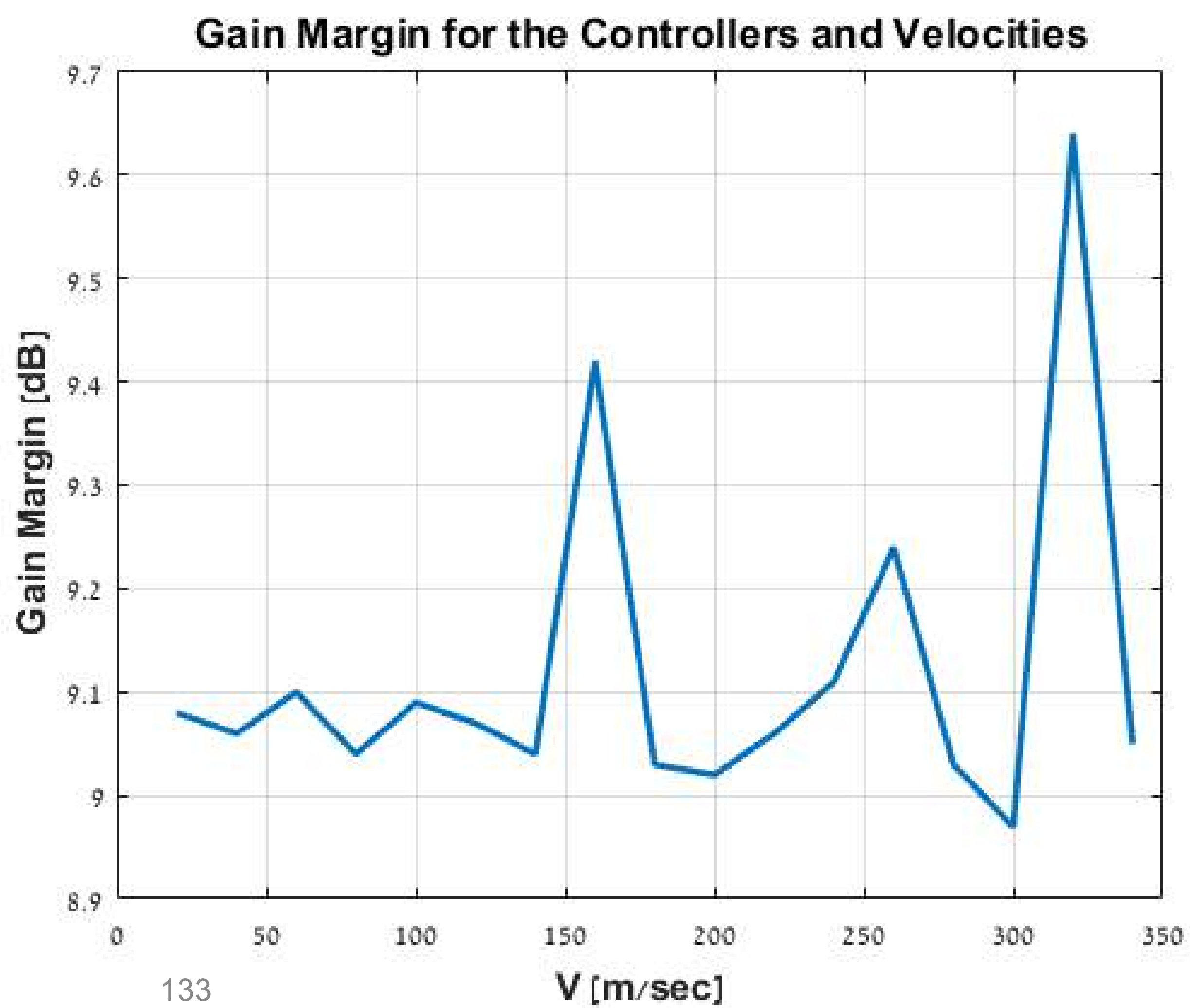
Yaw Control Loop Simulation Results

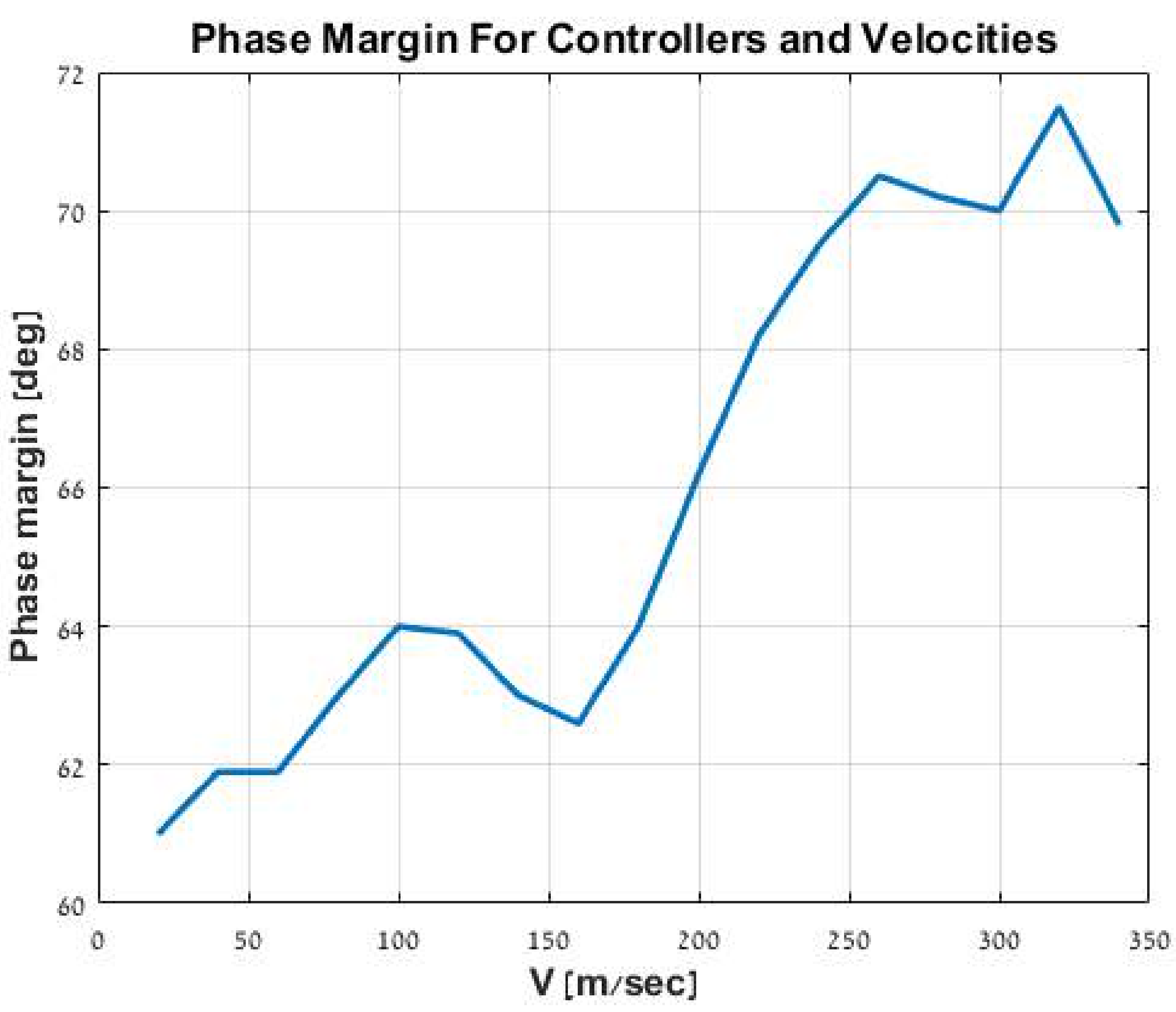




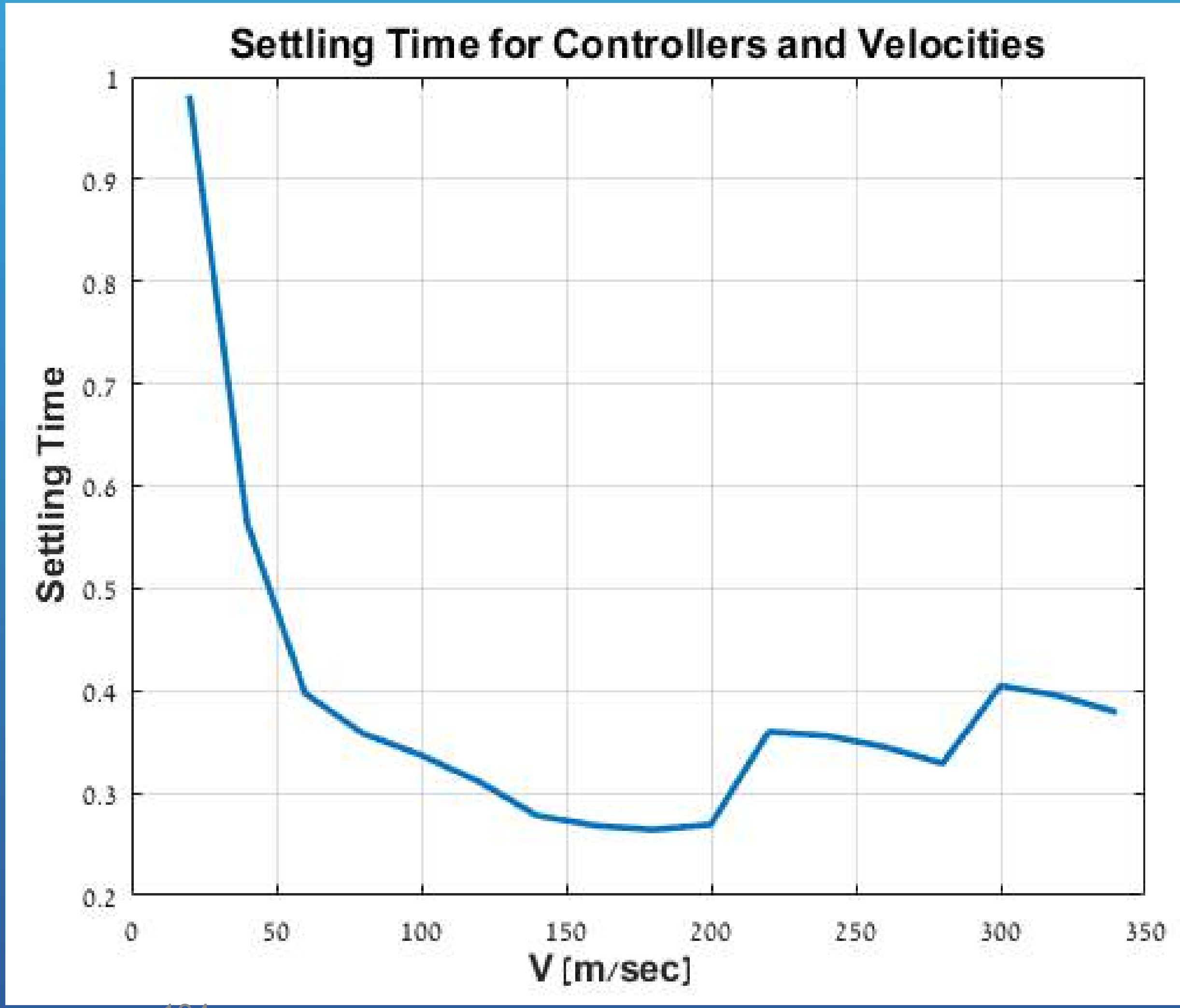
Yaw Control Loop Simulation Results

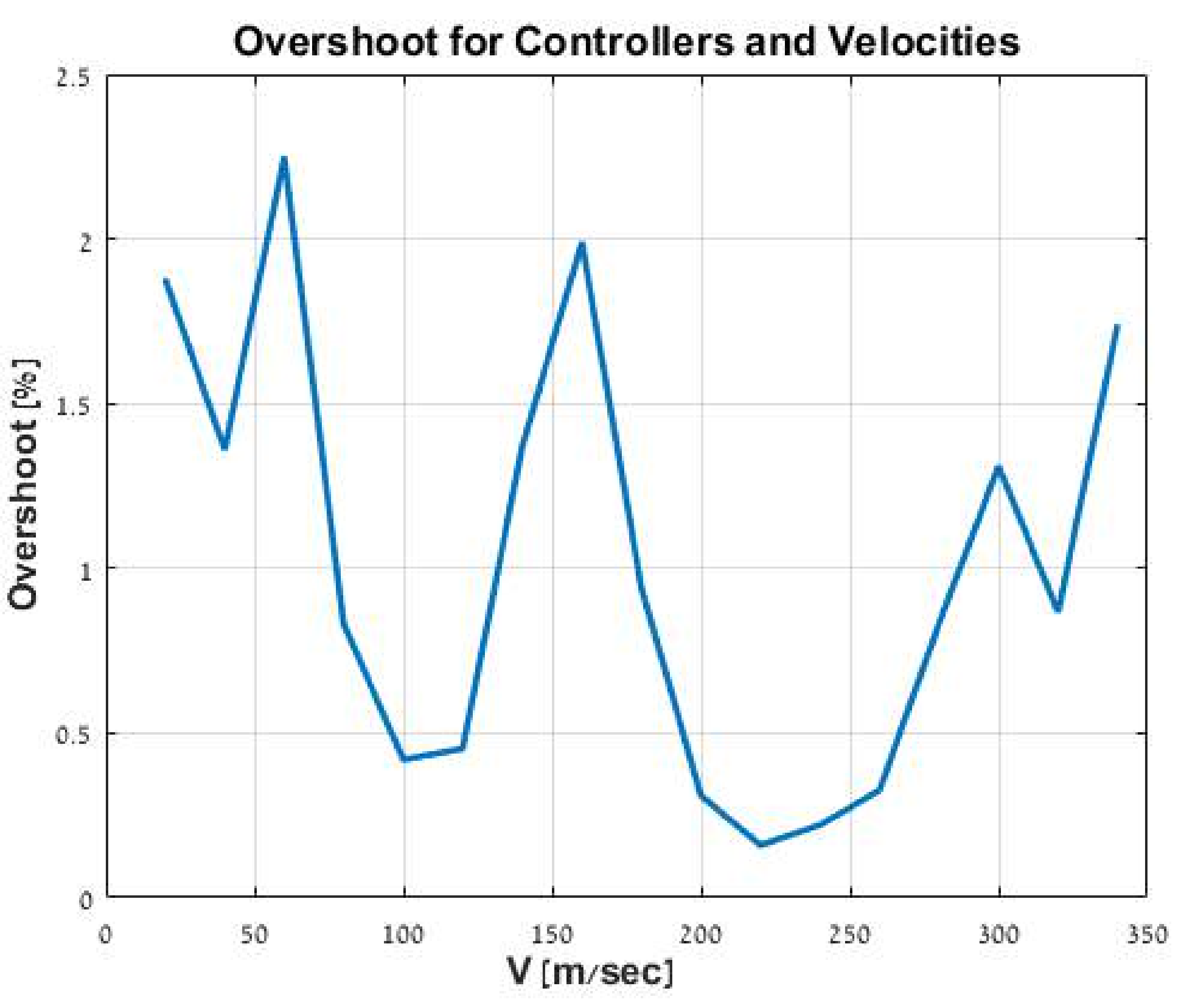
(different from pitch because we found different controllers as a result of Varity in aerodynamic coefficients.)





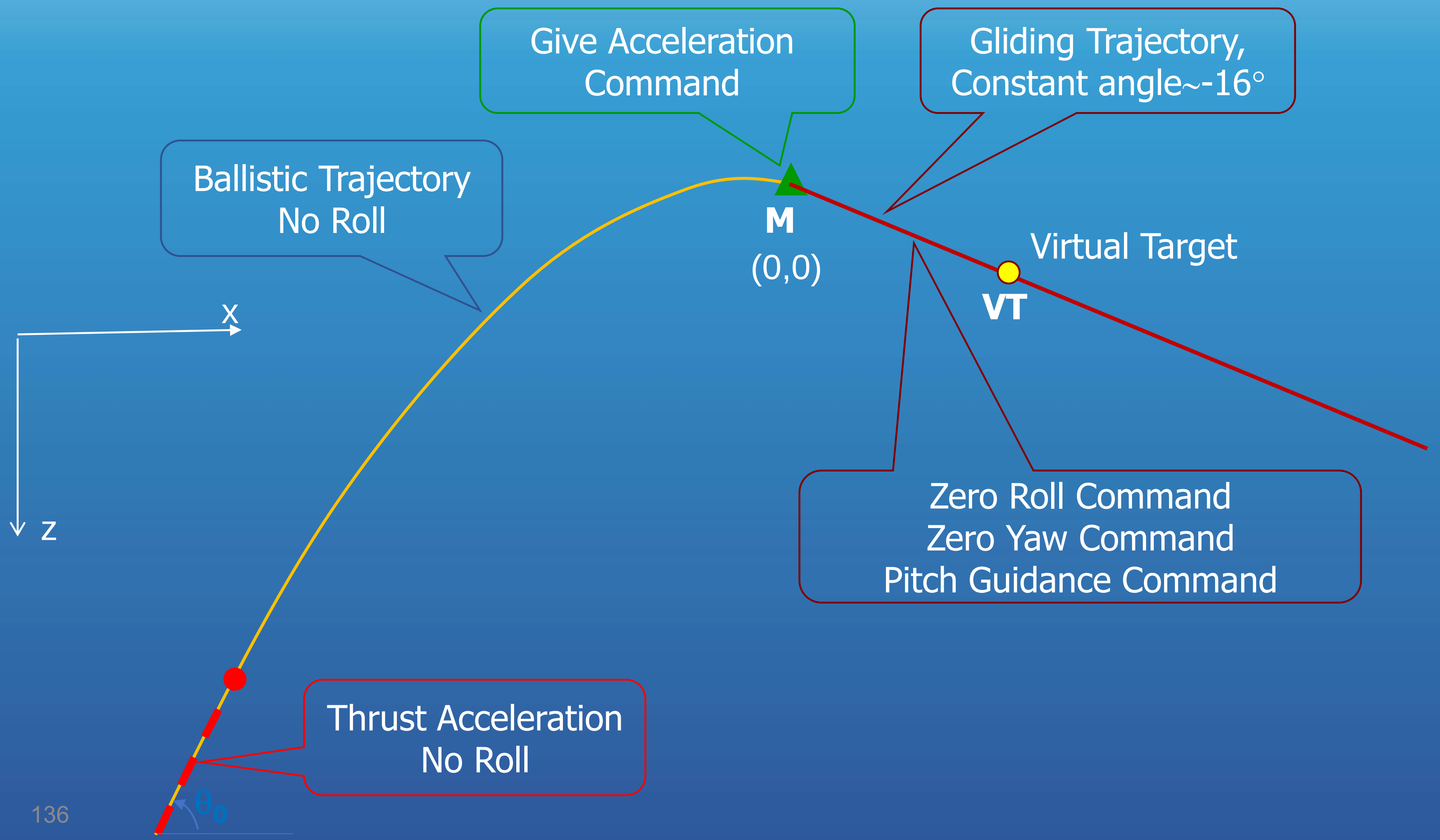
Yaw Control Loop Simulation Results





GUIDANCE

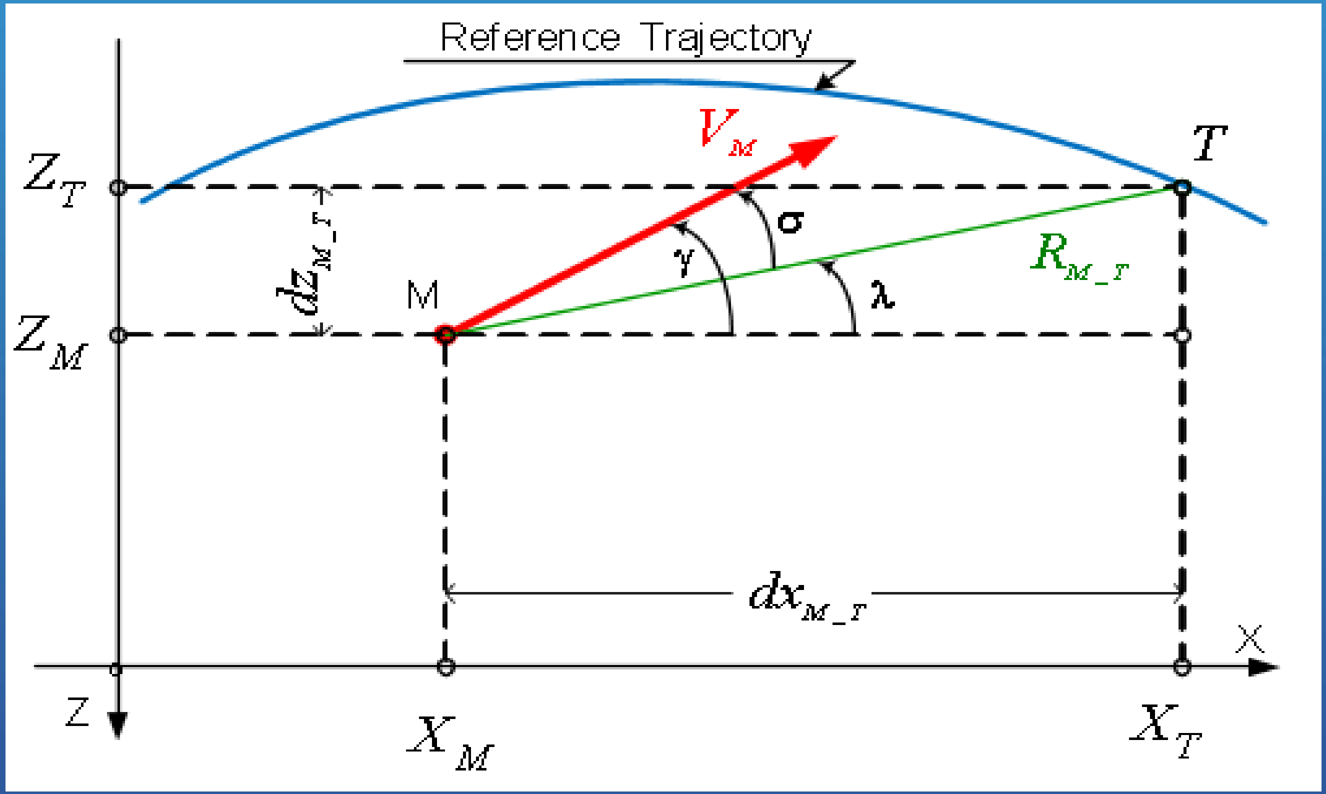
Simple Explanation



Proportional Navigation Guidance Law

- The proposed guidance law is used to give an acceleration command in the pitch plane so we can glide in maximum horizontal Range.

$$a_{zc} = -V_M \cdot K_{nav} \cdot \lambda = \frac{{V_M}^2 \cdot K_{nav} \cdot \sin\sigma}{R_{M-T}}$$



FOC: North-East-Down

Guidance Requirements

- **Using the Proportional Navigation Guidance law, the following requirements are needed:**

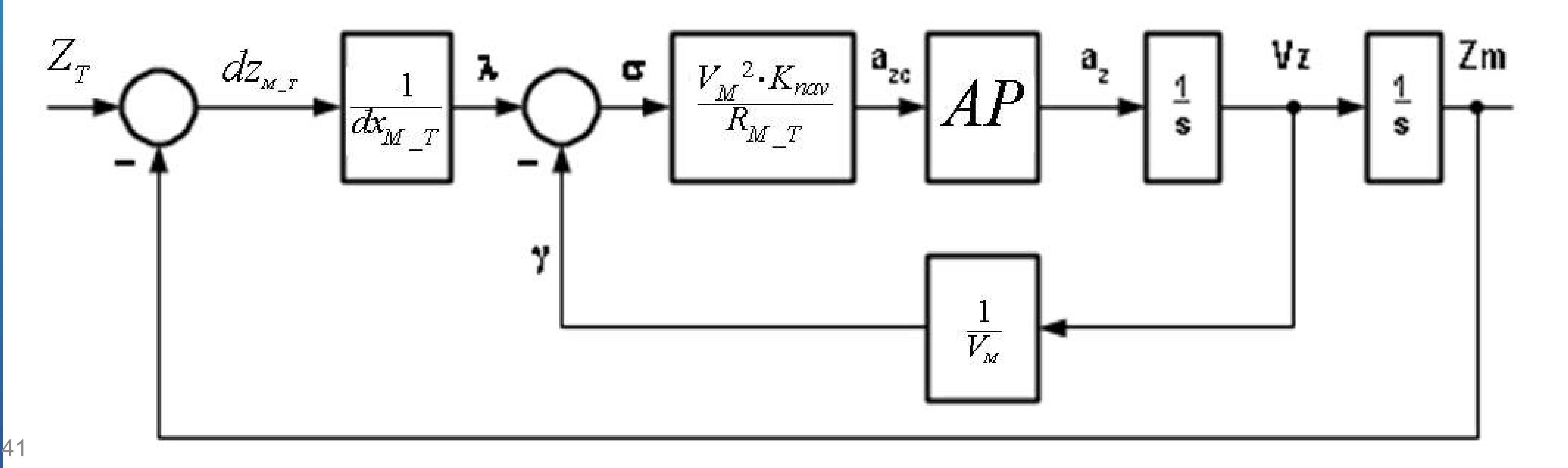
1. Vertical Error can't exceed 10 meters.
2. Overshoot will not exceed 10% for step input.
3. Gain Margin should be larger than 9 dB and Phase Margin larger than 45 degrees.
4. The difference in bandwidth should be in ratio of 6:1 between the Guidance loop and the slowest auto pilot loop (Control Loop).
5. Max Horizontal Range.

