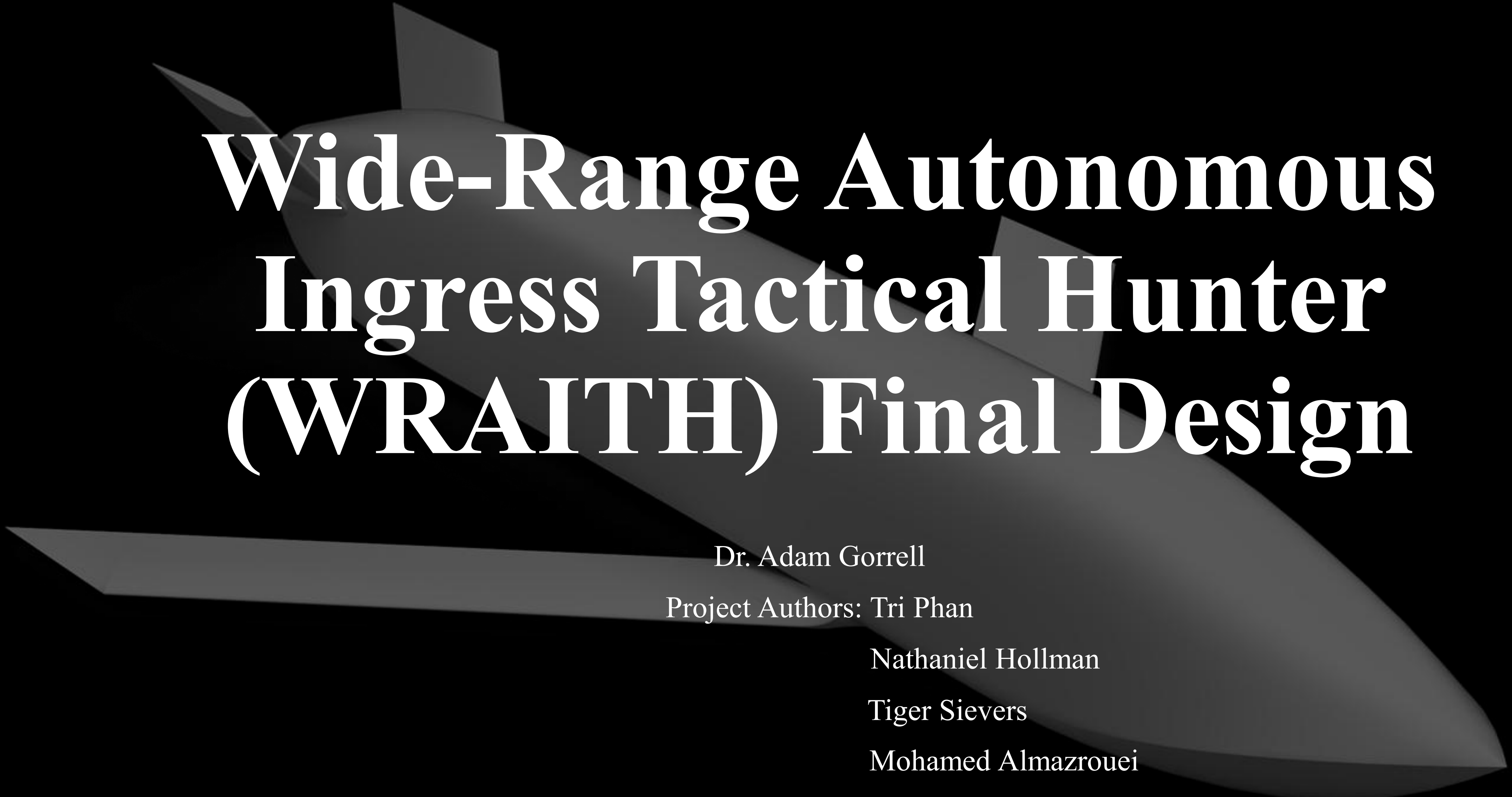


Wide-Range Autonomous Ingress Tactical Hunter (WRAITH) Final Design

Dr. Adam Gorrell

Project Authors: Tri Phan

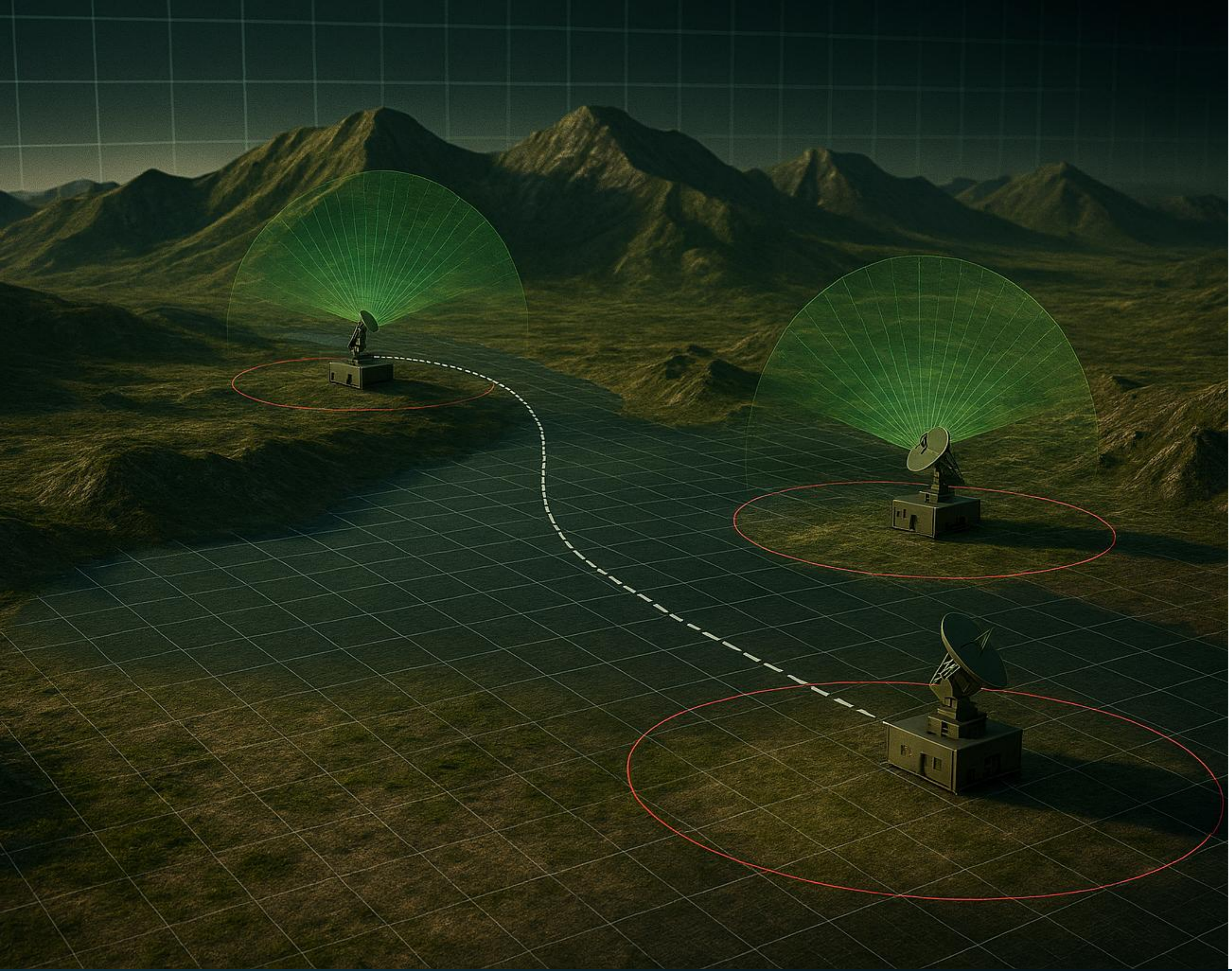
Nathaniel Hollman

Tiger Sievers

Mohamed Almazrouei

Background – JASSM Baseline

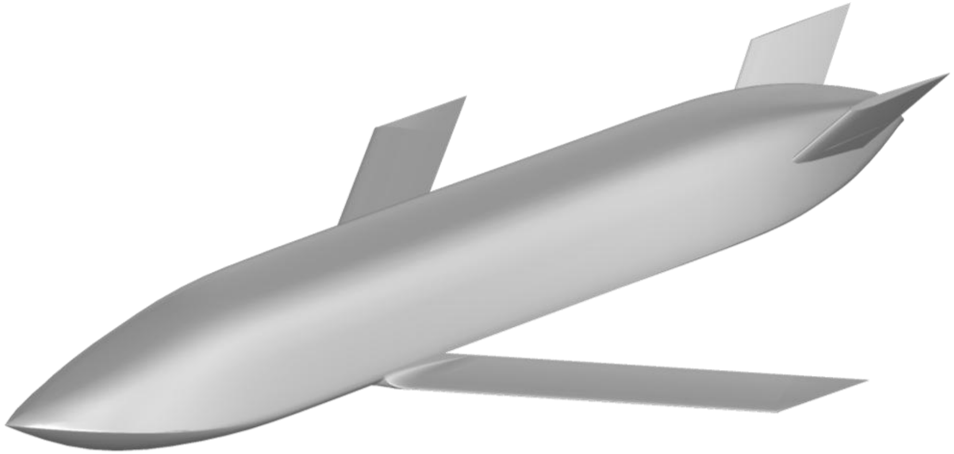
- Long Range, Subsonic Cruise Missile
- Shallow Bunker Buster
- ~250nm Range
- Launched via crate, bomber rotary launcher, or fighter
- Fuselage shaped for reduced radar signature



CONOP

- Increase range by more than 20%
- Avoid radar by flying at a ground altitude of 1,000 ft or less