Guidance Loop (Pitch Plane)

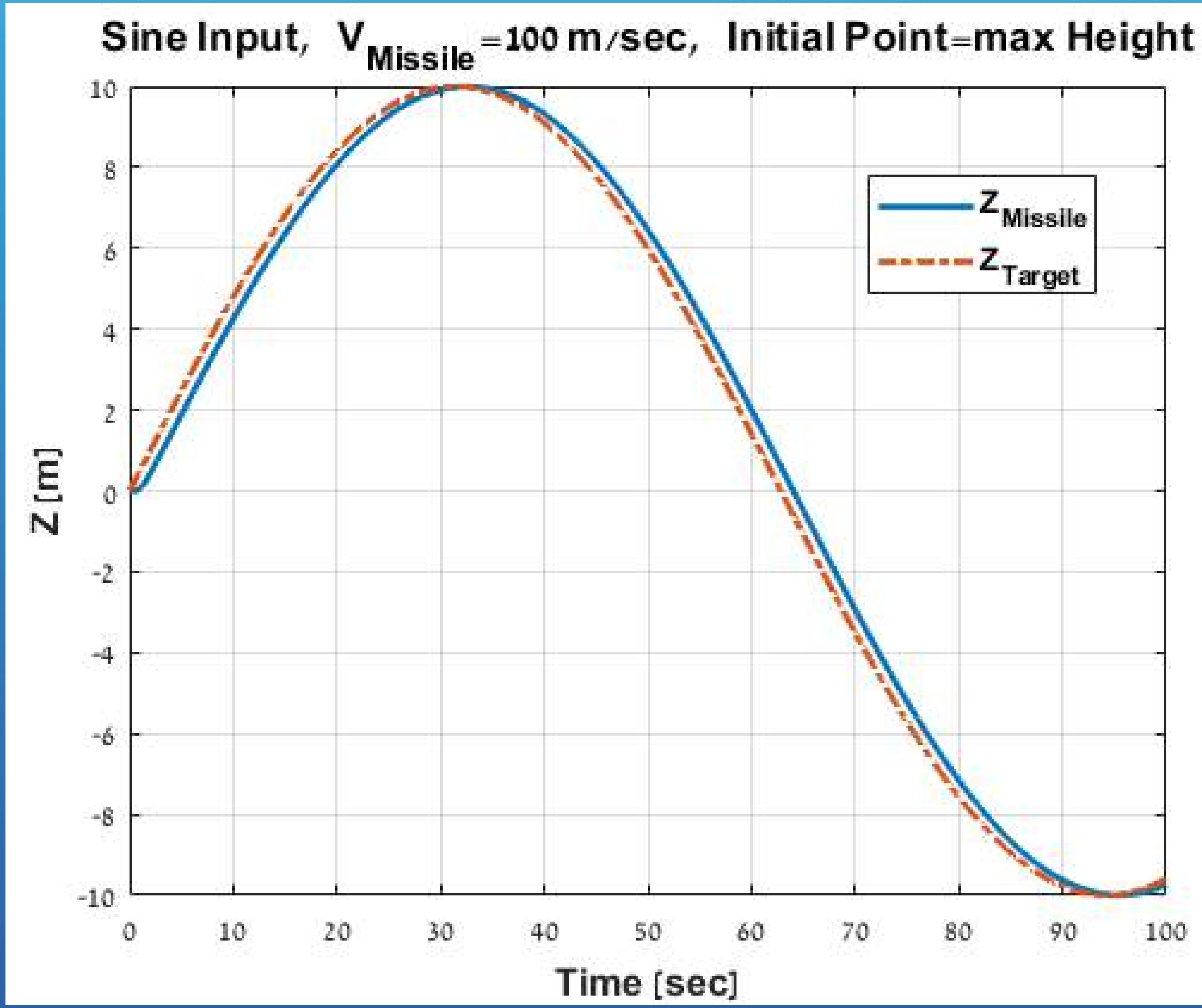
- **We can choose and design the following parameters in the loop analysis:**

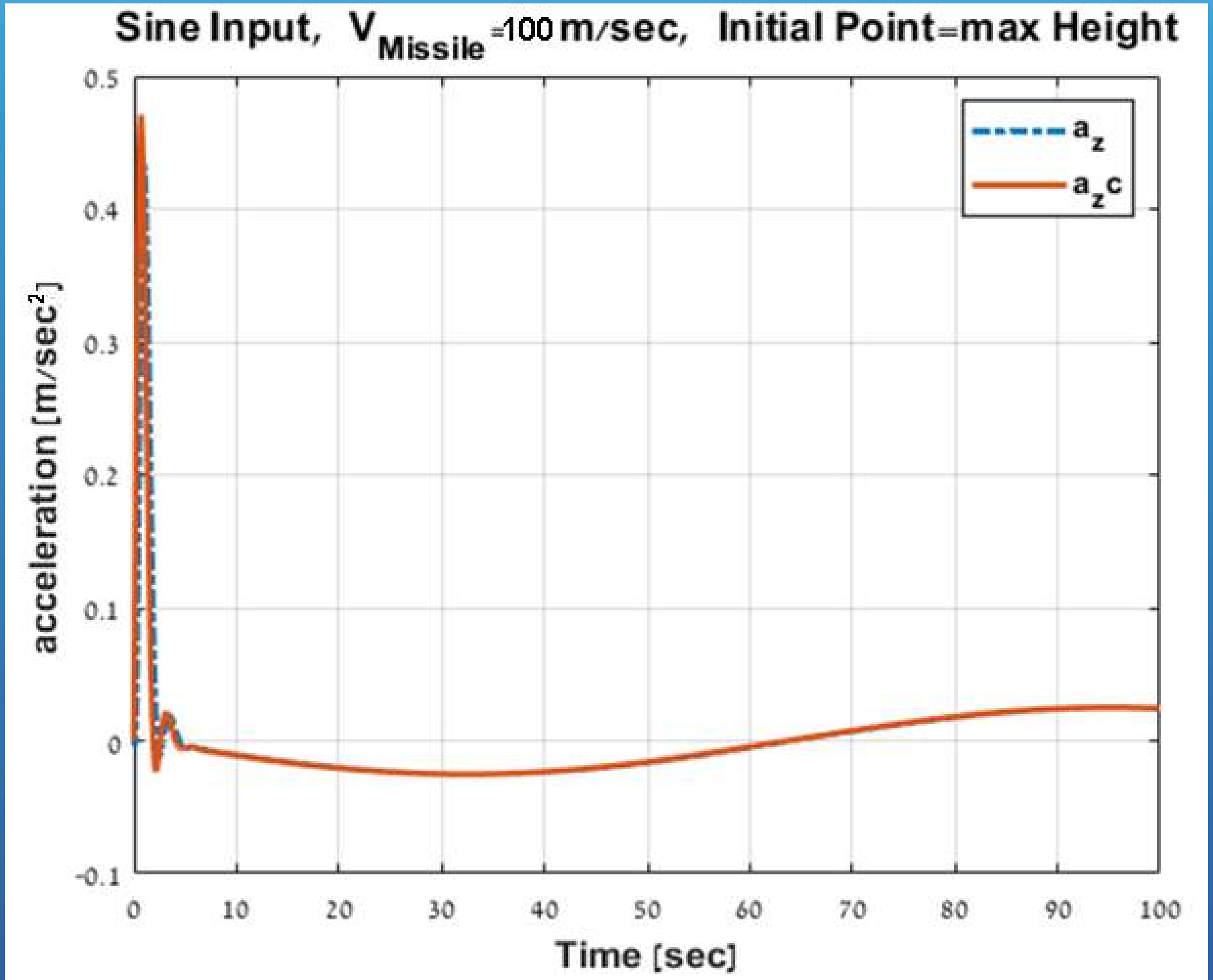
- **K_nav (=3, which is the optimal value for PN)**