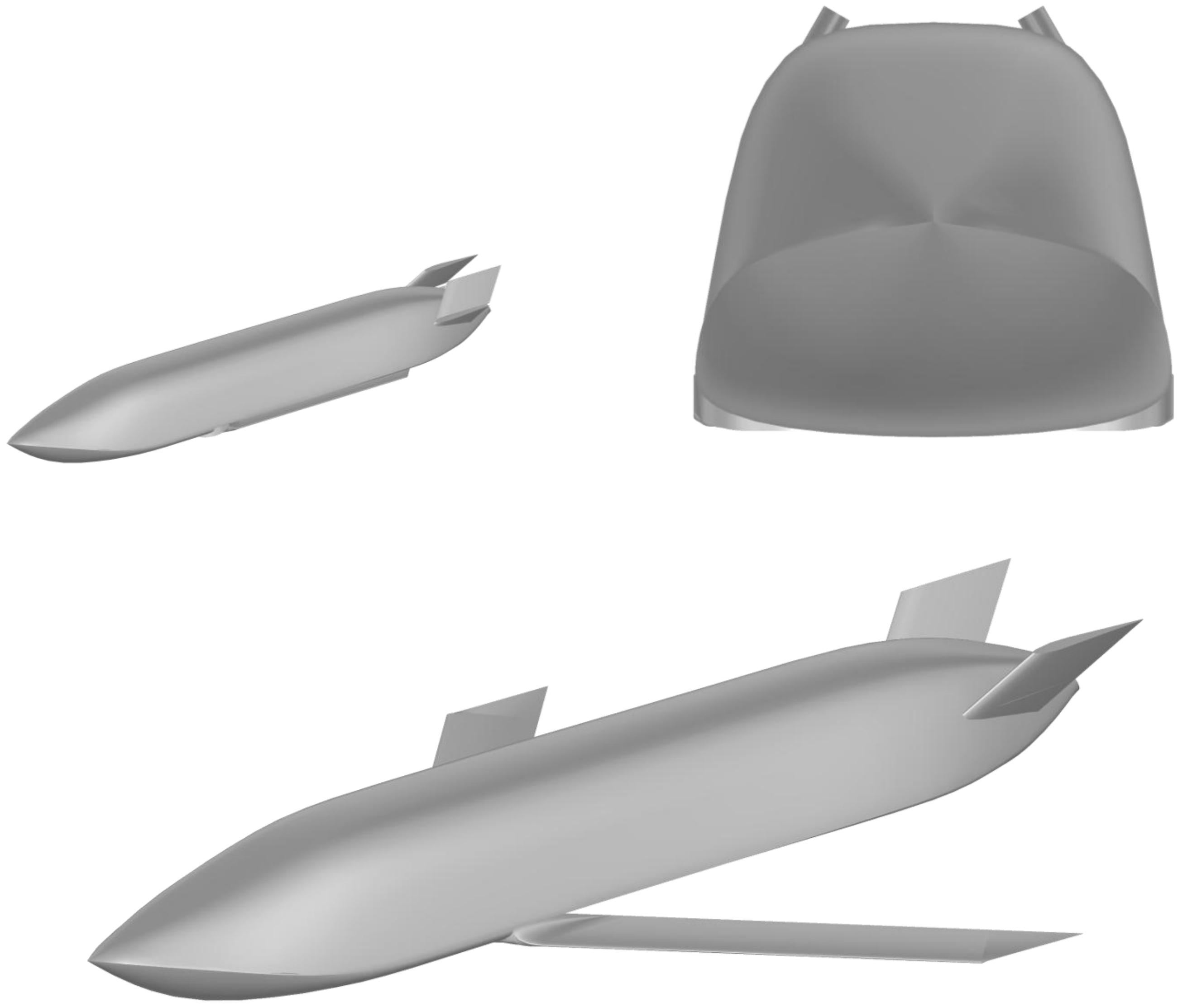
General Design, JASSM to WRAITH



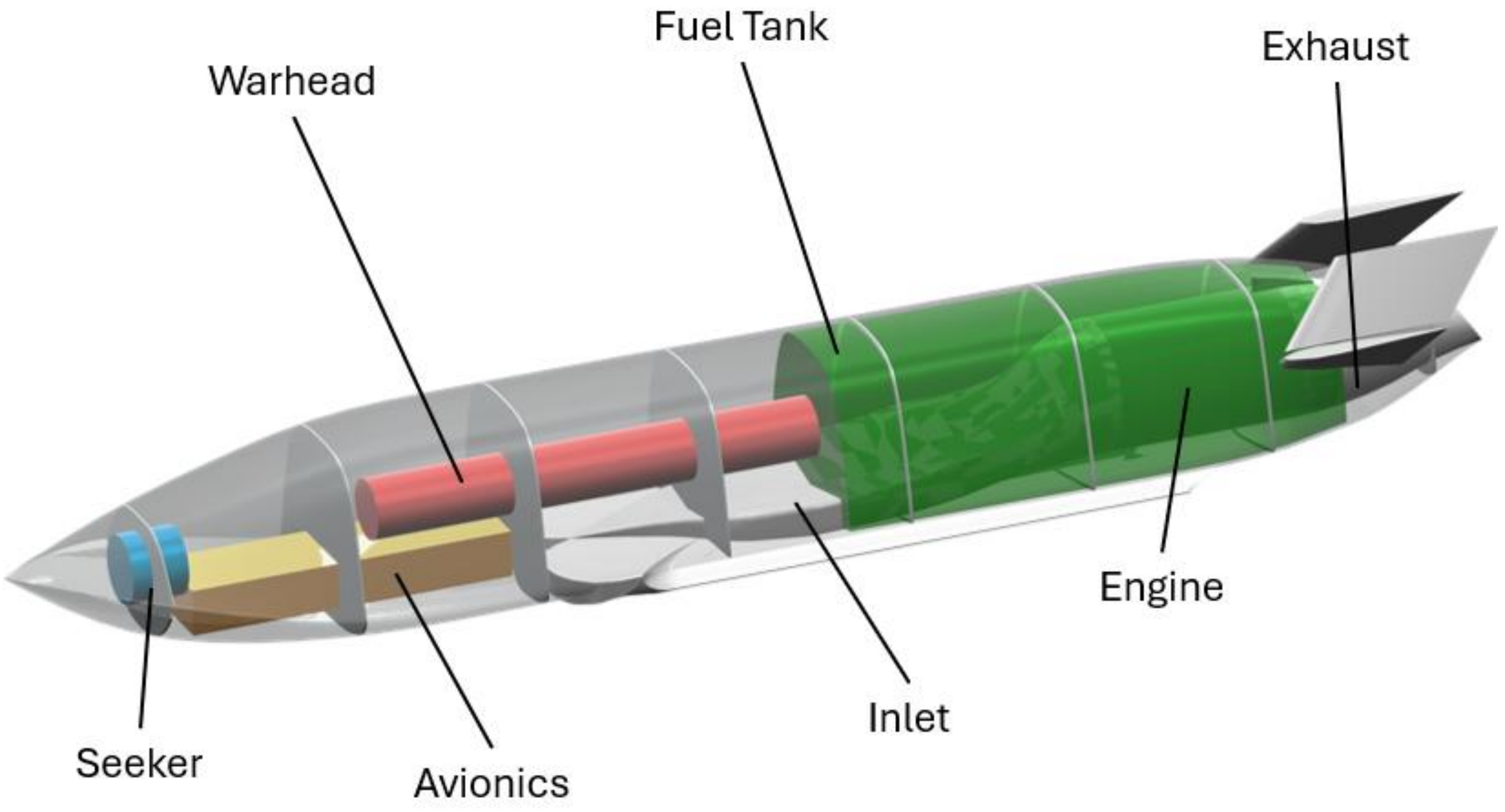
- Changed Empennage to V-Tail Configuration
- Improved Efficiency of the Engine
- Weight reduction