- **Range between Missile and Target. (RVT)**

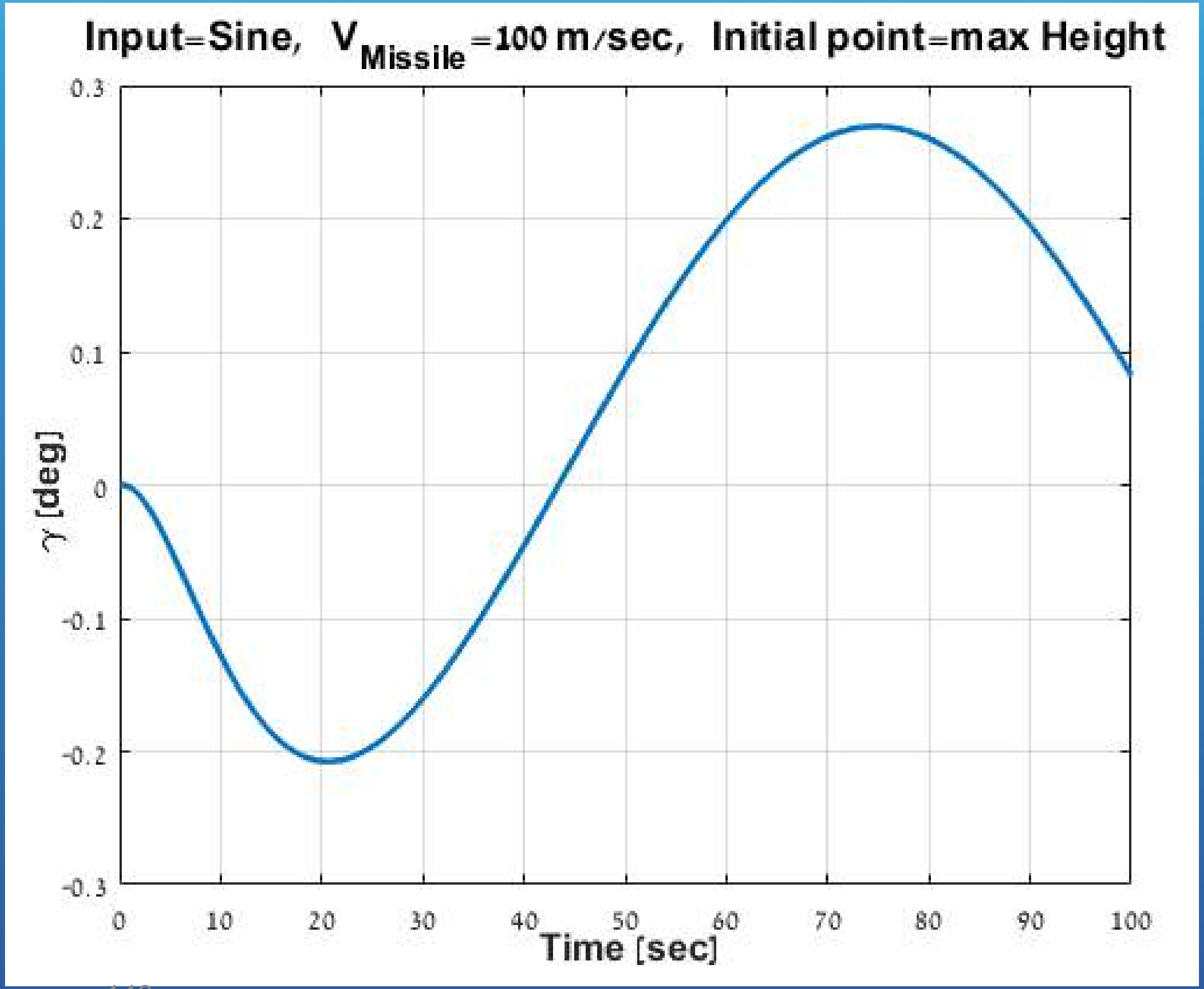


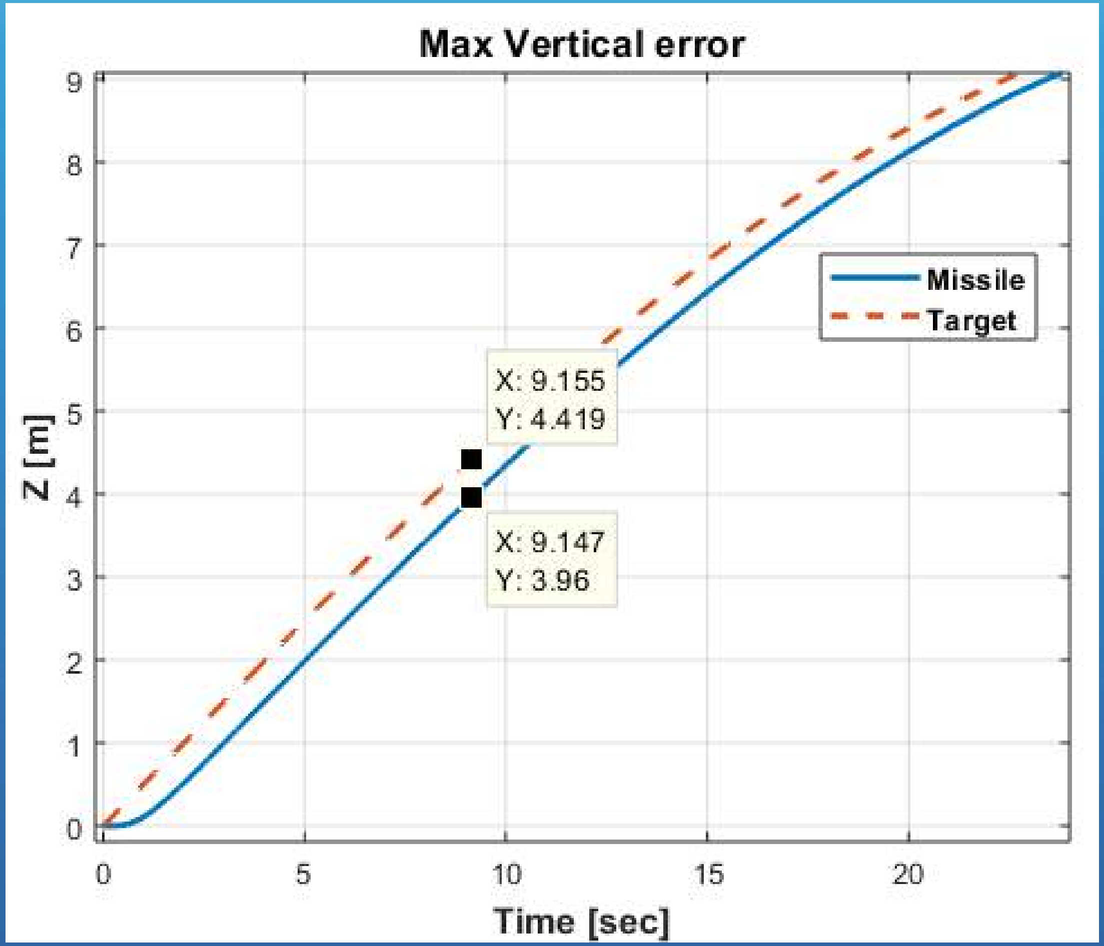
Guidance Loop Results- Sine input





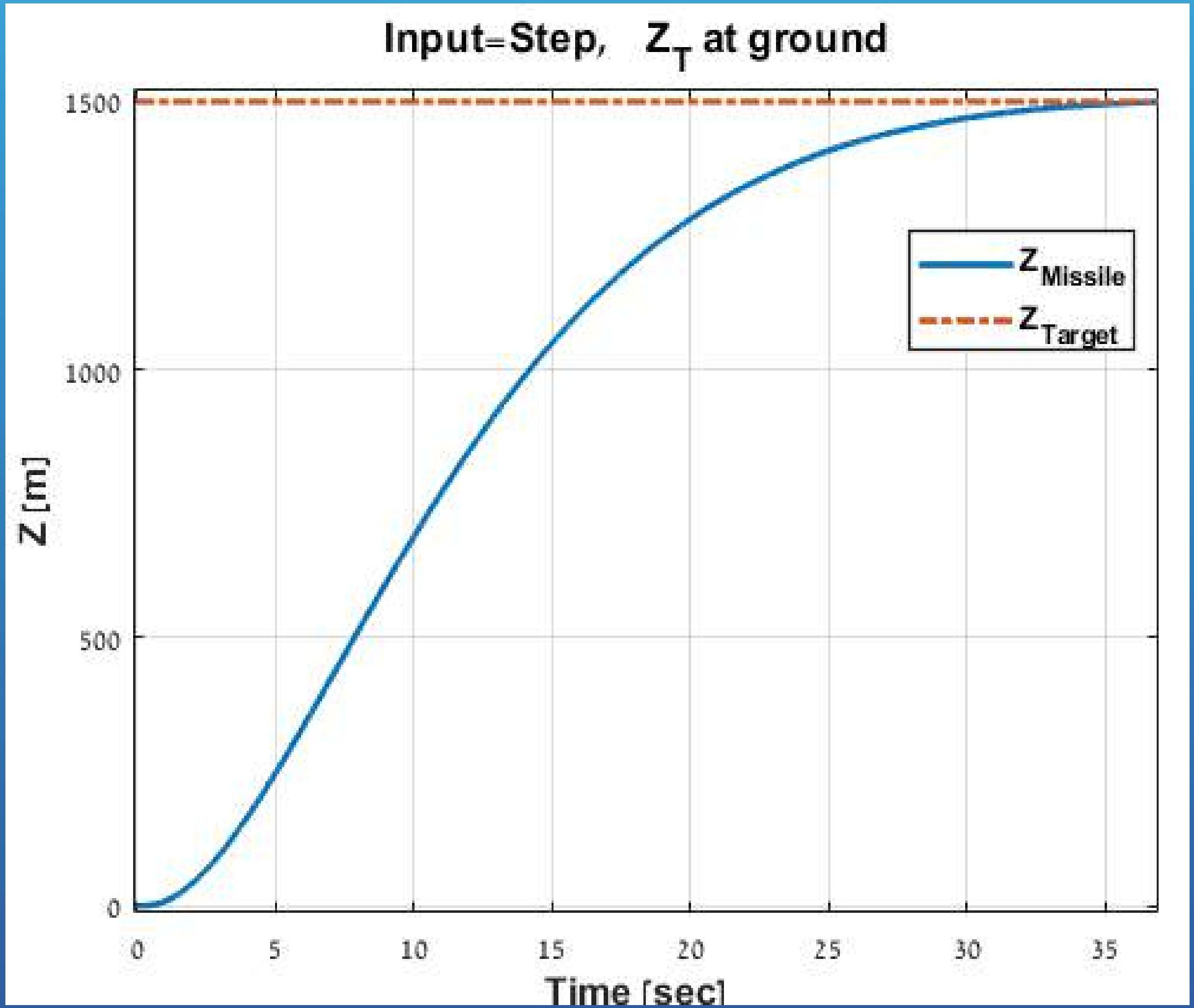
Guidance Loop Results- Sine Input

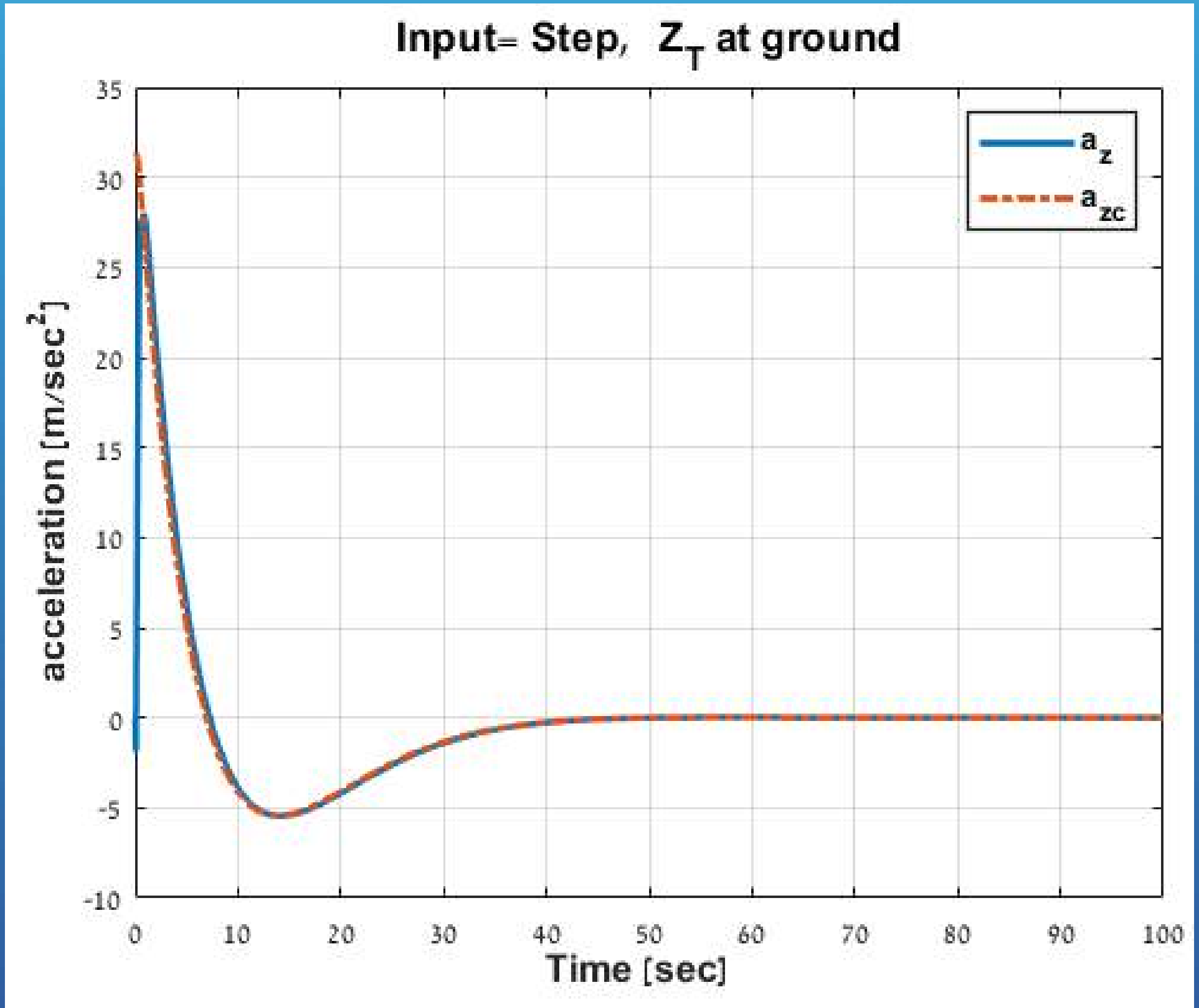




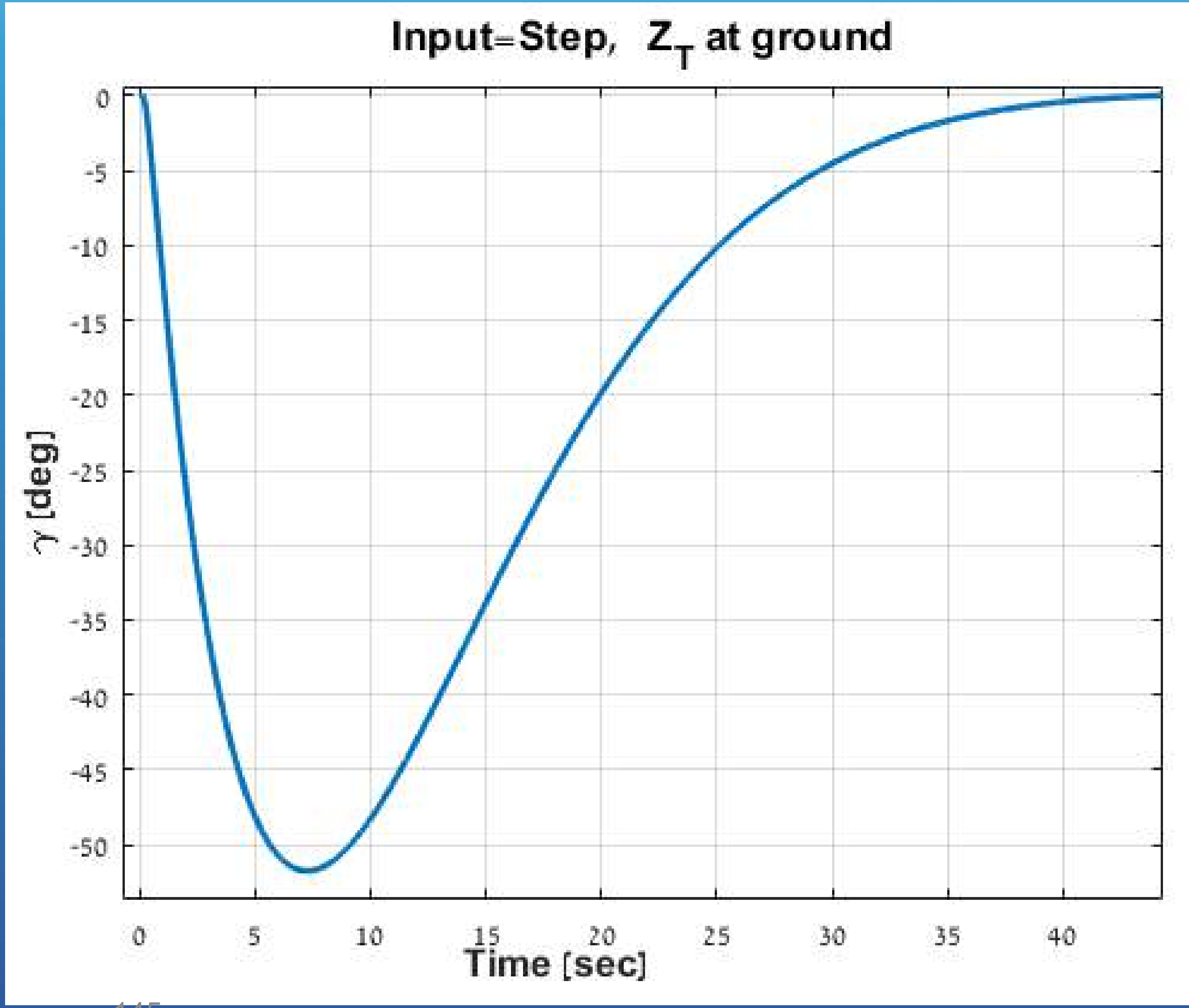
Max Z_Error- 0.46m.

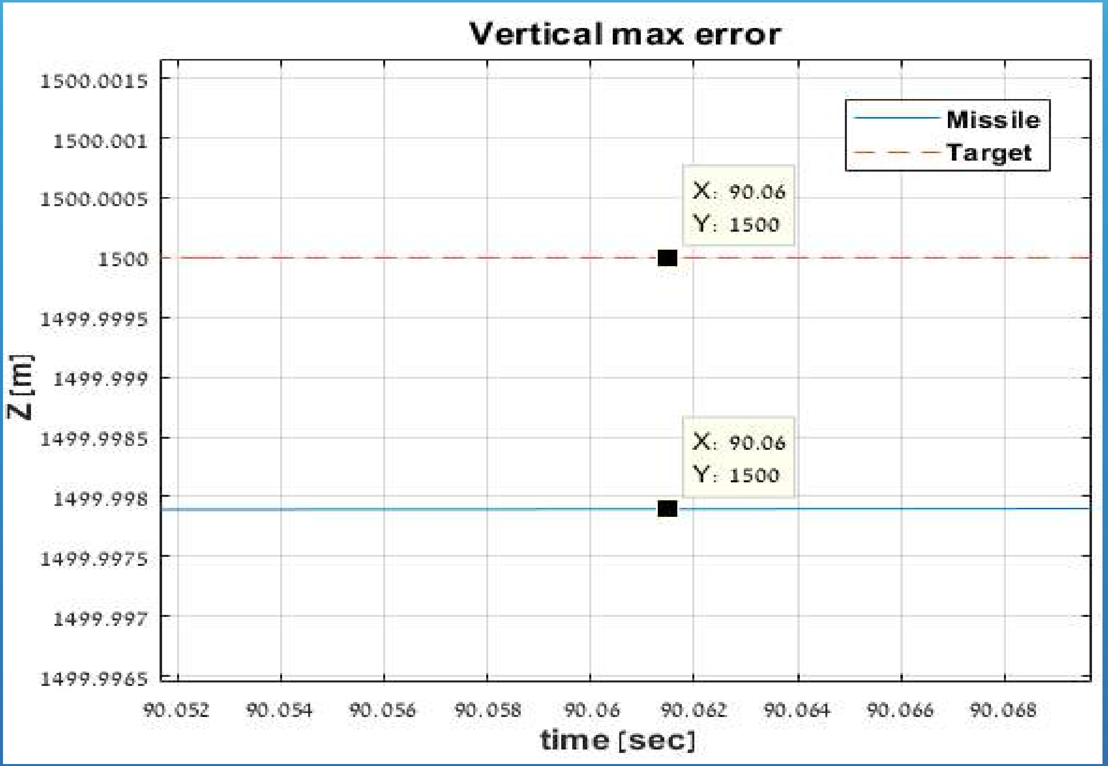
Guidance Loop Results –Step input





Guidance Loop Results –Step input





Gain Margin- 15 dB.
Phase Margin- 70 deg
Steady State Error- 0.002m.

NAVIGATION

Navigation Goal

- Navigation: To produce the navigation pose vector to make loop closer for the guidance loop and for other needs while minimizing the pose error.

Last Year and Last Semester

- Last year:
  - Last year team added an IMU model to the simulation and tested it.
- Last semester:
  - IMU model verification
  - A task layout for the current semester was established
    - Building a strapdown algorithm and integrate it in the simulation
    - Building an INS error generator as a replace to GPS and EKF model in the simulation
    - Test the GPS receiver with advanced GPS test equipment

Strapdown Algorithm

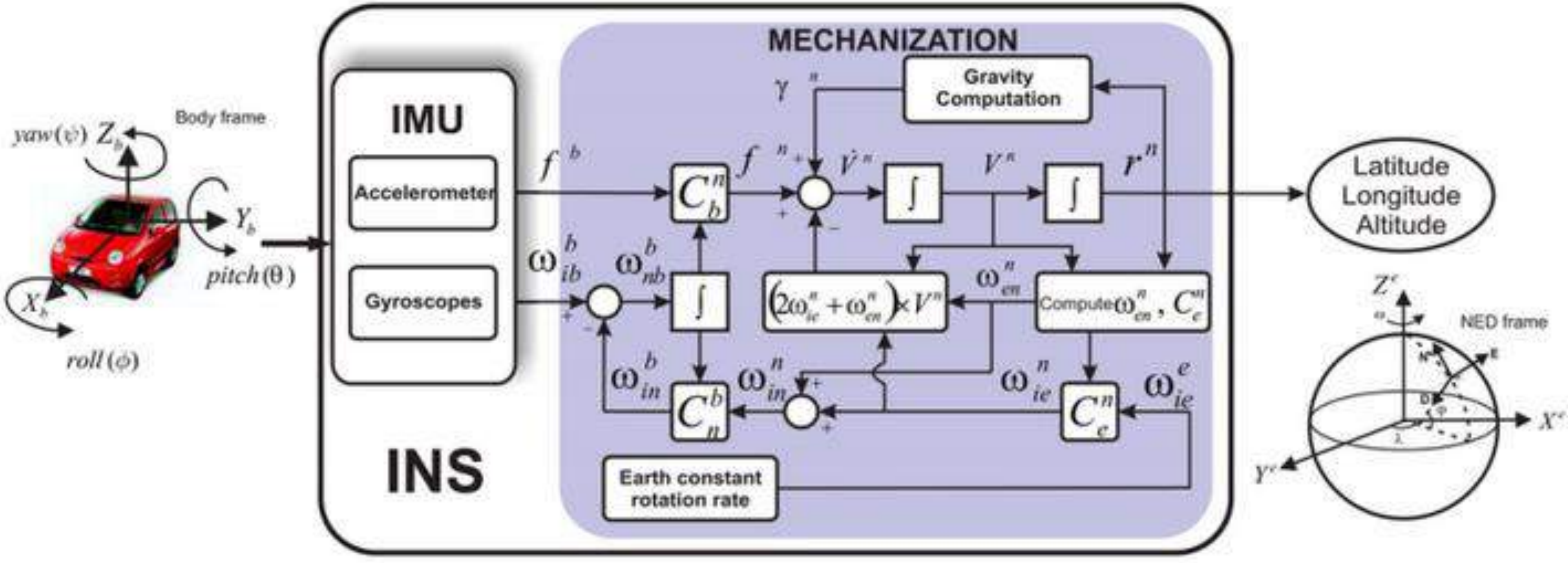
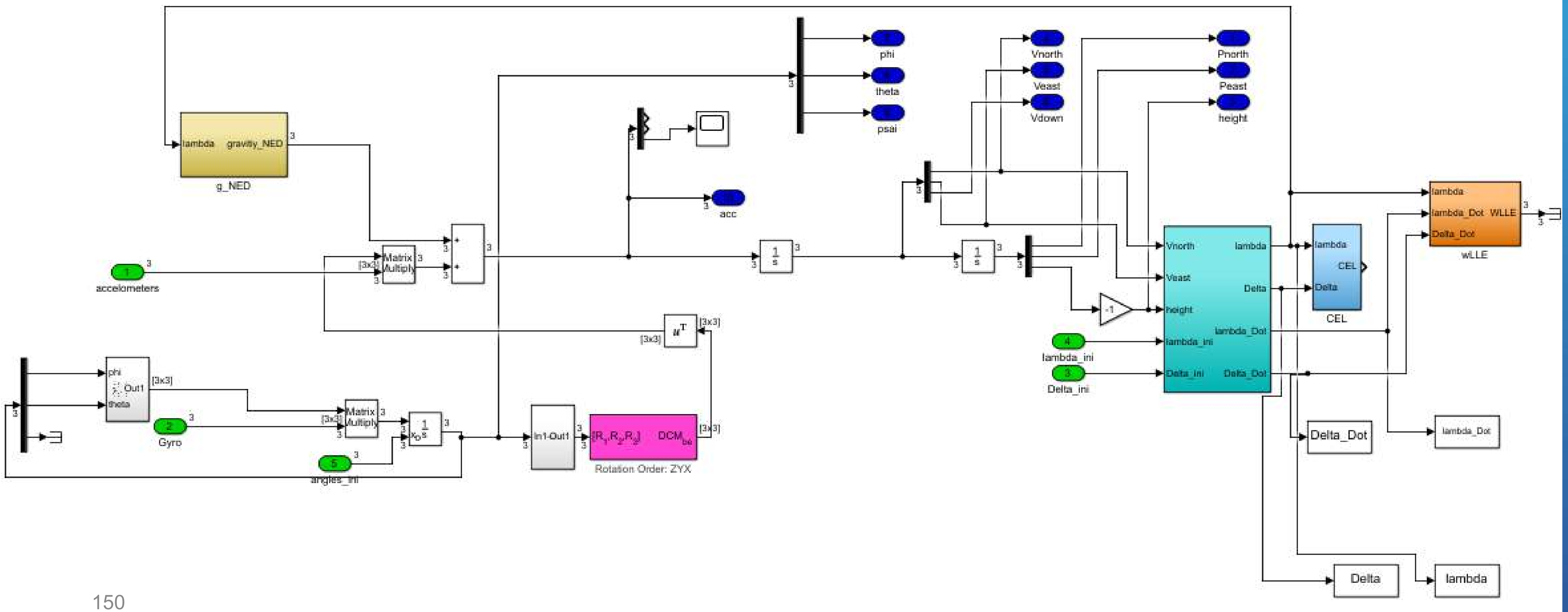
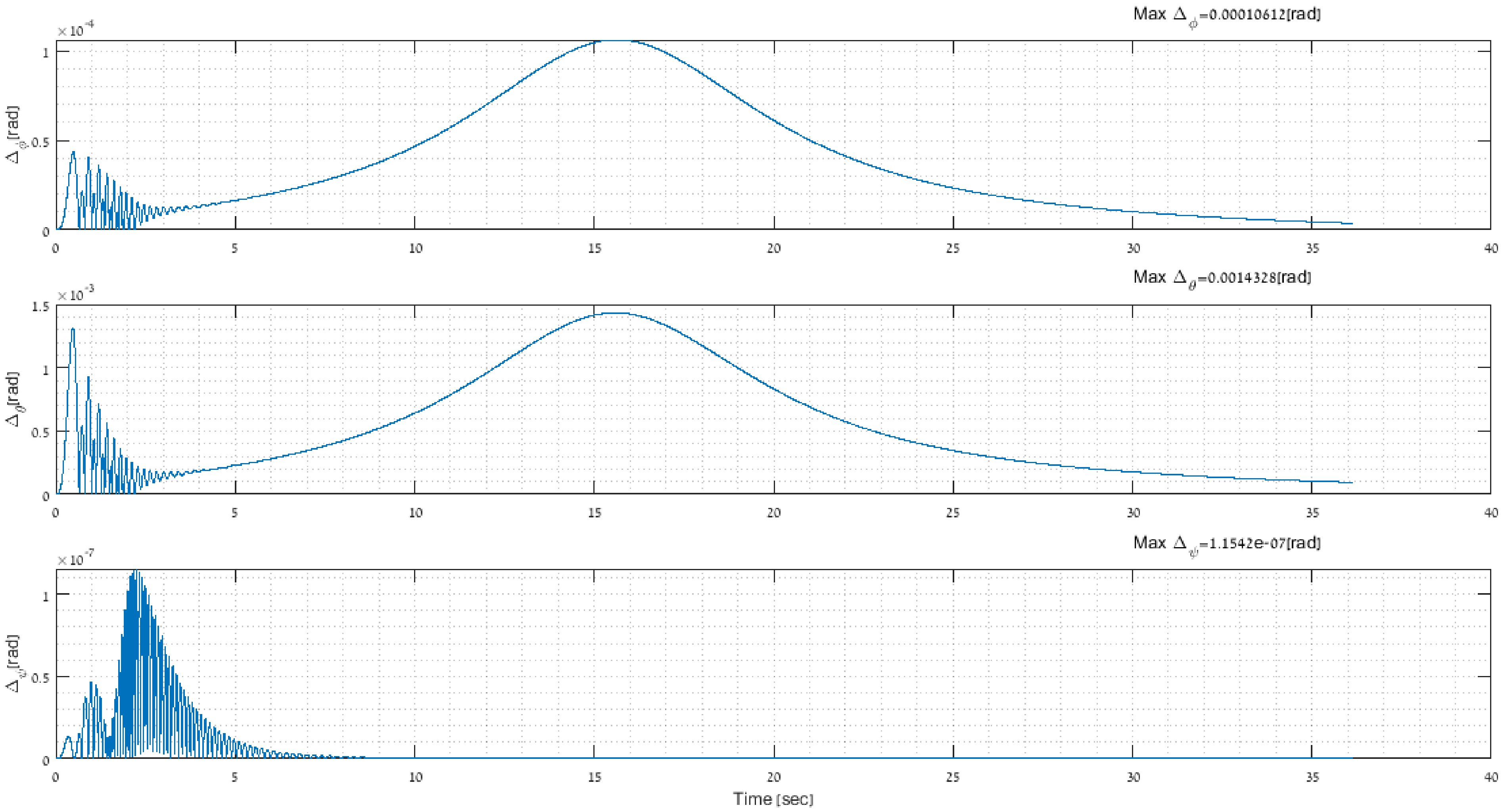


Image from: Schultz, C.E. INS and GPS Integration. M.Sc. Thesis, Technical University of Denmark, July 2006

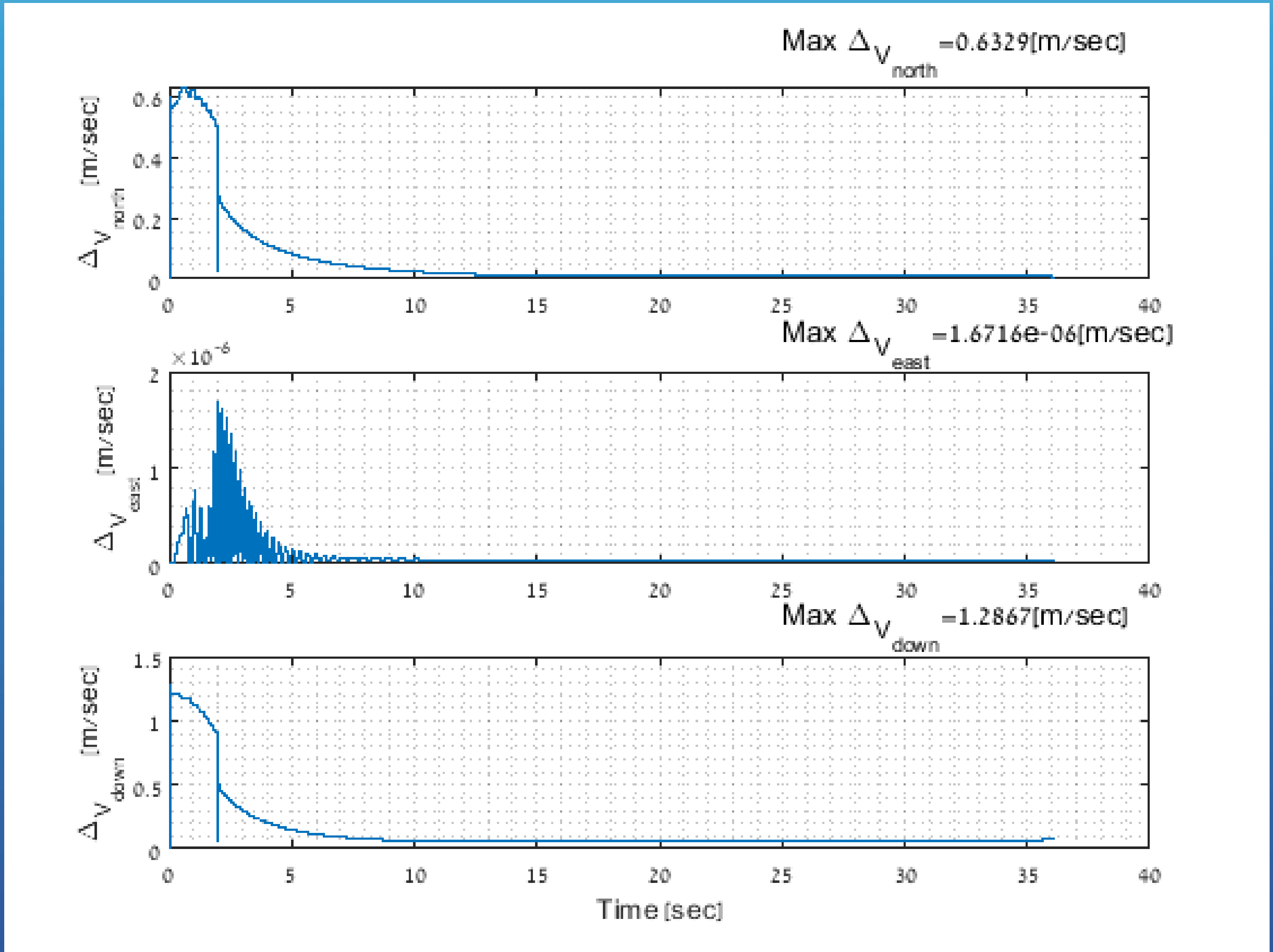
Strapdown Algorithm-Block Diagram



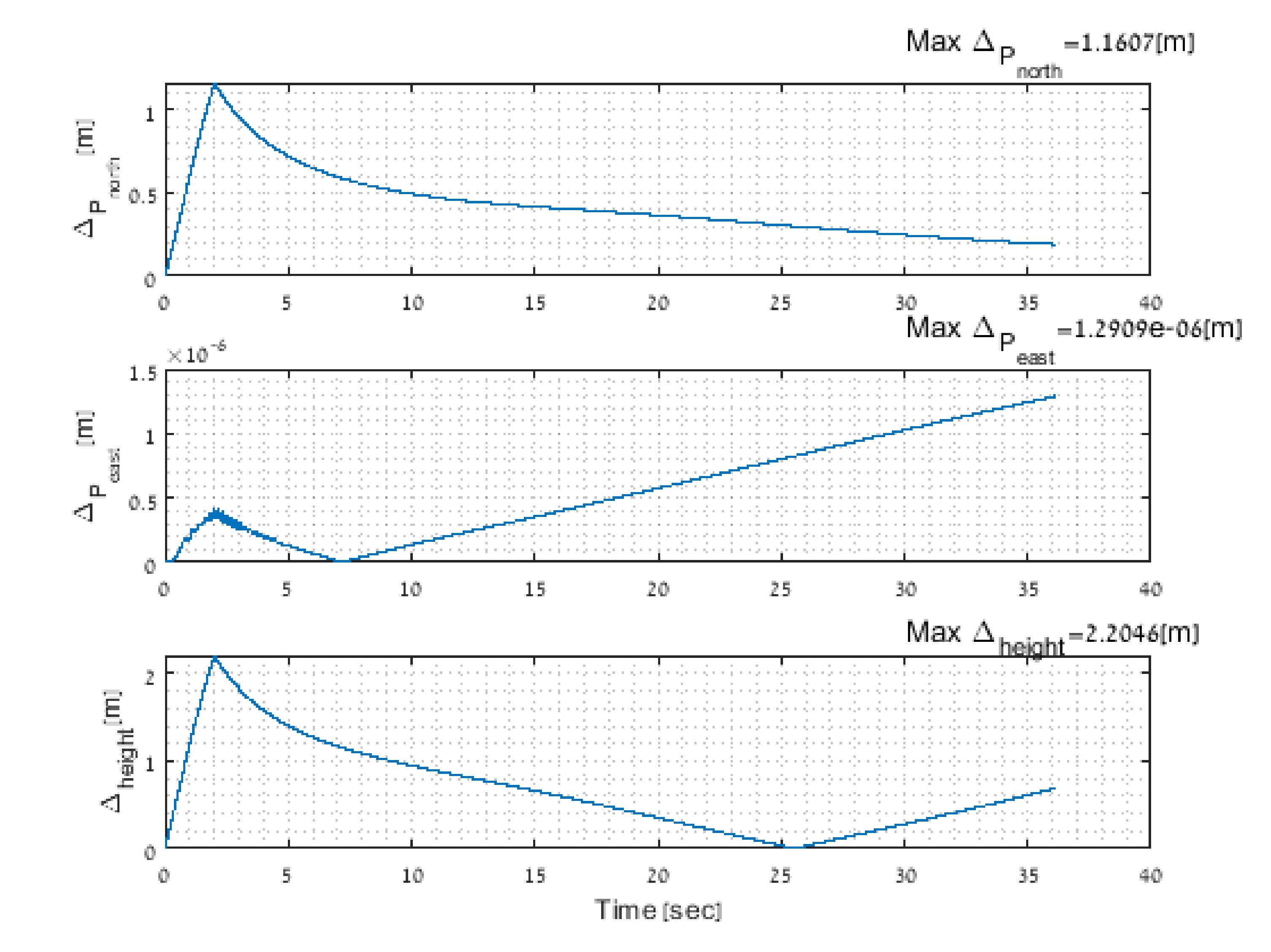
Strapdown Algorithm- Angle Error



Strapdown Algorithm- Velocity Error



Strapdown Algorithm- Position Error



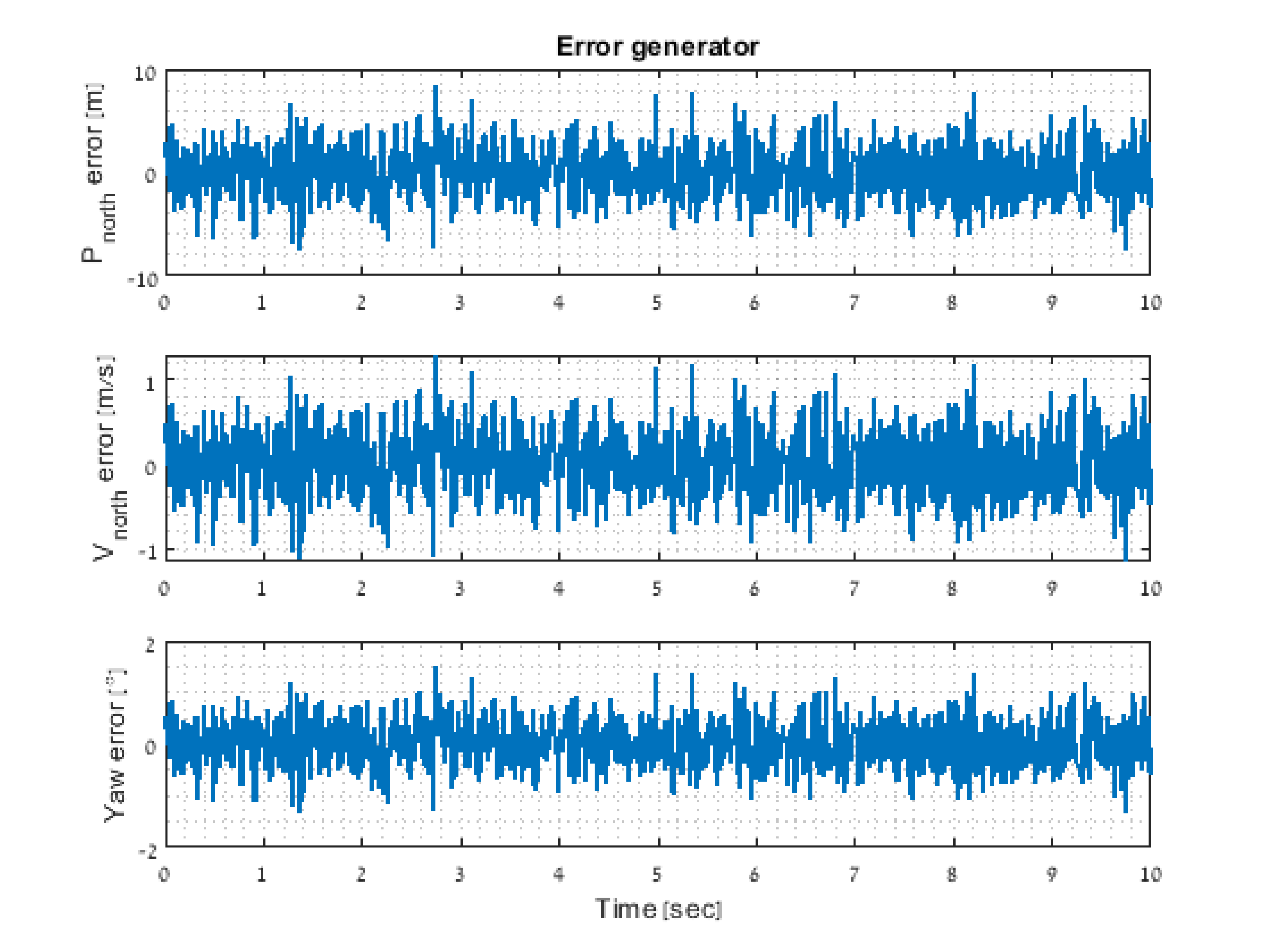
Strapdown Algorithm- Neglection Validation

Angle error over a minute	Velocity error over a minute	Position error over a minute
$\Delta_{angle} = 5.8[mrad] = 0.33[\deg]$	$\Delta_V = 0.51\left[\frac{m}{\sec}\right]$	$\Delta_P = 15.3[m]$

INS Error Generator

- To simulate the total navigation solution with suitable errors an error generator was made
- The error generator produce an error that corresponds to the GPS errors
- All the 9 element where modeled as gauss distributed variables followed by white noise
- The distributions are based on data from experiments, Wikipedia and an article, A Galileo IOV assessment: Measurement and position domain, and detailed in the follow document, "Error Generator".

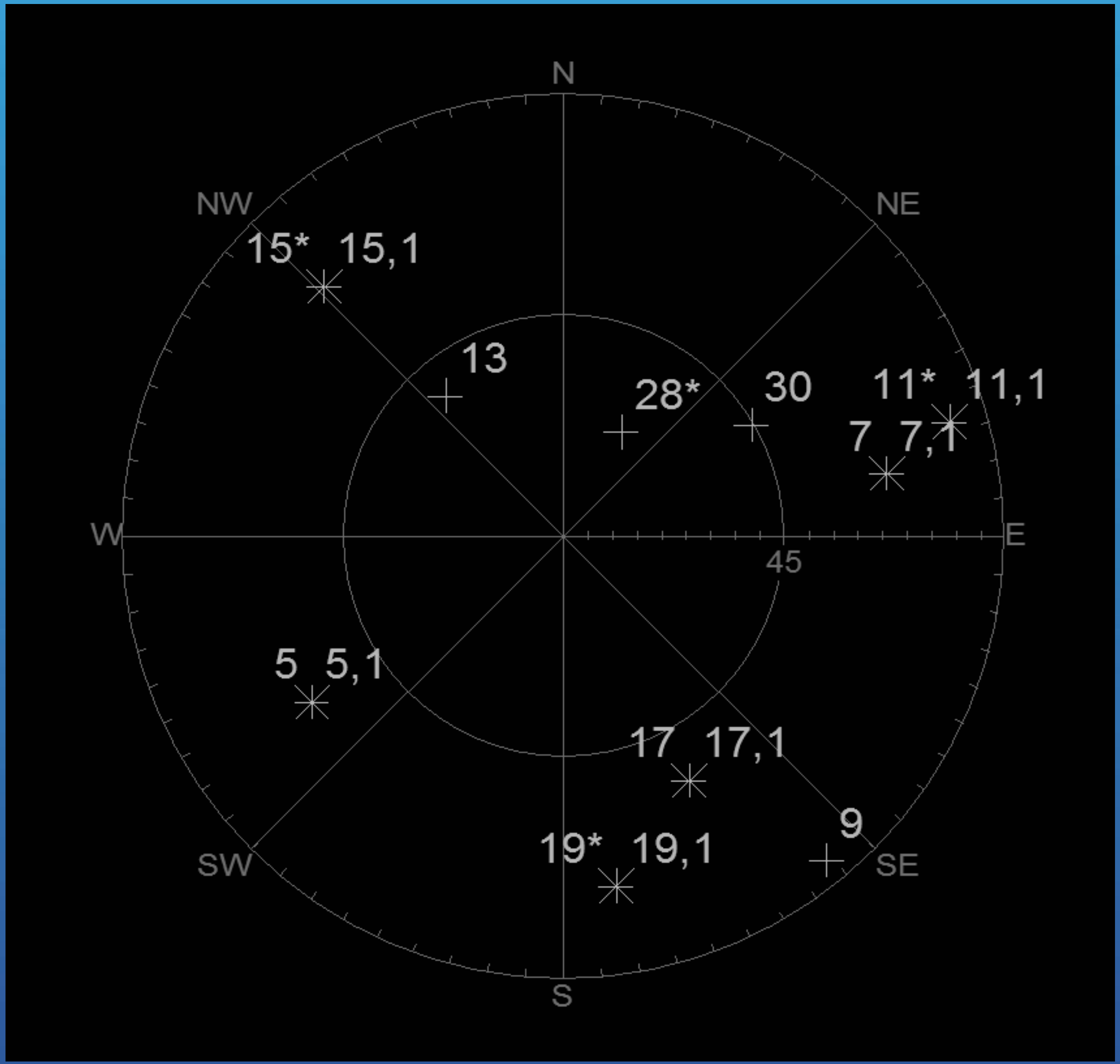
INS Error Generator



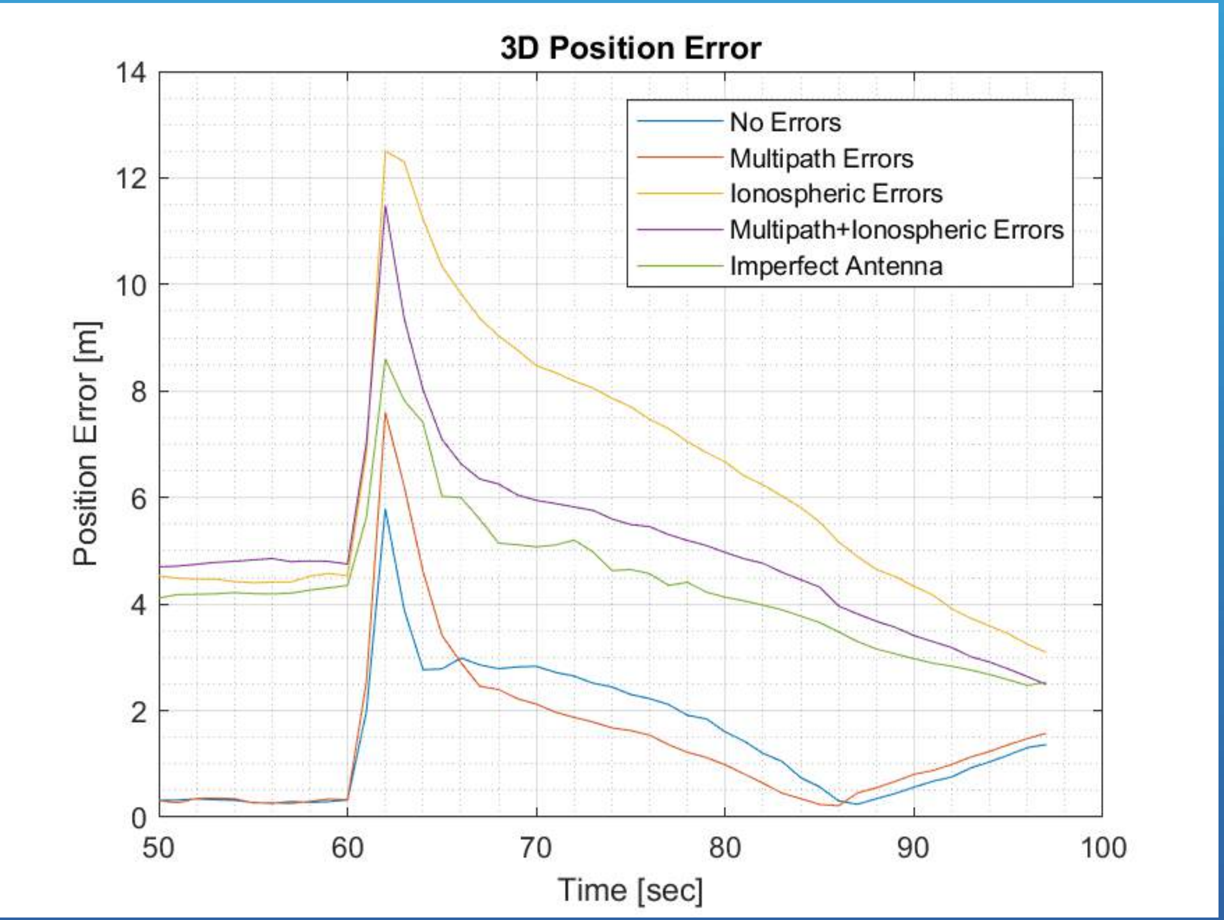
GPS Testing-Scenario Modeling

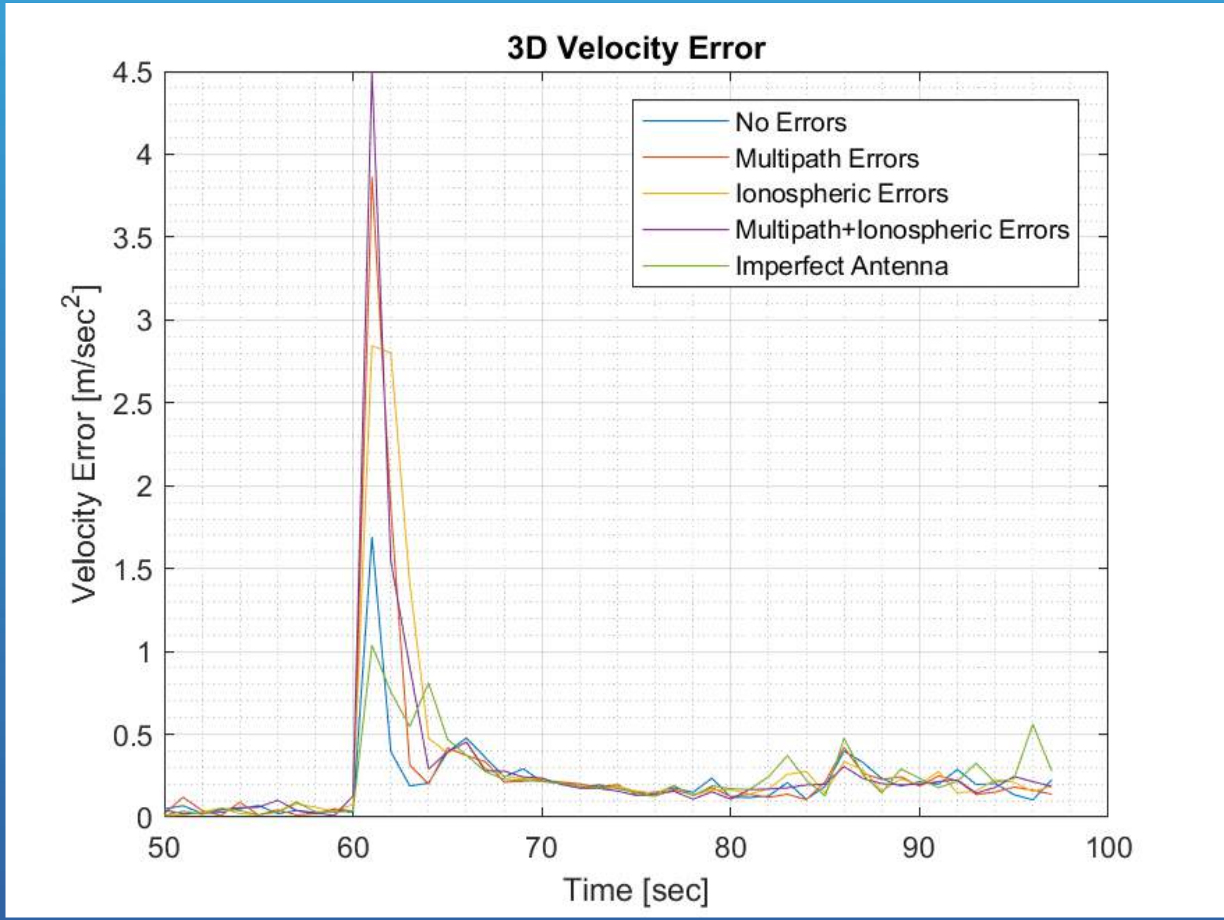
- Equipment- Spirent GNSS-9000
- Scenario date: may 5th 2018 07:00:00 UTC
- Tropospheric Model: STANAG 324.8
- Ionosphere Model: by Klobuchar coefficients.
- Multipath: 6 multipath ground reflection with 15dB attenuation as presented in sky view
- Satellites position: presented in sky view
- Antenna model: maximal attenuation (46 dB) at the bottom
- GPS signal attenuation: -120dBm

GPS Testing-Sky View

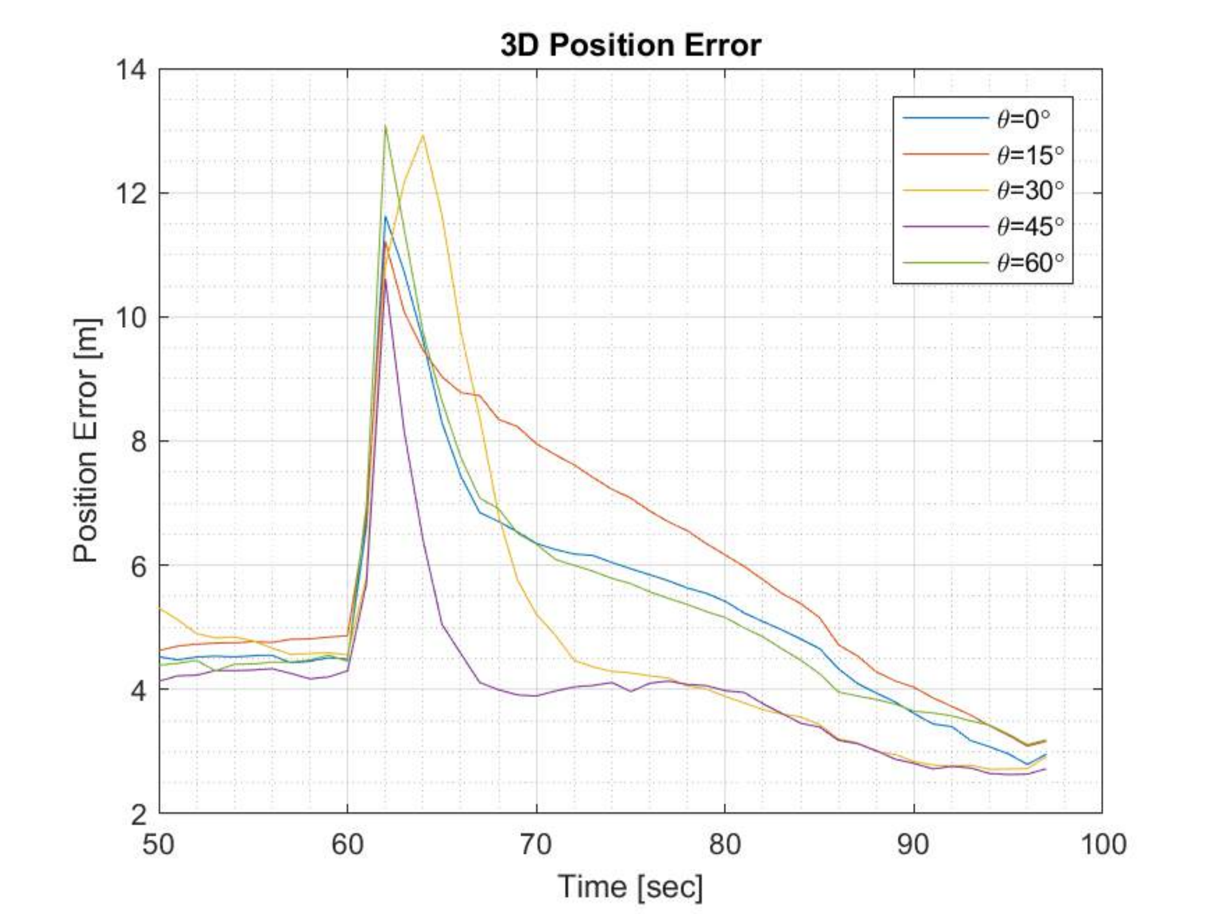


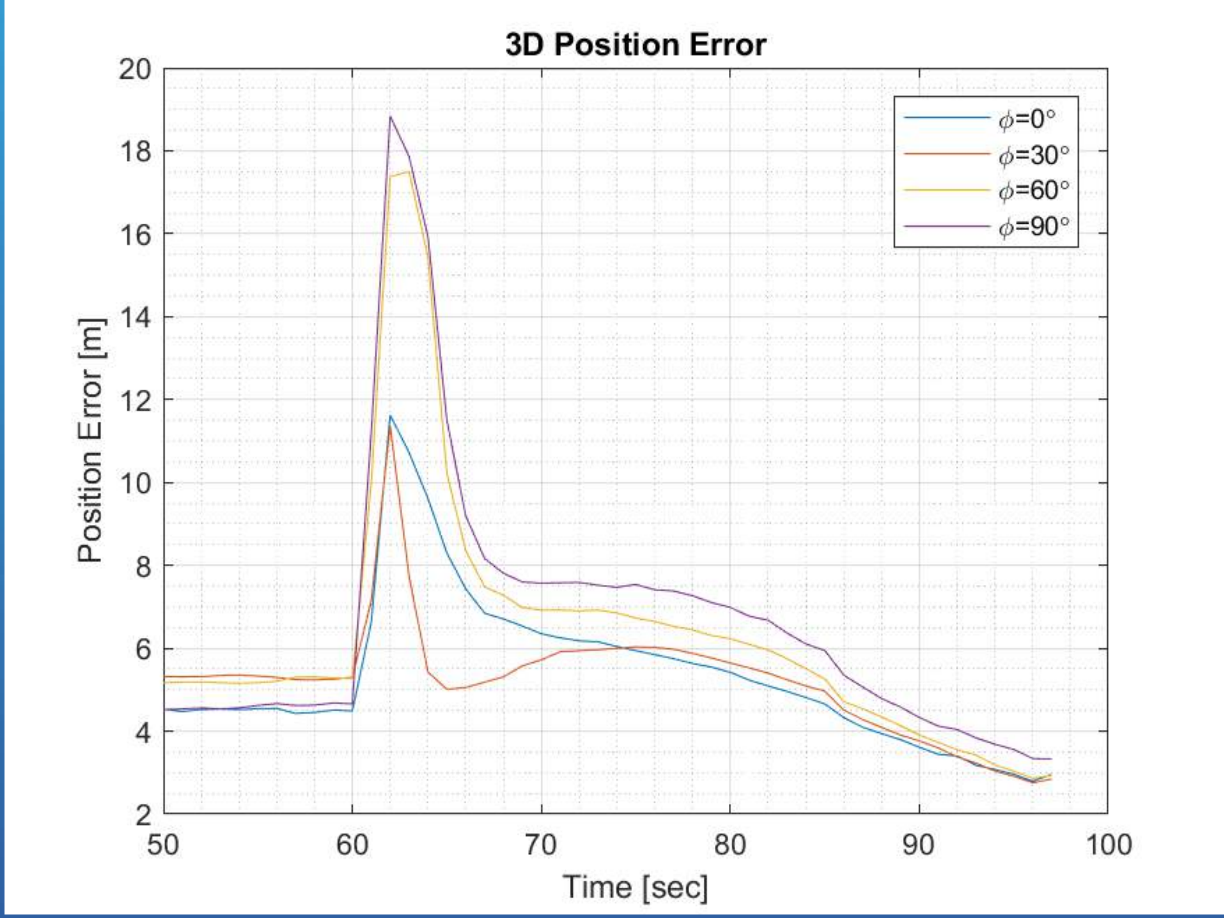
GPS Testing-Position and Velocity Errors





GPS Testing-Position and Velocity Errors due to Pitch and Roll angles





GPS Testing-Summary

	Not recommended	Fix lost	Comments
Acceleration	>4g		5 up to 10 seconds “GPS blind”
Roll Angle	>30°	>90°	At 180° roll there is a “bad fix” from multipath
Pitch angle	>65°	>65°~70°	On ground

IMU-Testing Goals

- Would the current IMU function with acceleration above 4g
- How big is the error due to the above acceleration in estimated solution mode.
- What are the IMU’s model error (Biases/Drifts)

IMU-Testing

Tests number	Test name	Goal 1	Goal 2	Goal 3	Special Equipment
First test	Static test	IMU coordinate frame	Sanity check	IMU biases/drifts	non
Second test	Error due to rotation	Model the IMU’s error due to roll rate	Model the IMU’s error due to pitch rate	Model the IMU’s error due to roll and pitch rate	3 axis simulator (Gimbal)
Third test	Error due to high acceleration	Check the error that developed due to accelerations above 4g			High rotating speed motor >3.14 [Hz]

SIMULATION

Simulation

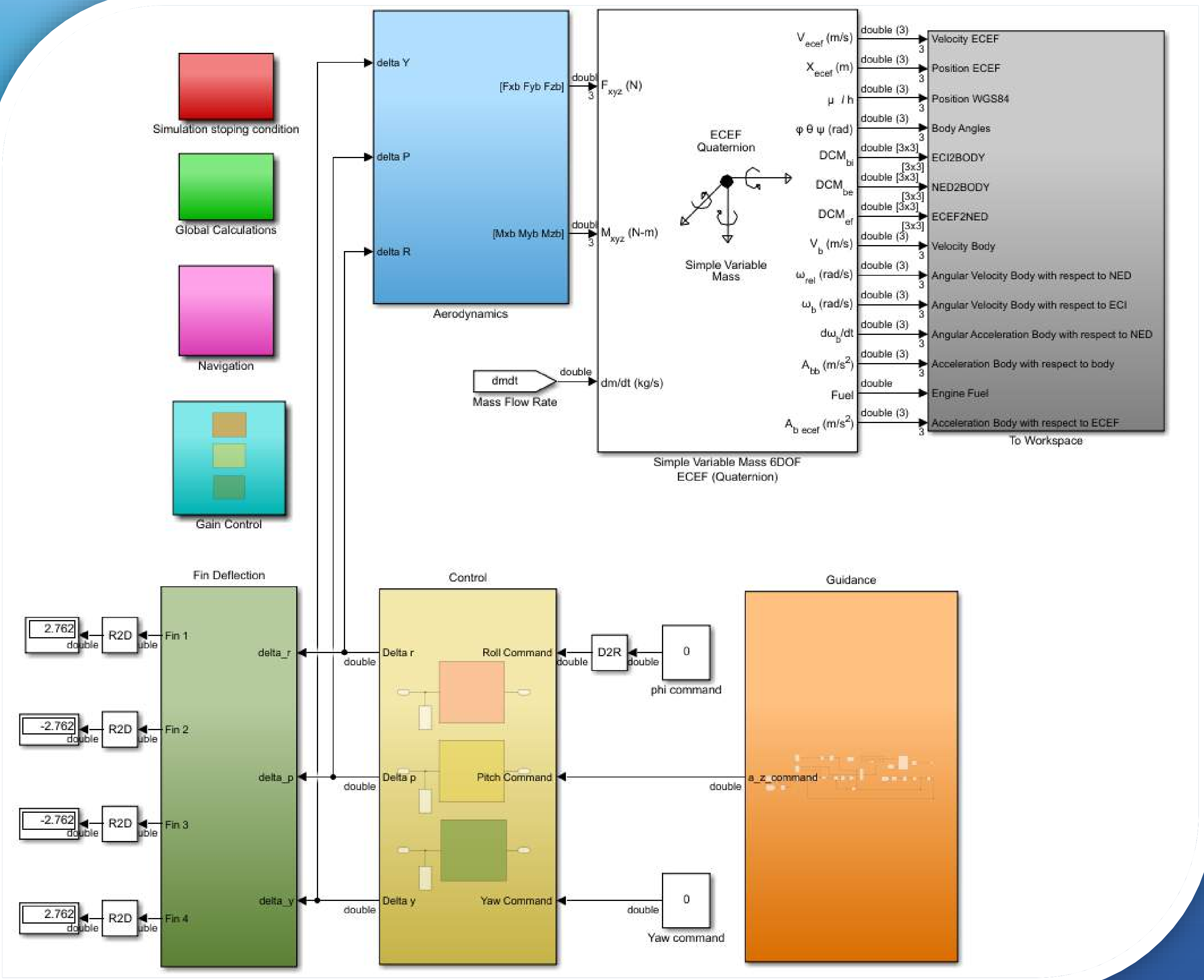
What can we do with the simulation?

- Test new design parameters such as mass, aerodynamic designs, different launch angles and more.
- Test control start times for Roll, Pitch and Yaw. (Fully working)
- Test the PN Guidance Law developed with different gains and target placements. (Not working fully yet - Bug)
- Estimate, analyze and improve performance.
- In future versions – Monte Carlo scattering on several parameters such as the motor and mass, winds and atmosphere scattering.

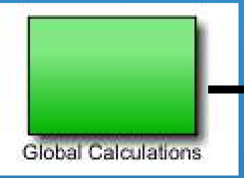
Simulation

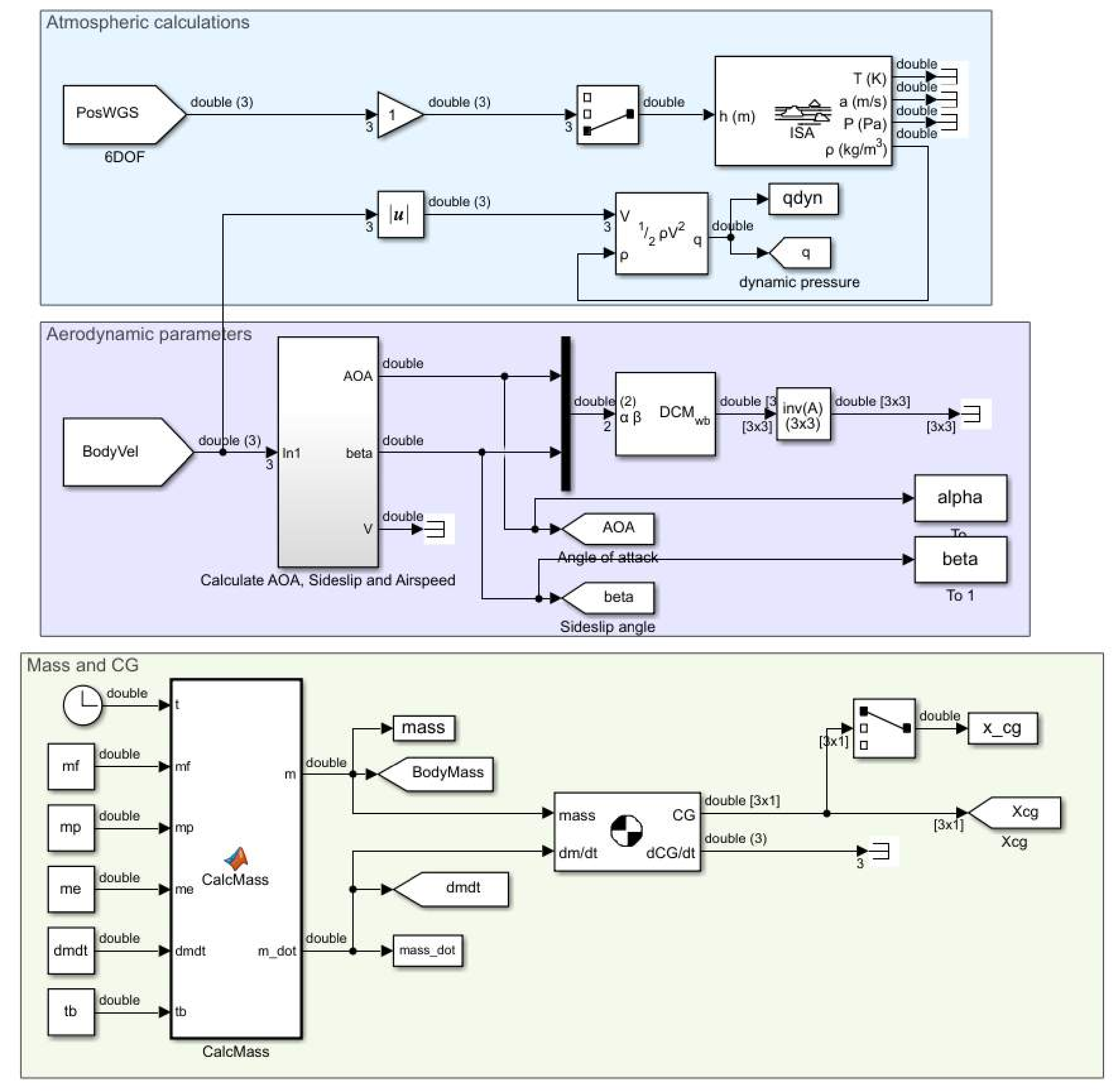
Our Simulation contains:

- 6DOF Equation solver
- Aerodynamic model
- Navigation with strapdown algorithm and error generator.
- CG Movement and mass change, AOA, Slip Angle and atmospheric parameters calculations.
- Gain selection as function of Aero Velocity, using spline interpolation.
- Control for Roll, Pitch and Yaw.
- PN Guidance law for tracking reference trajectory.
- Fins deflection model.

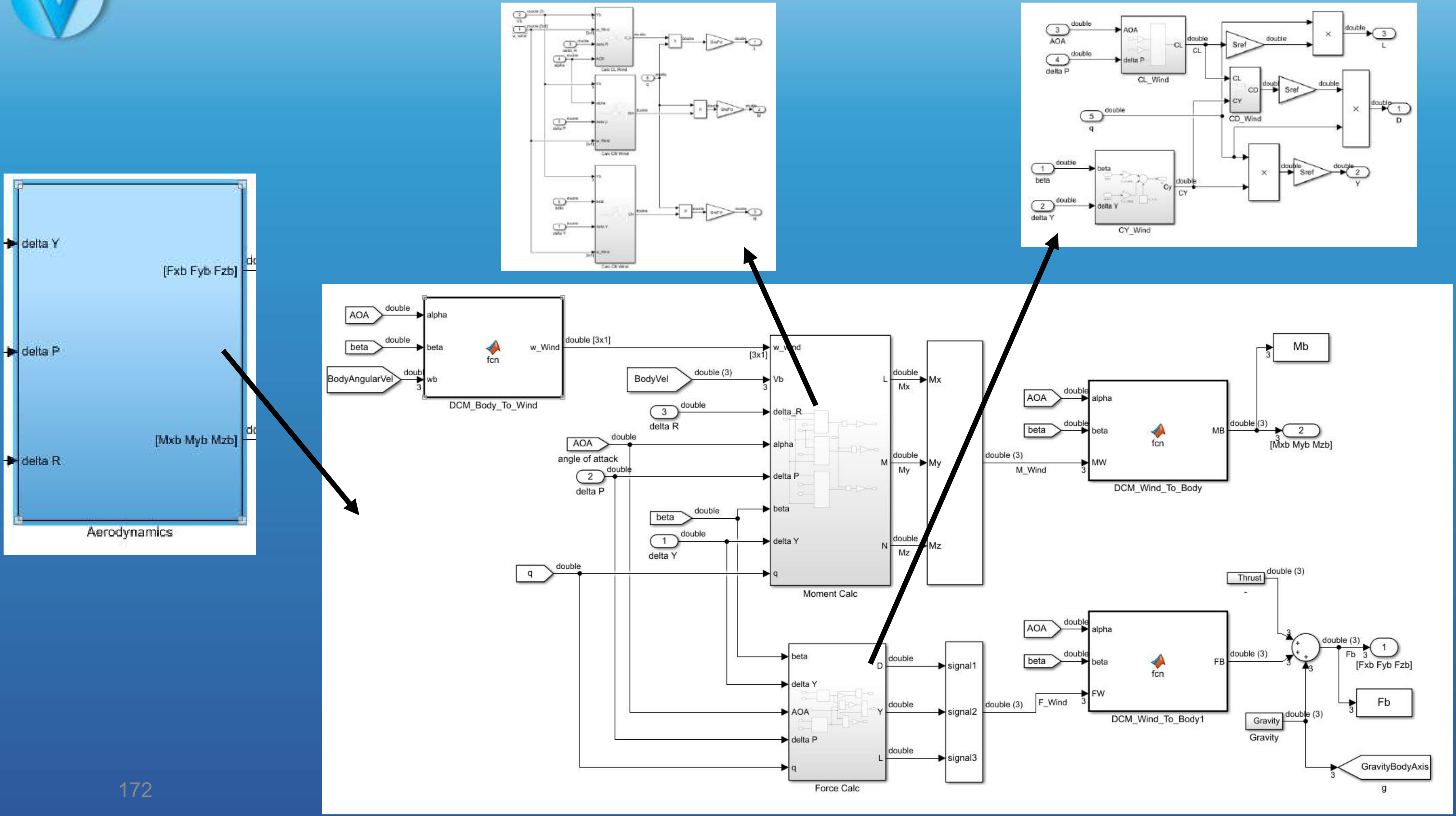


Global Calculations

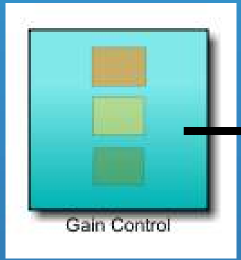


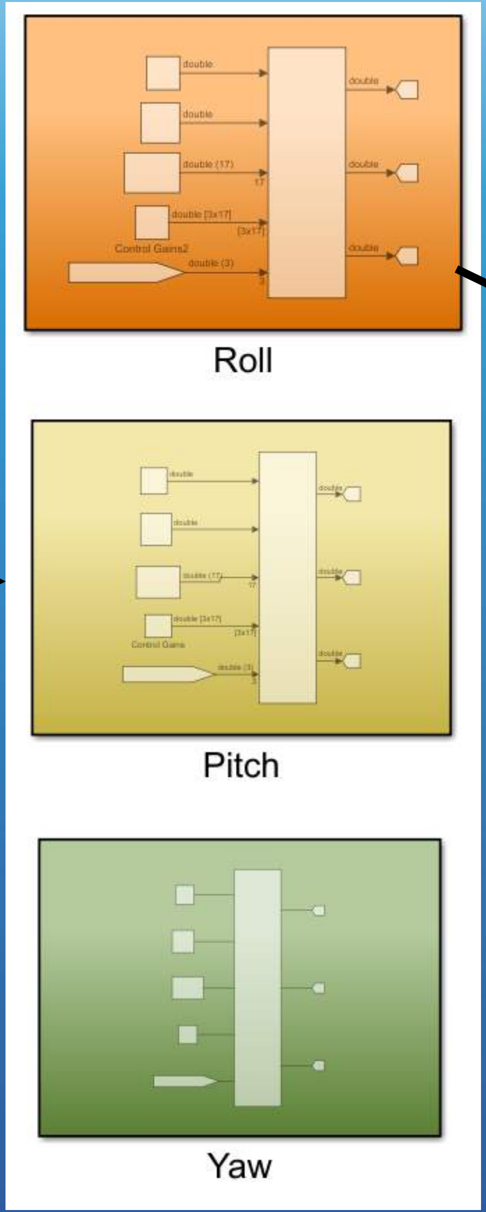


Aerodynamic Model

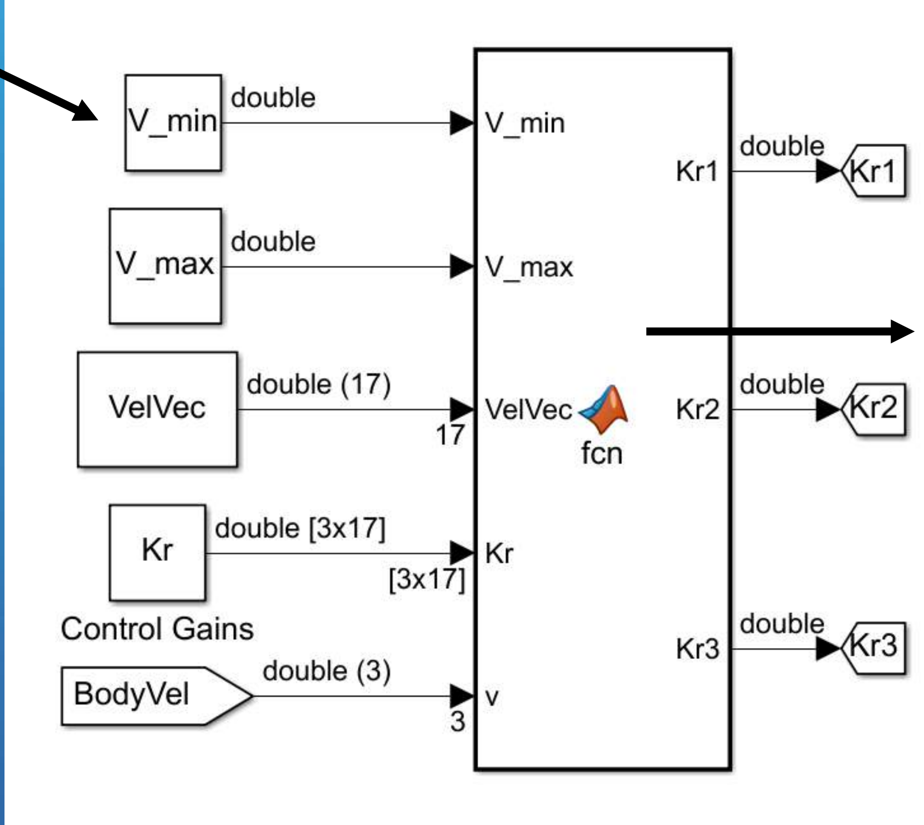


Gain Selection



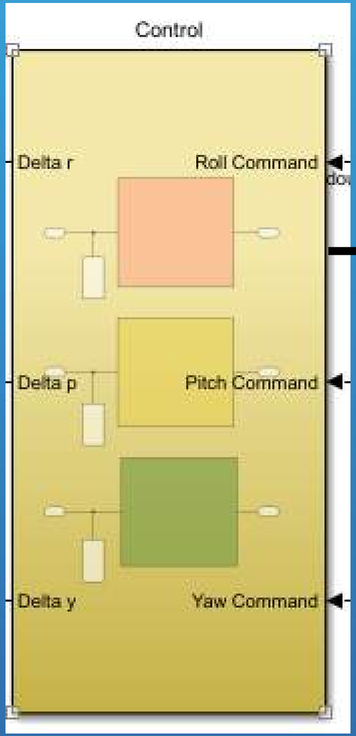


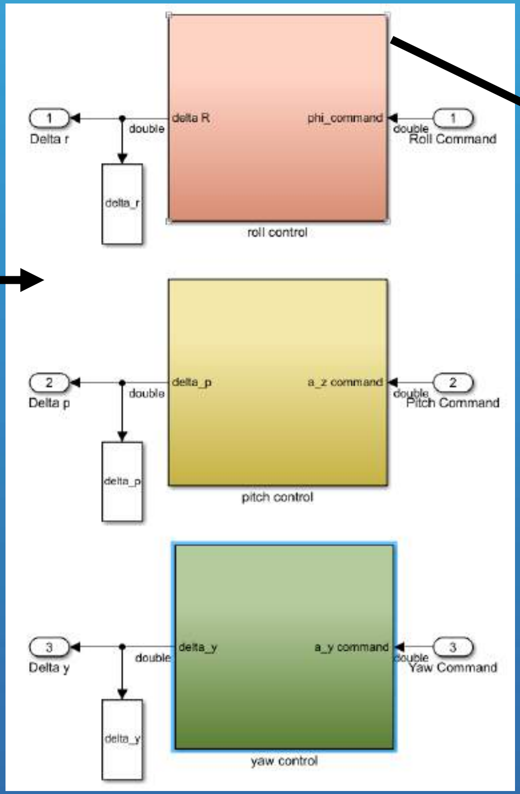
$$V_{min} = 20\left[\frac{m}{s}\right], \qquad V_{max} = 340\left[\frac{m}{s}\right]$$



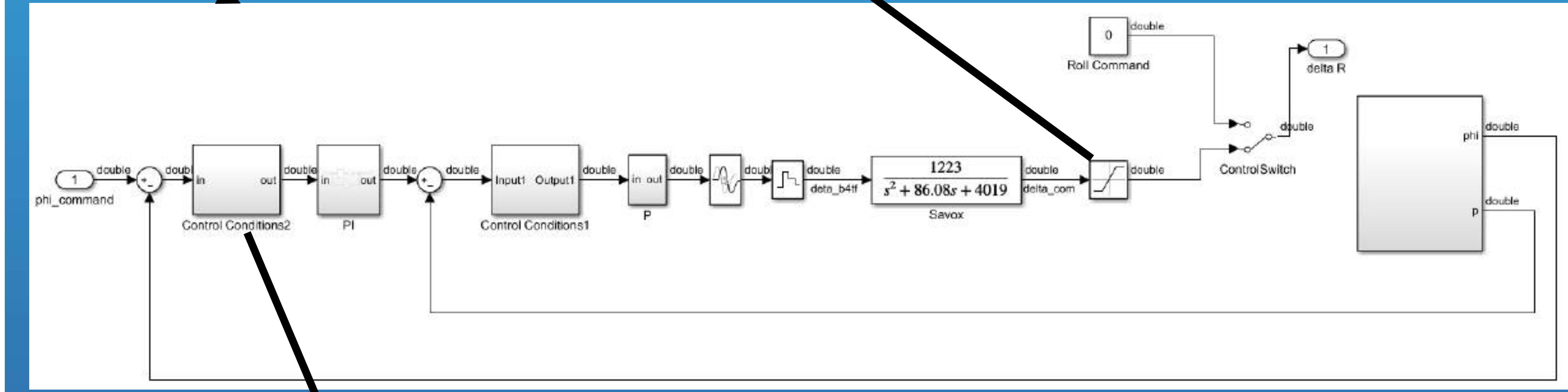

```
function [Kr1,Kr2,Kr3] = fcn(V_min, V_max, VelVec, Kr, v)

if (norm(v) > V_min || norm(v) < V_max)
    Kr1 = interp1(VelVec,Kr(1,:),norm(v),'spline');
    Kr2 = interp1(VelVec,Kr(2,:),norm(v),'spline');
    Kr3 = interp1(VelVec,Kr(3,:),norm(v),'spline');
else
    Kr1 = 0;
    Kr2 = 0;
    Kr3 = 0;
end
end
```

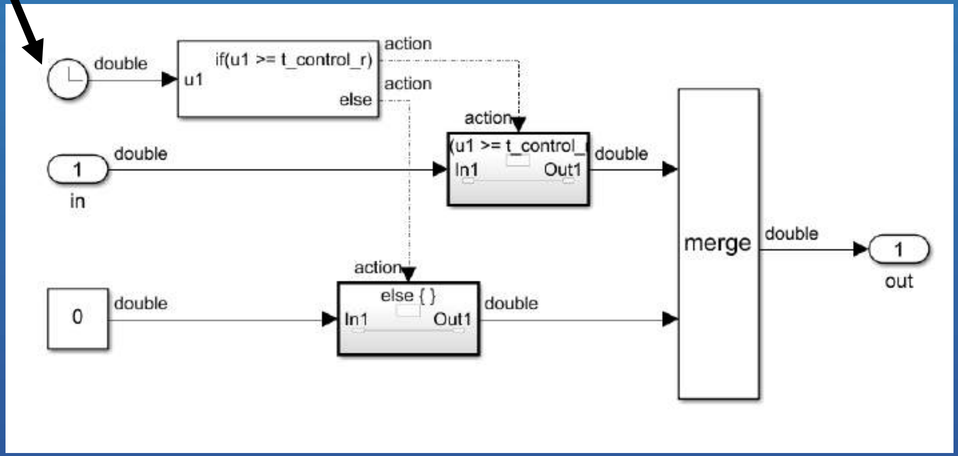
Control



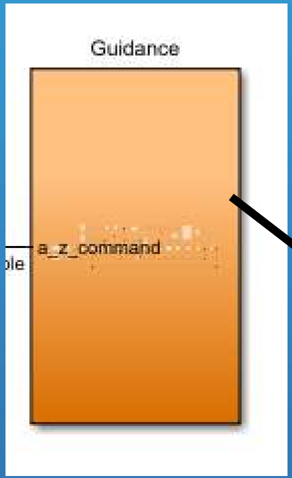


$$\delta_{min} = -20°$$
$$\delta_{max} = 20°$$

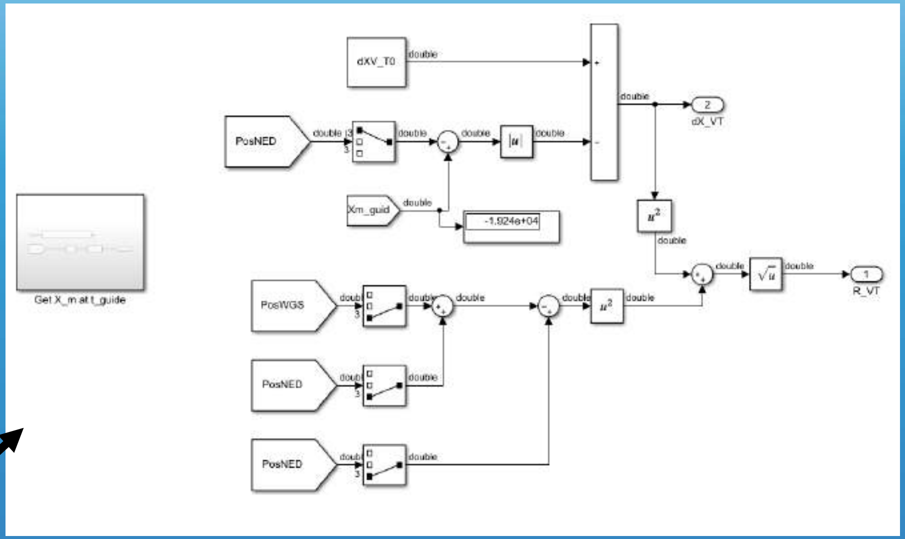




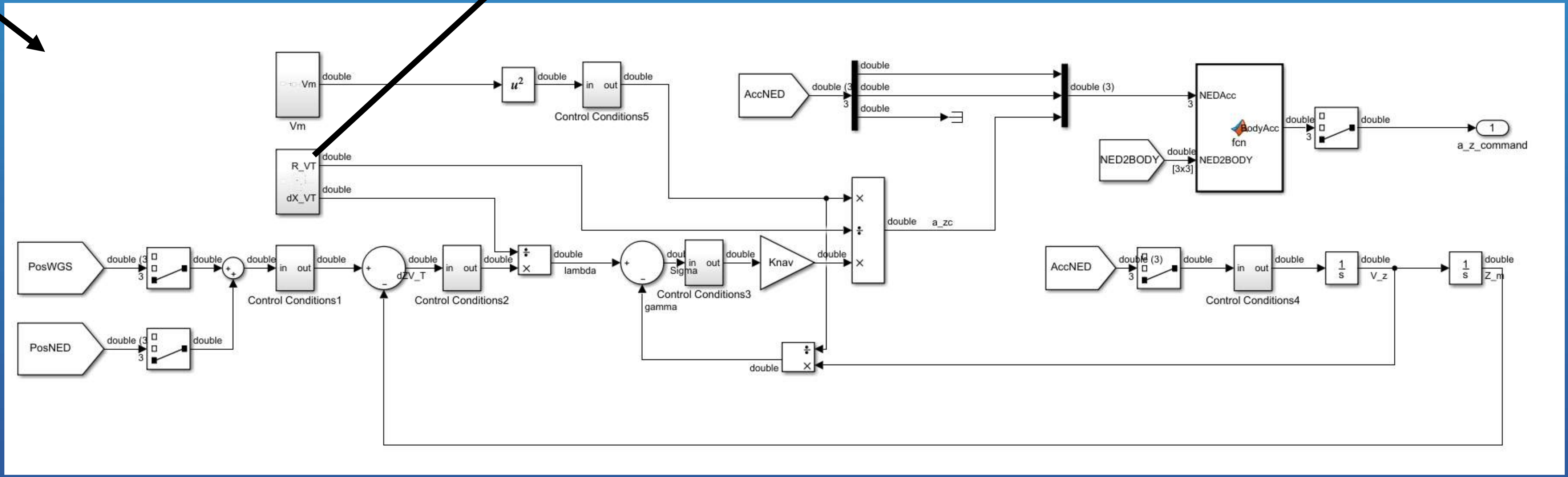
Guidance



Guidance
a_z_command



dXV_T0
PosNED
Xm_guid
-1.924e+04
Get X_m at t_guide
PosWGS
PosNED
PosNED
dX_VT
R_VT
double



Vm
Vm
double
Control Conditions5
R_VT
dX_VT
AccNED
double (3)
NEDAcc
BodyAcc
fcn
NED2BODY
NED2BODY
[3x3]
a_z_command
PosWGS
PosNED
Control Conditions1
dZV_T
Control Conditions2
lambda
Sigma
Control Conditions3
gamma
Knav
a_zc
AccNED
Control Conditions4
V_z
Z_m

Simulation design parameters for performance tests – Ballistic trajectory

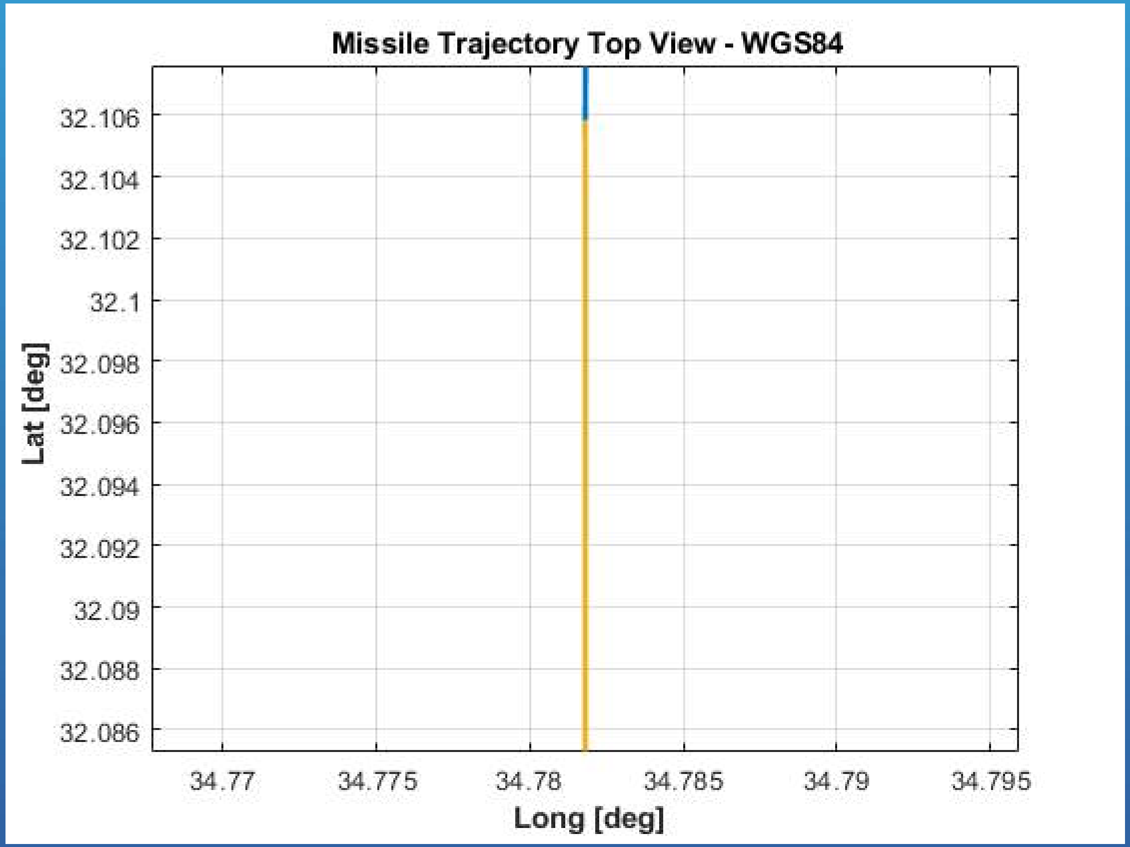
- Tested aerodynamic designs: Wingless, Back long wings, Middle short wings.
- Launch angles: $\Phi_0 = 0°, \Psi_0 = 0°, \Theta_0 = 70°$
- No control

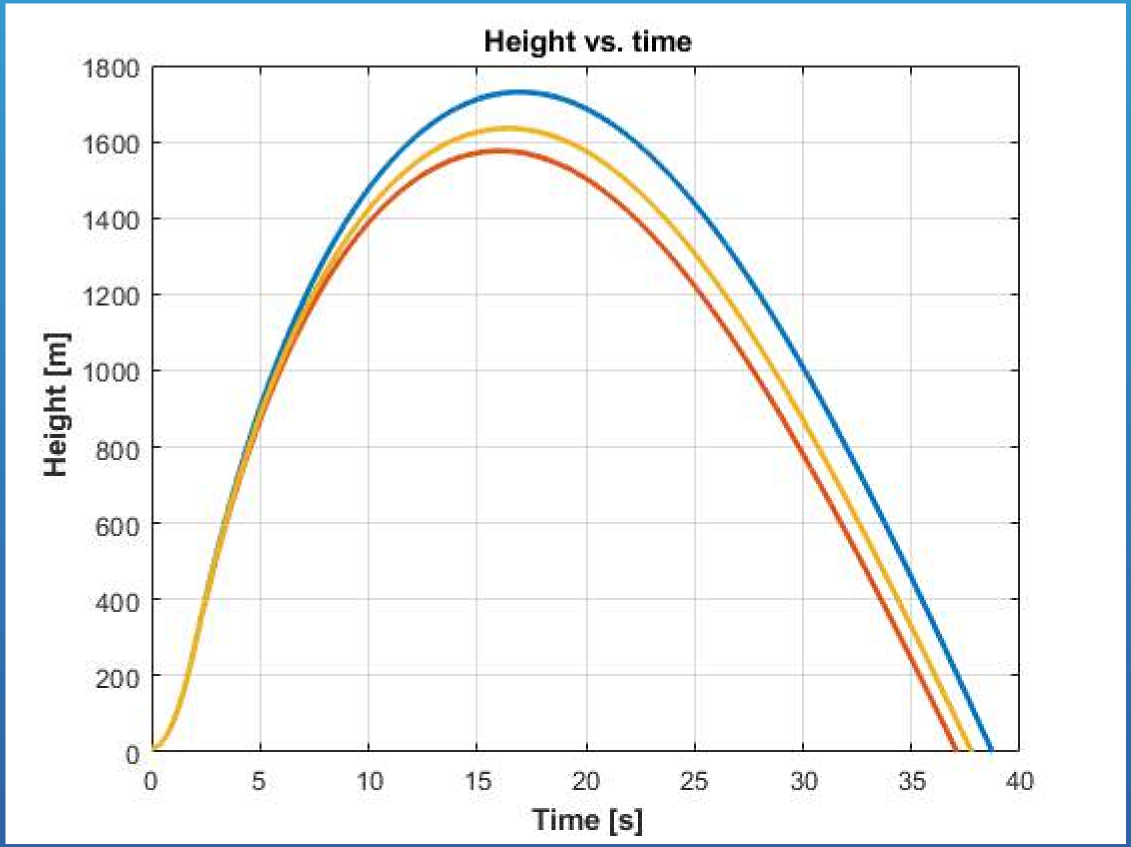
Simulation Results – Ballistic Trajectory

Results	No Wings	Long Back Wings	Short Middle Wings
Max height [m]	1730	1576	1635
Max Range [m]	1882	1660	1724
Flight time [s]	38.7	37.1	37.7

✓First goal – Height of 1500[m]

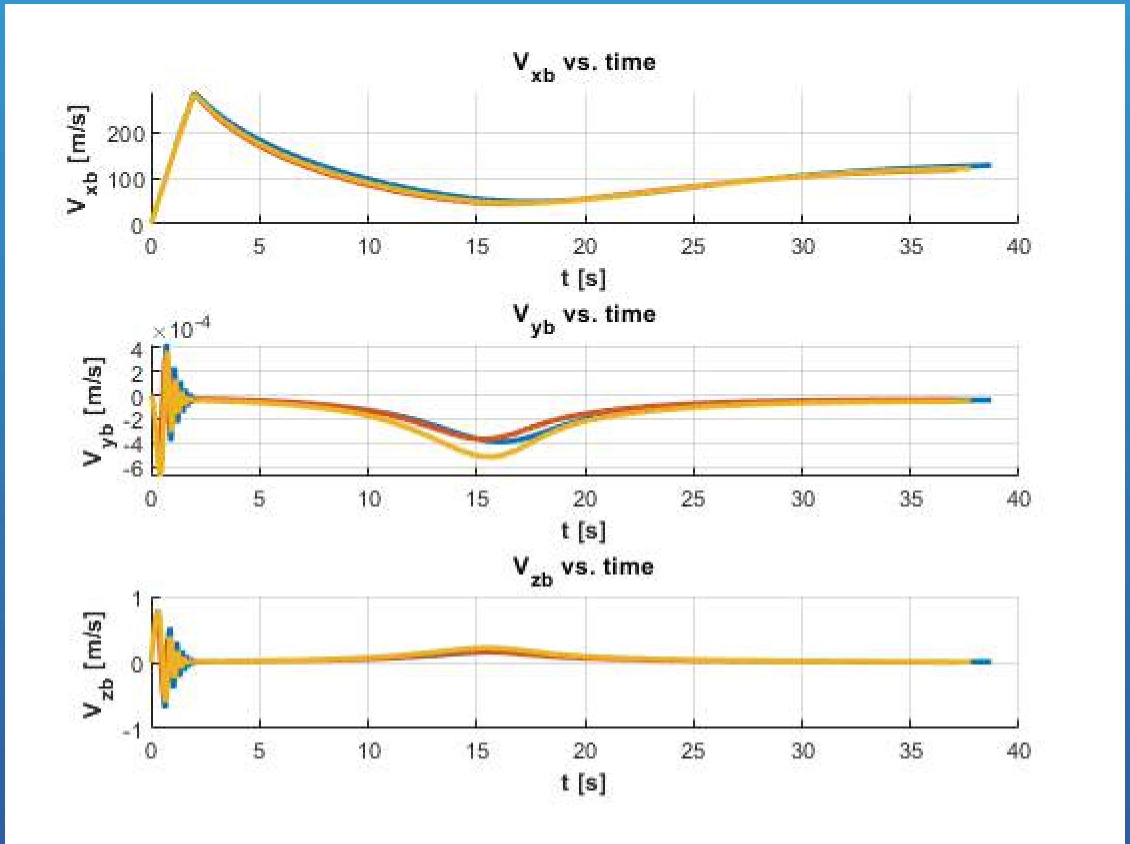
Simulation Results – Ballistic Trajectory

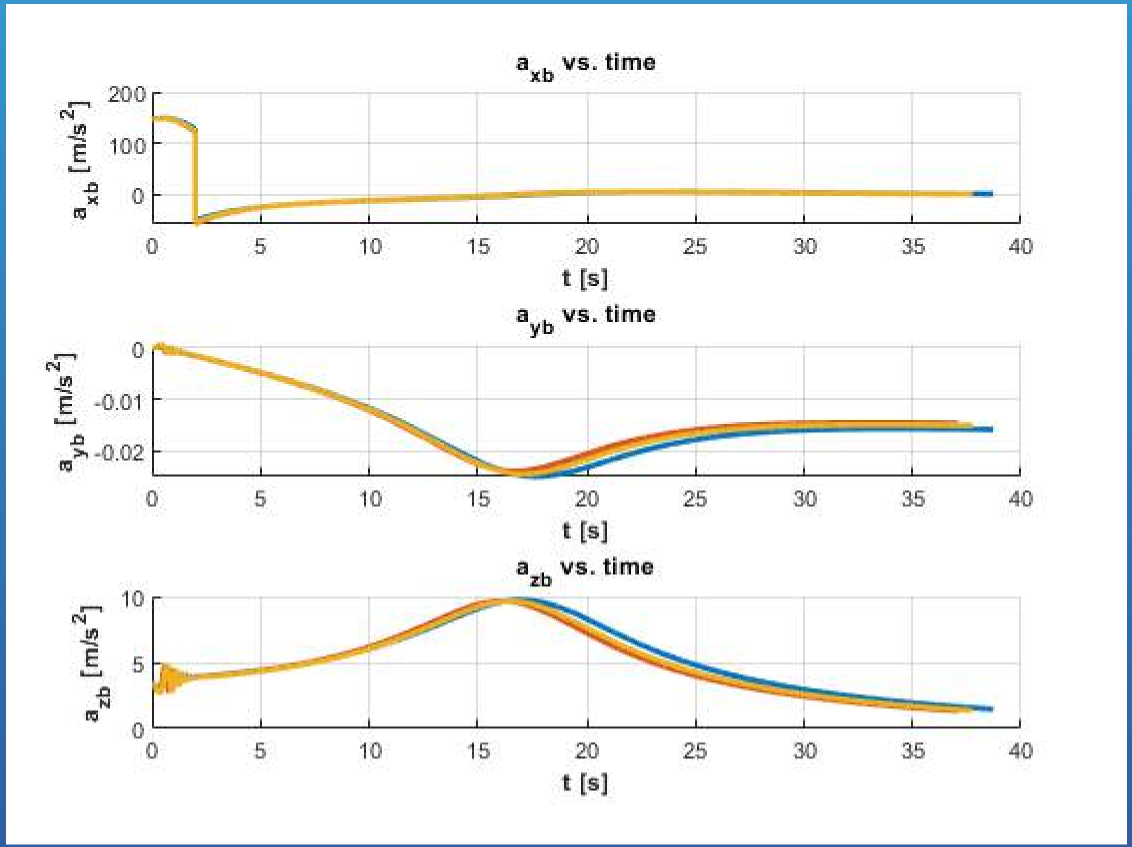




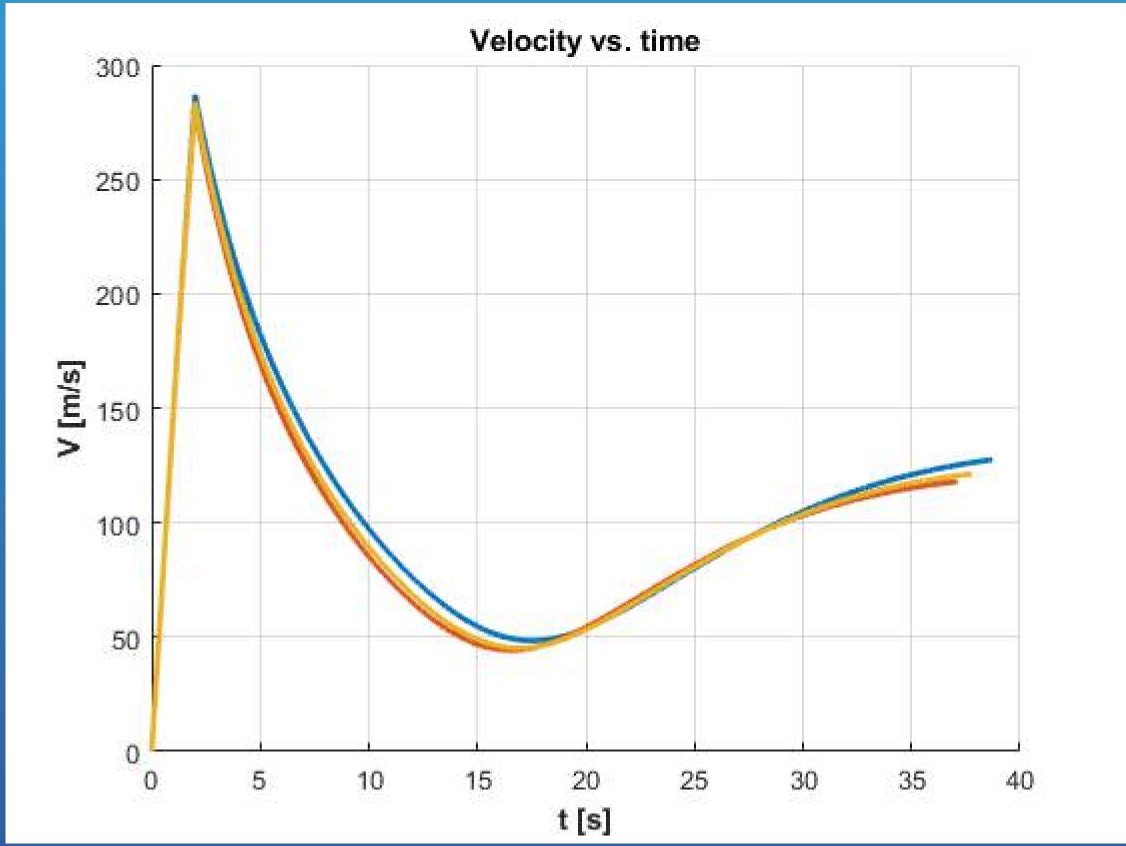
Simulation Results – Ballistic Trajectory

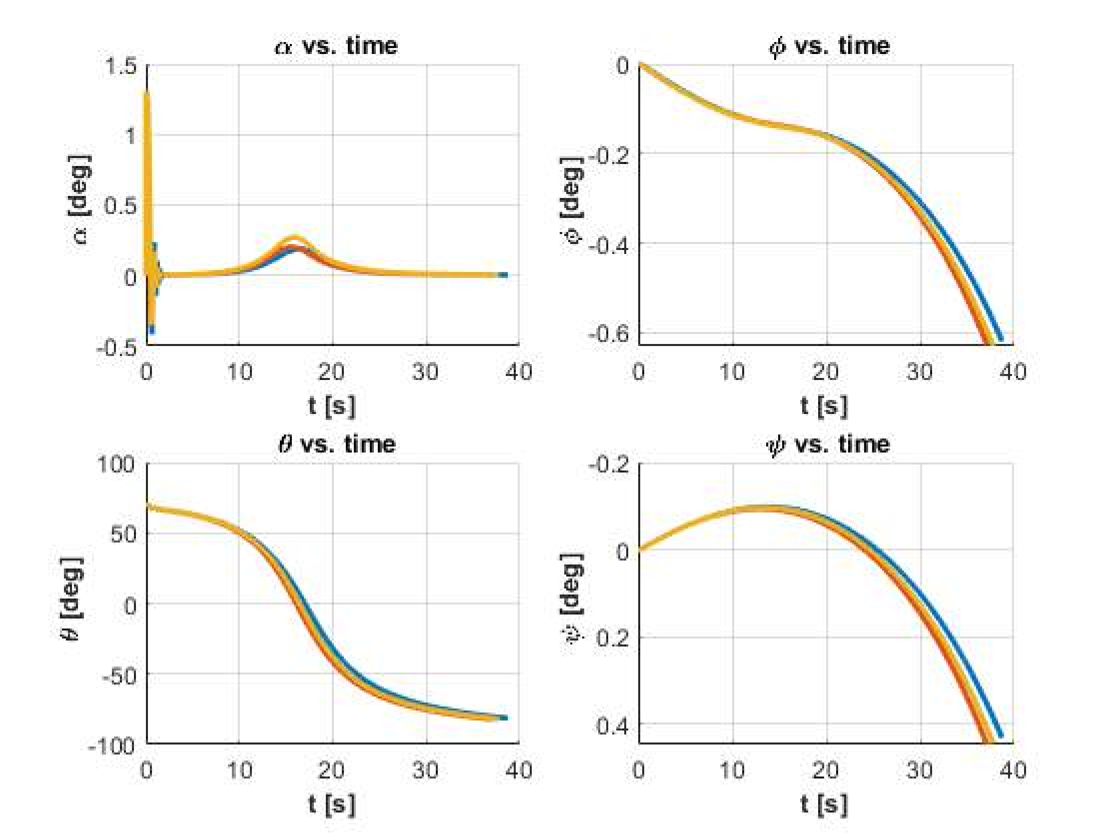
No Wings
Long Back Wings
Short Middle Wings



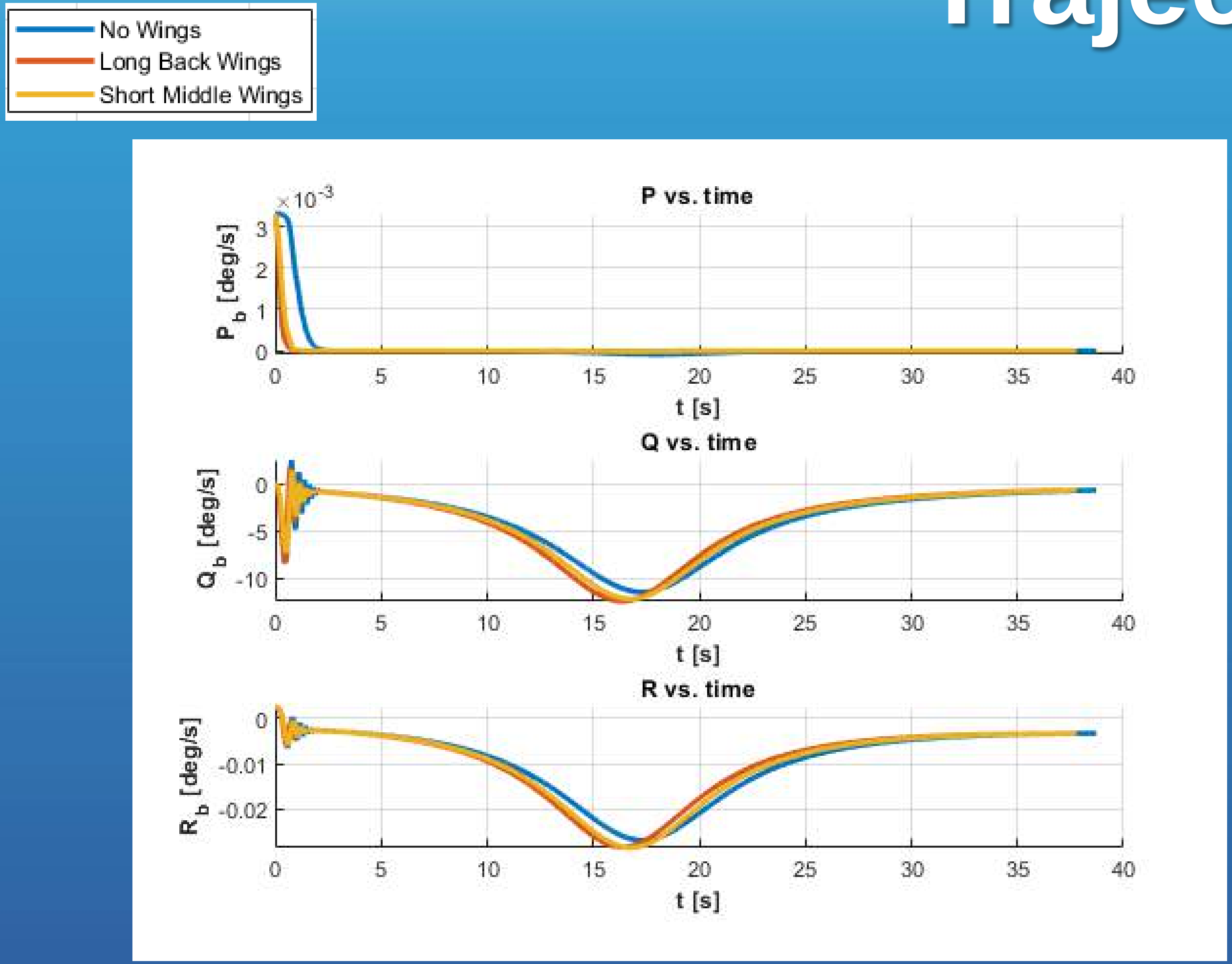


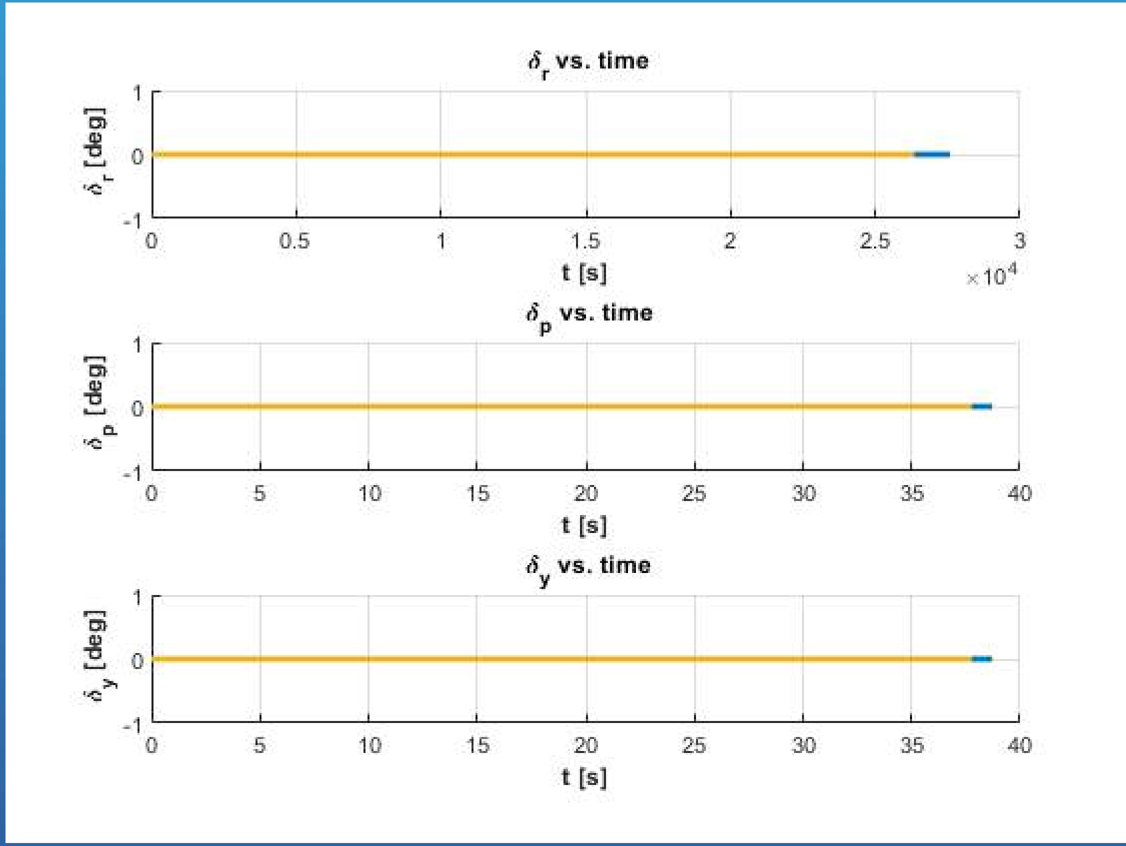
Simulation Results – Ballistic Trajectory





Simulation Results – Ballistic Trajectory



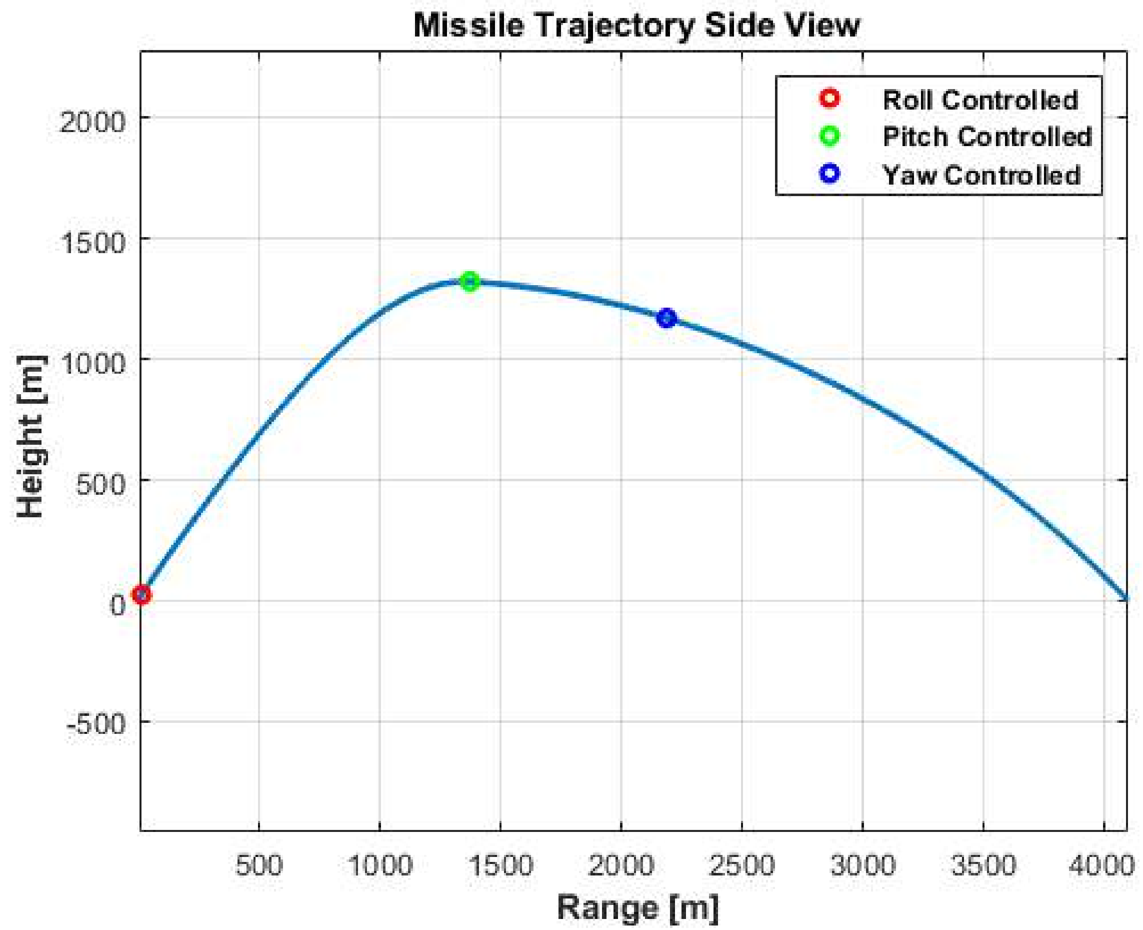


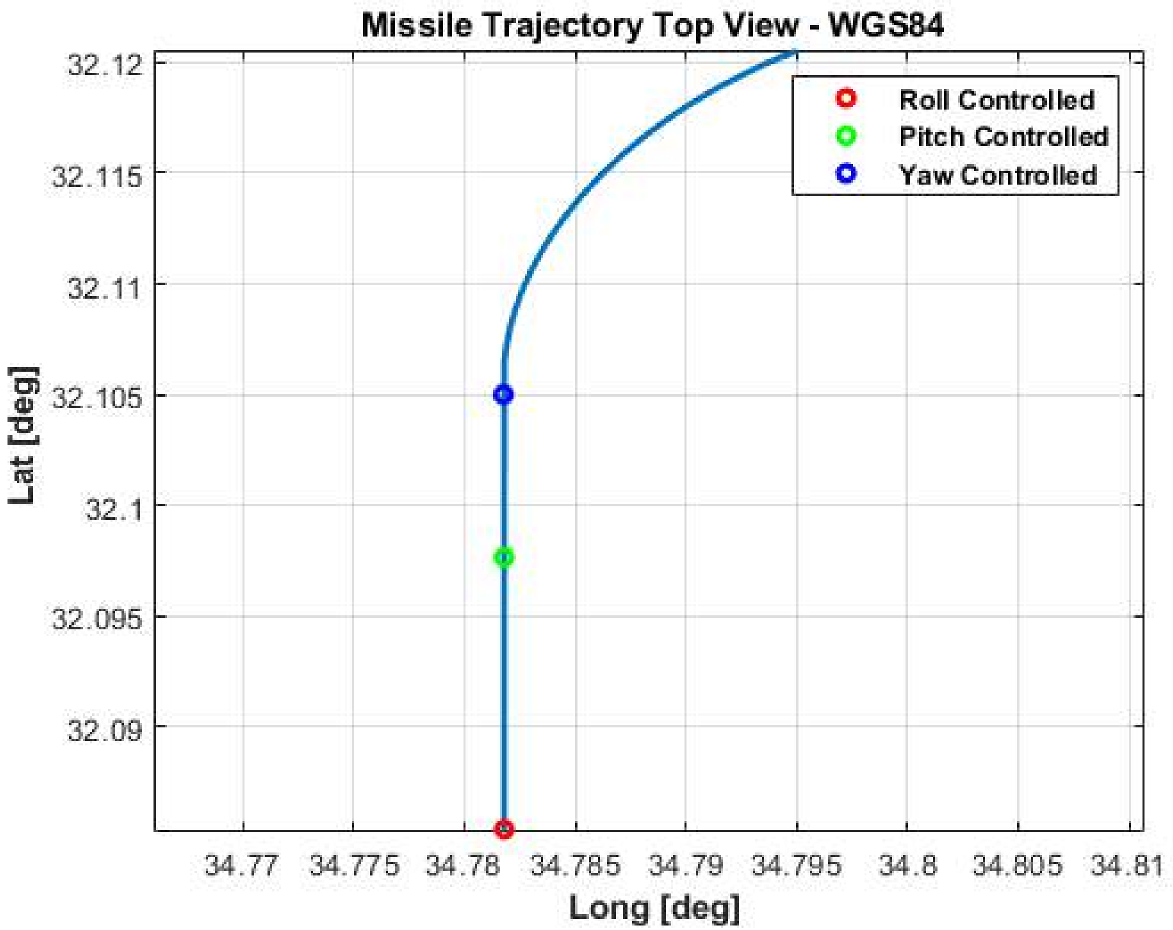
Simulation design parameters for performance tests – Controlled

- Tested aerodynamic design: **Back long wings**.
- Launch angles: $\Phi_0 = 0°, \Psi_0 = 0°, \boldsymbol{\Theta_0 = 60°}$
- Control min and max velocities: $V_{max} = 340\left[\frac{m}{s}\right], V_{min} = 20\left[\frac{m}{s}\right]$
- Control surfaces deflection limits: $\delta = \pm 20°$
- **Roll Command** values: $\Phi = \begin{cases} 0°, & t > 10\ [s] \\ 45°, & 0.5 \le t \le 10\ [s] \end{cases}$
- **Pitch Command** values: $a_z^c = 0.75\left[\frac{m}{s^2}\right],\ t \ge 15[s]$
- **Yaw Command** values: $a_y^c = 2\left[\frac{m}{s^2}\right],\ t \ge 30[s]$

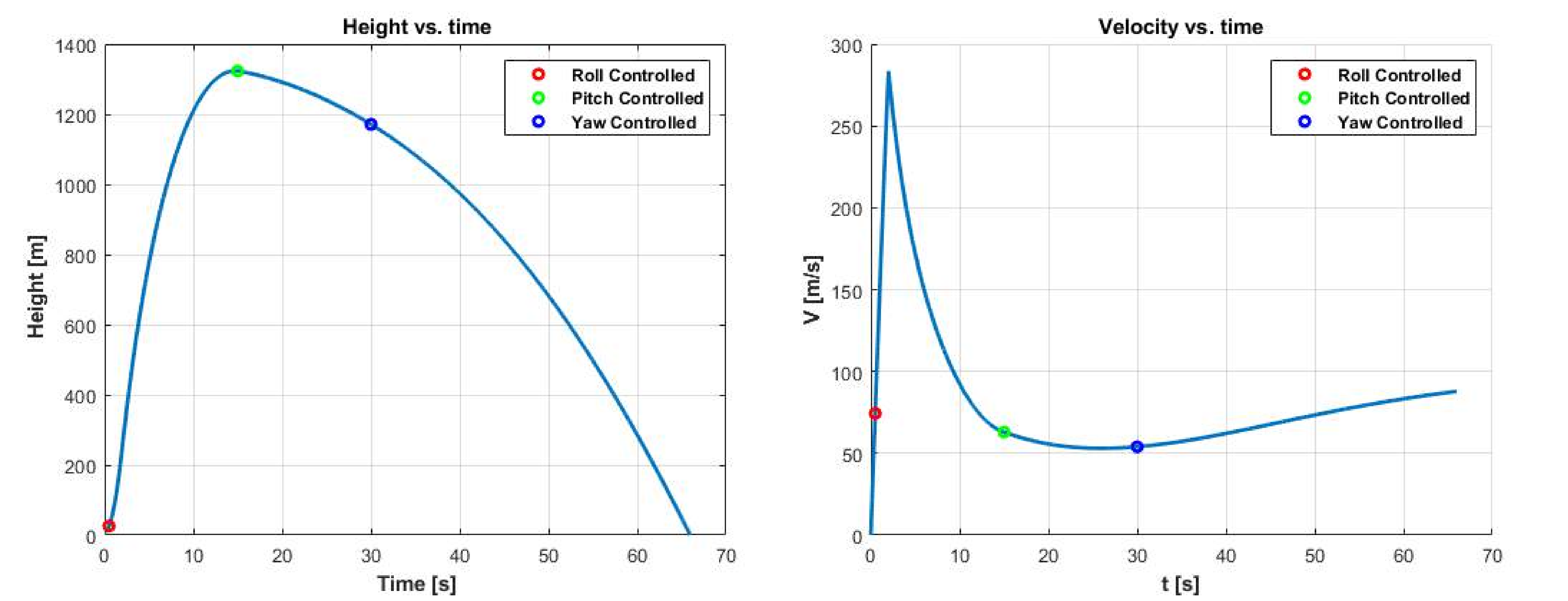
Results – Controlled

Max height: 1323.5589[m]
Max Range: 4099.3861[m]
Flight time: 65.9523[s]

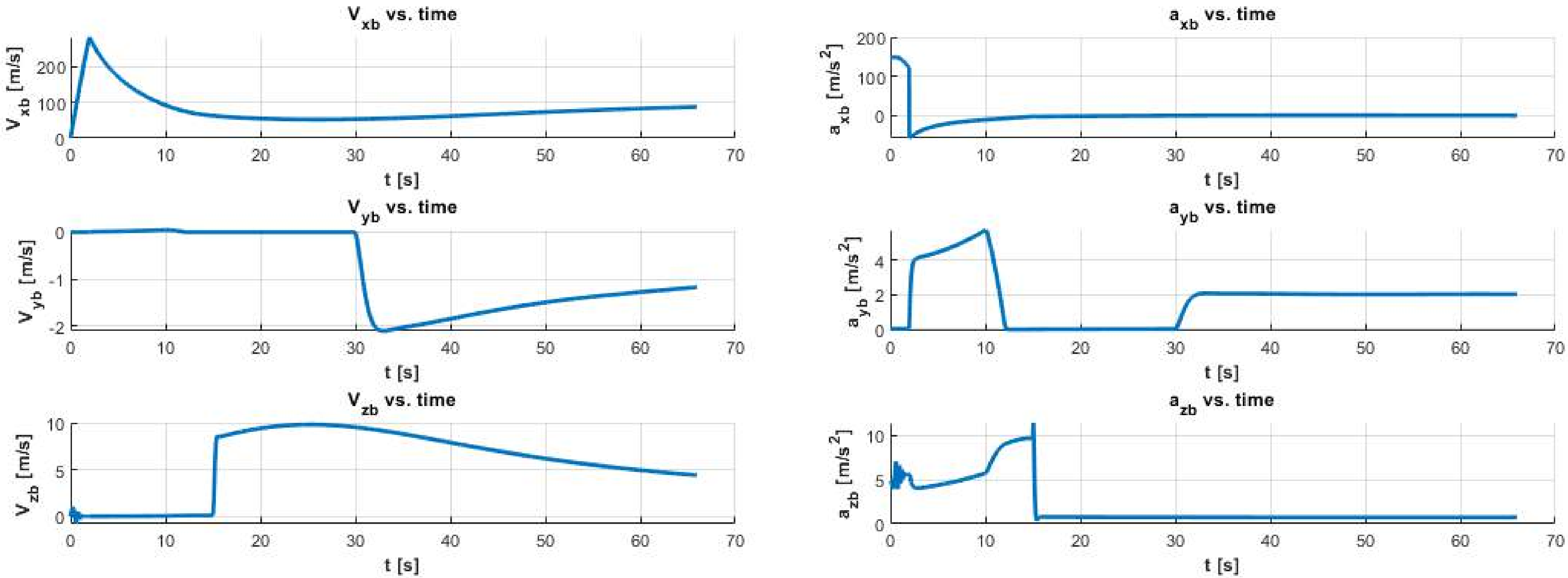




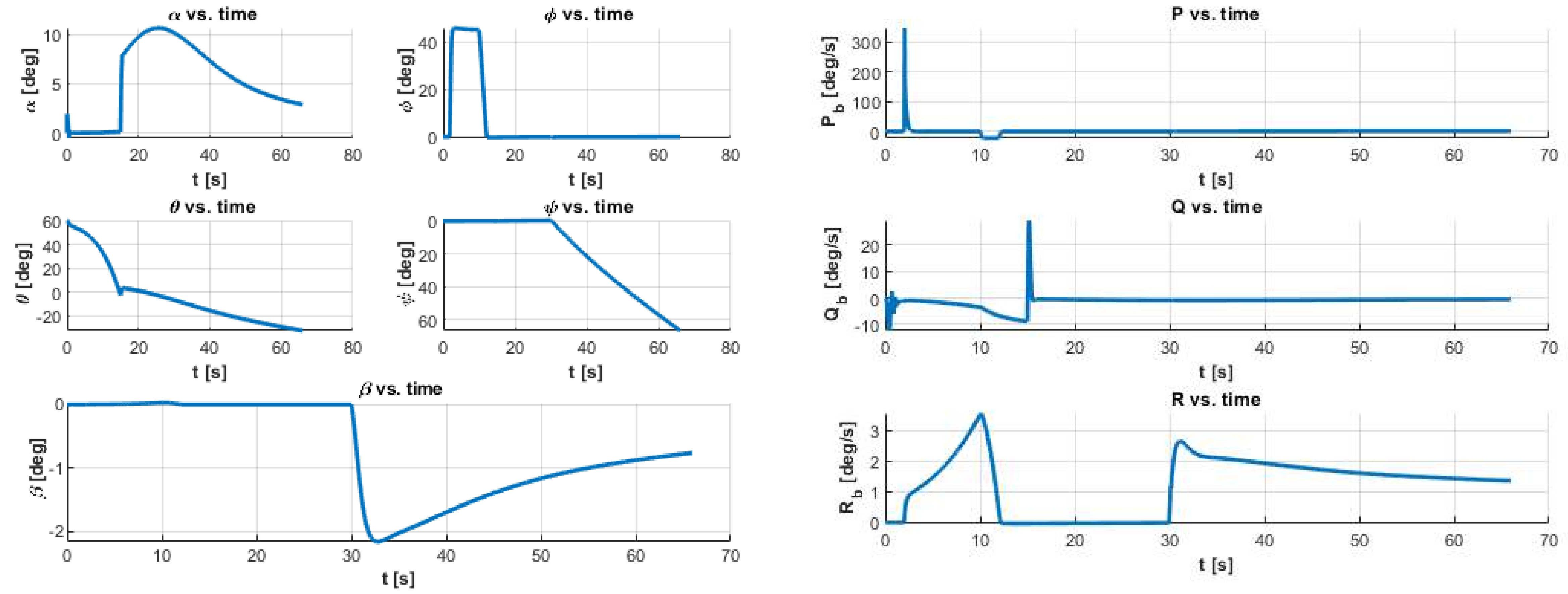
Results – Controlled



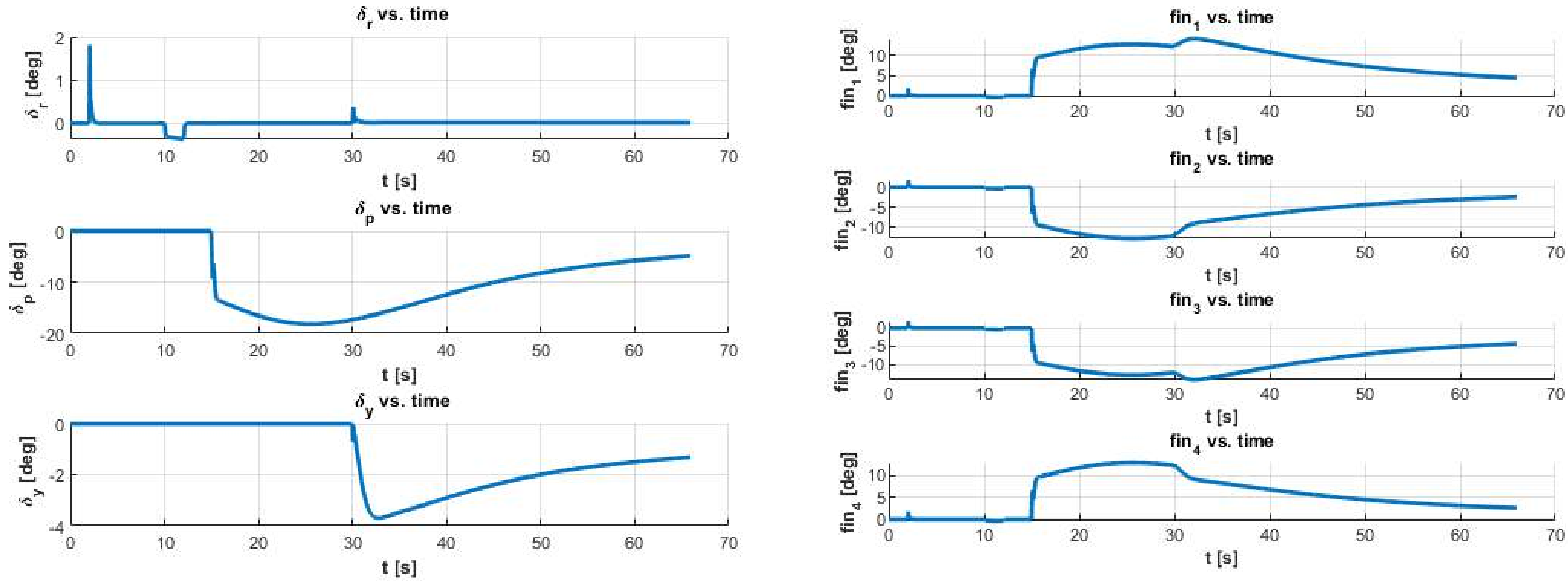
Results – Controlled



Results – Controlled



Results – Controlled

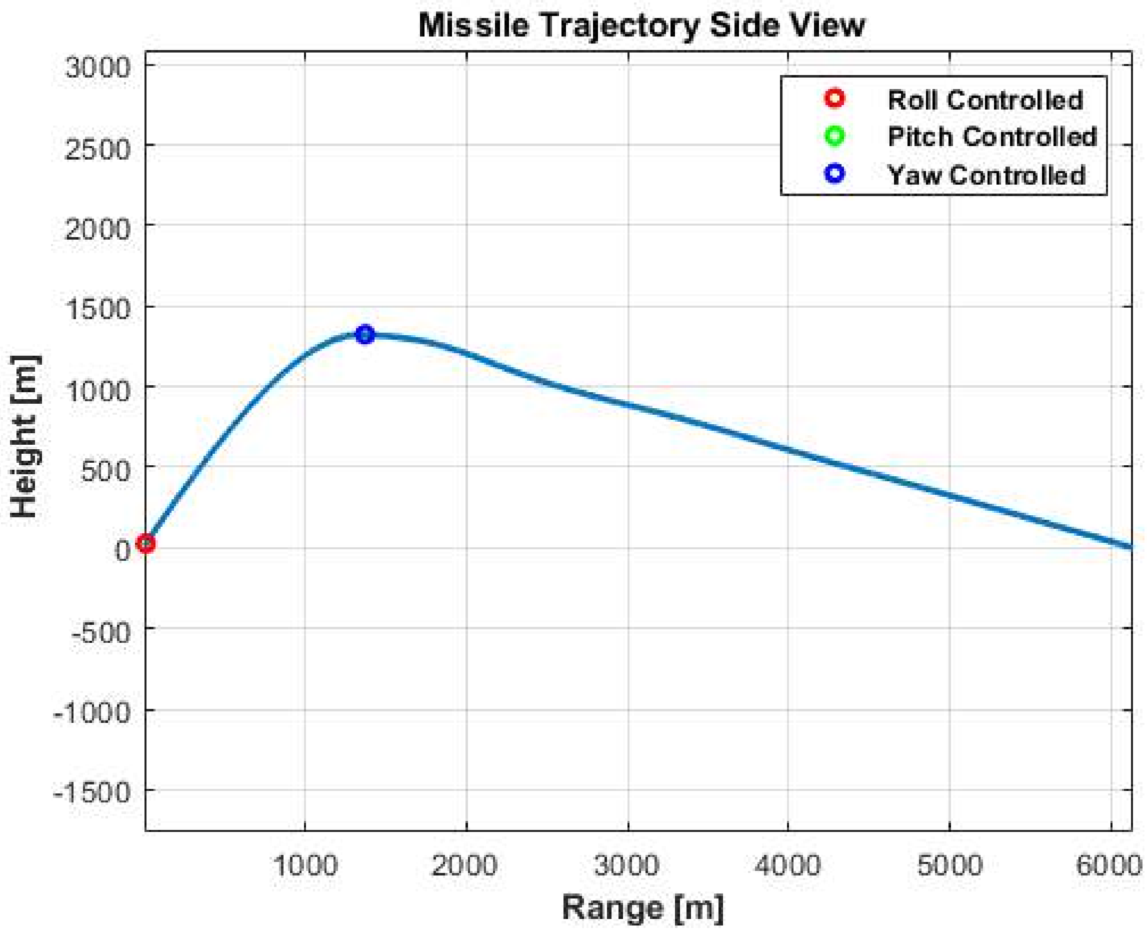


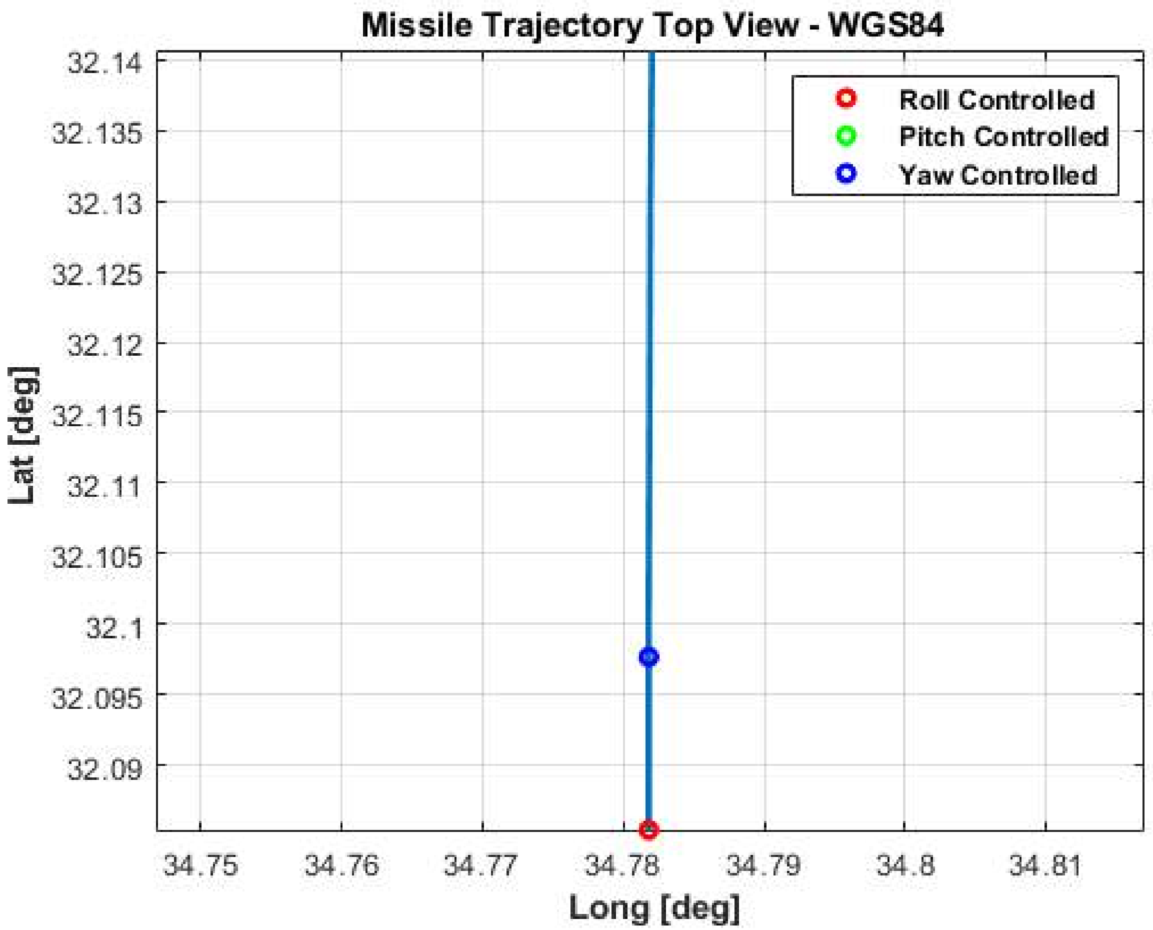
Simulation design parameters for performance tests – Gliding

- Tested aerodynamic design: **Back long wings**.
- Launch angles: $\Phi_0 = 0°, \Psi_0 = 0°, \boldsymbol{\Theta_0 = 60°}$
- Control min and max velocities: $V_{max} = 340 \left[\frac{m}{s}\right], V_{min} = 20 \left[\frac{m}{s}\right]$
- Control surfaces deflection limits: $\delta = \pm 20°$
- **Roll Command** values: $\Phi = 0,\ t \geq 0.5[s]$
- **Pitch Command** values: Not Controlled – constant $\delta_p = -15°,\ t \geq 15[s]$
- **Yaw Command** values: $a_y^c = 0 \left[\frac{m}{s^2}\right],\ \ t \geq 15[s]$

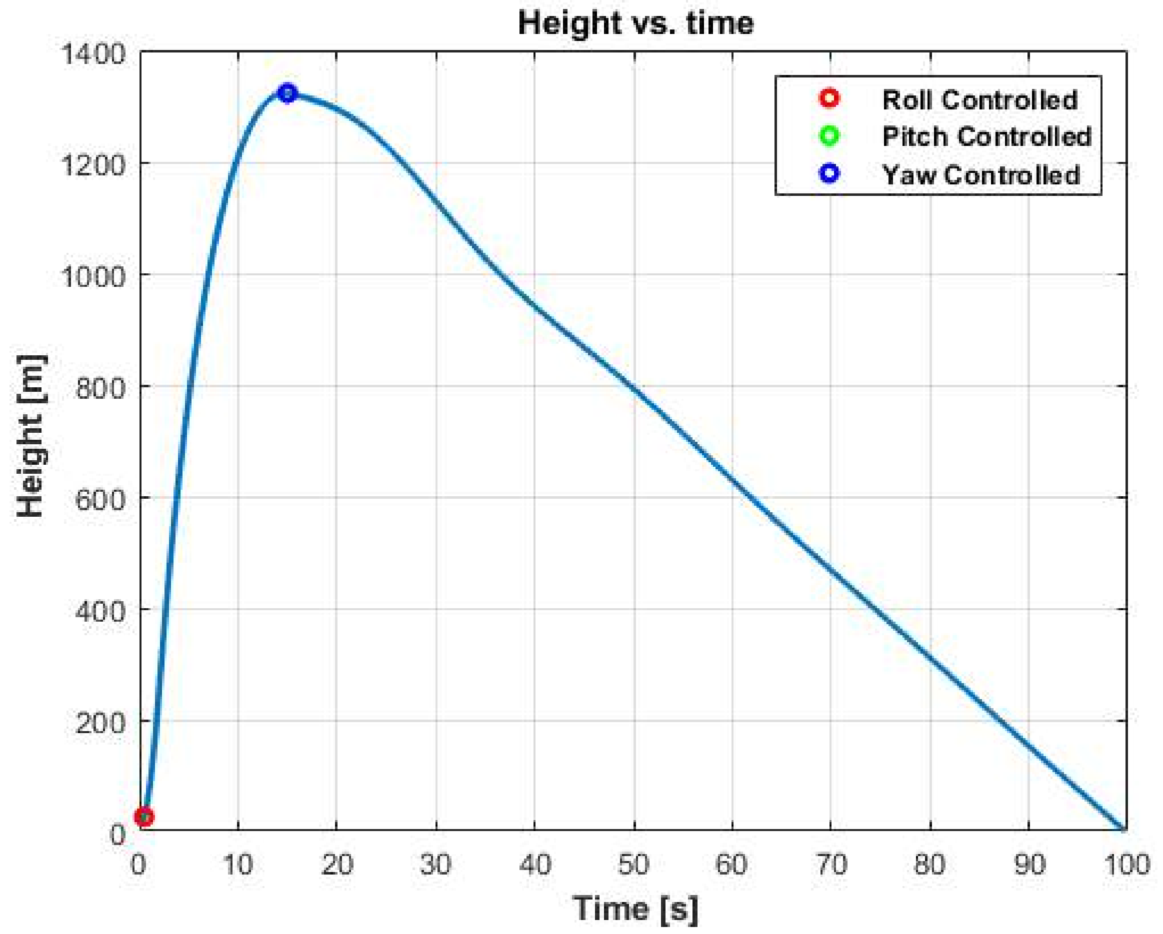
Results – Gliding

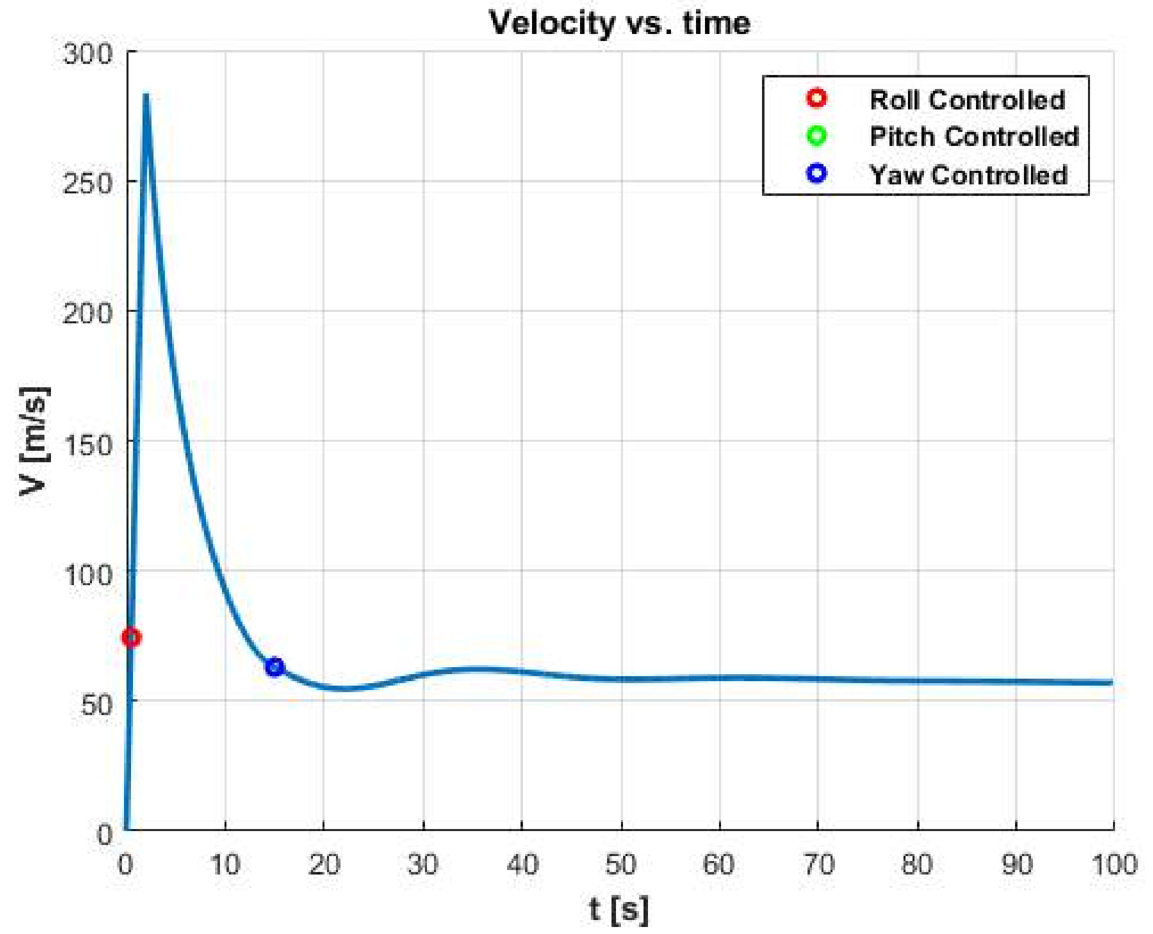
Max height: 1323.5589[m]
Max Range: 6137.8934[m]
Flight time: 99.751[s]



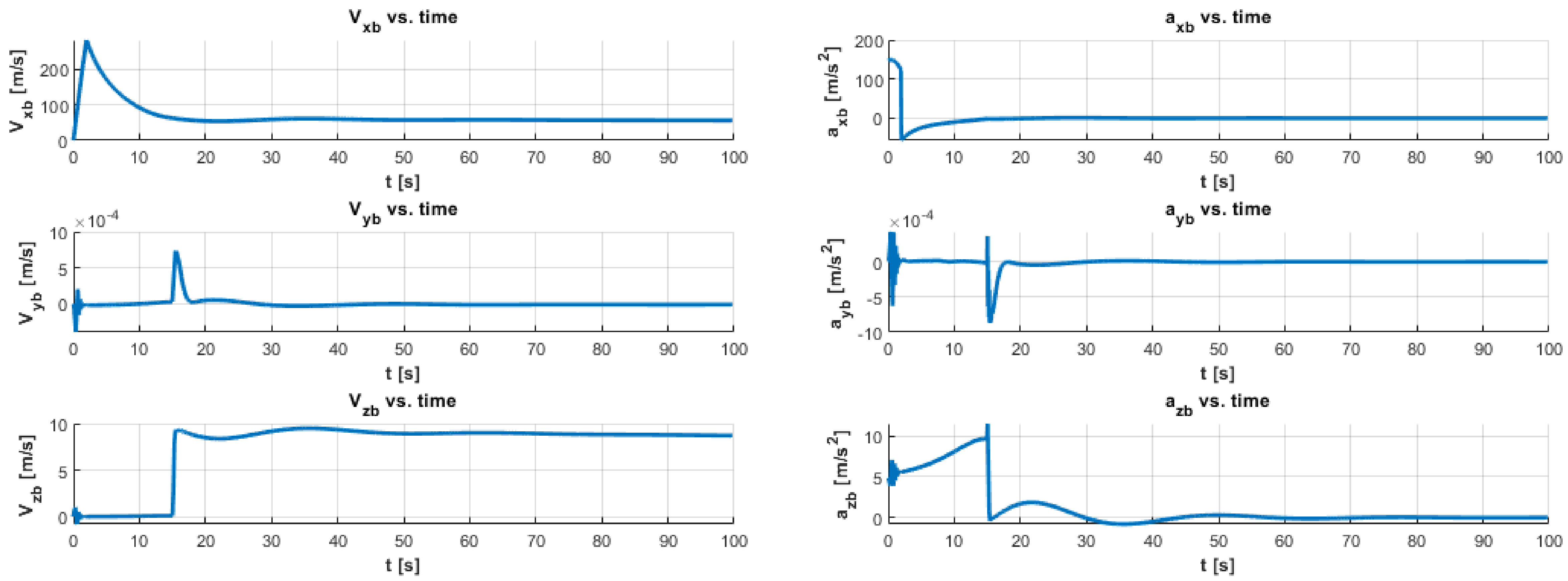


Results – Gliding

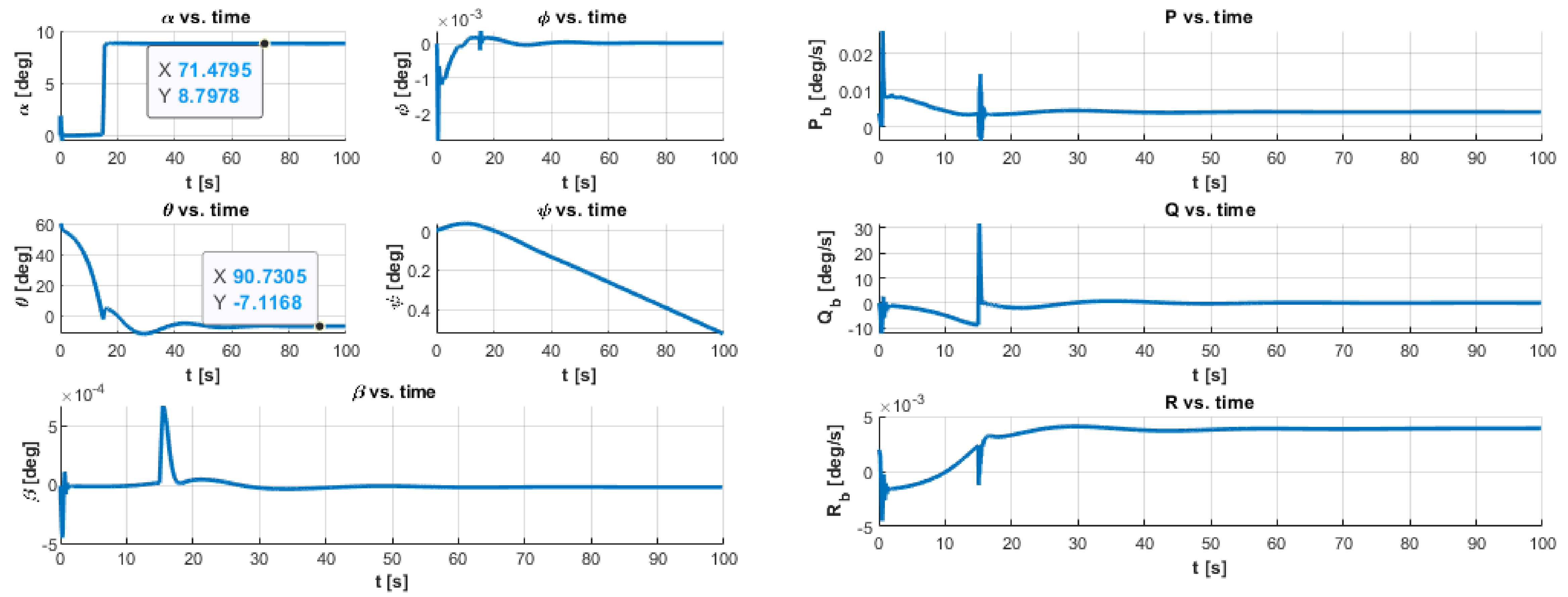




Results – Gliding



Results – Gliding



Results – Gliding