JASSM | Lockheed Martin

Stowed vs. Deployed

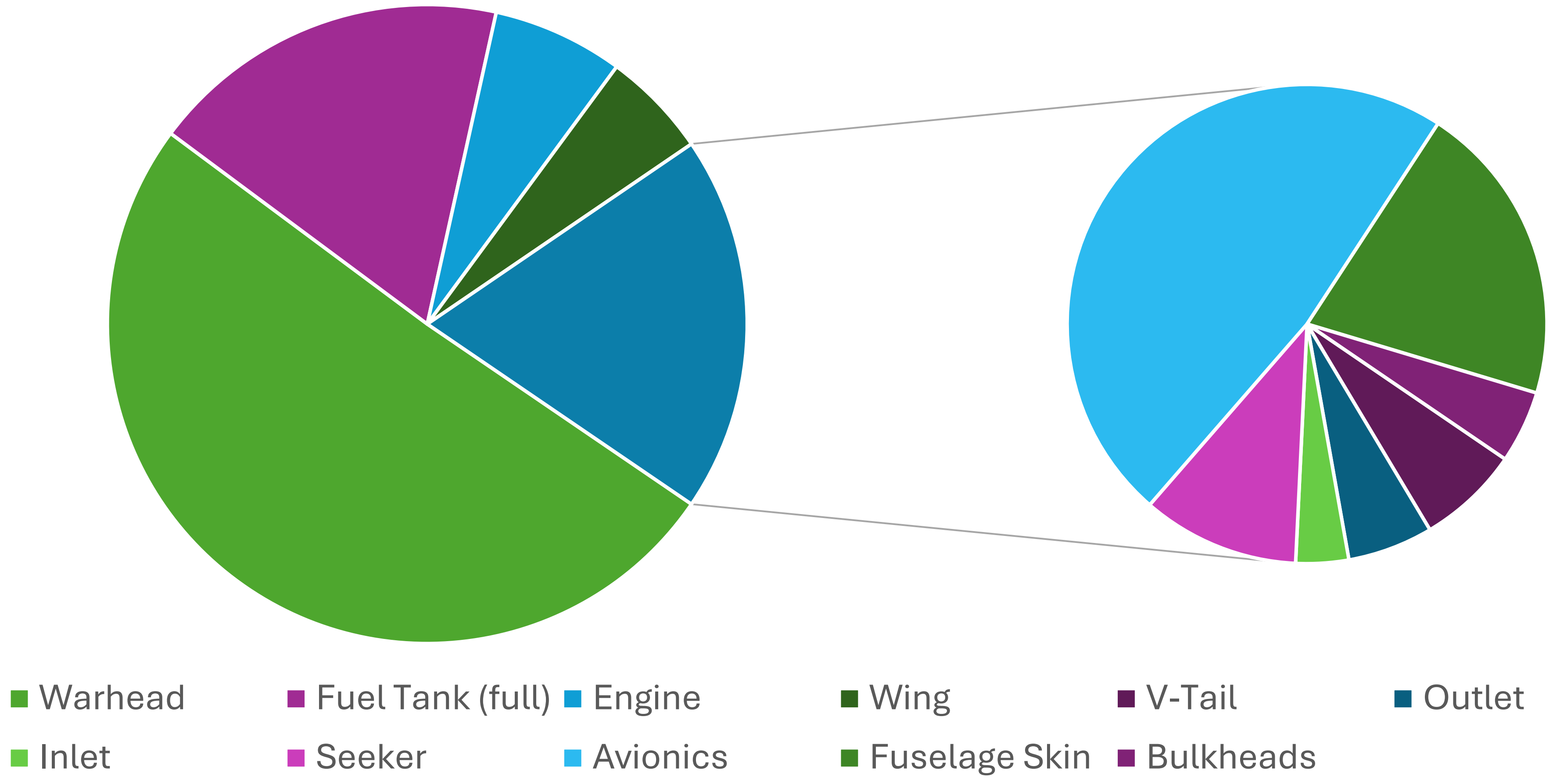


WRAITH Components



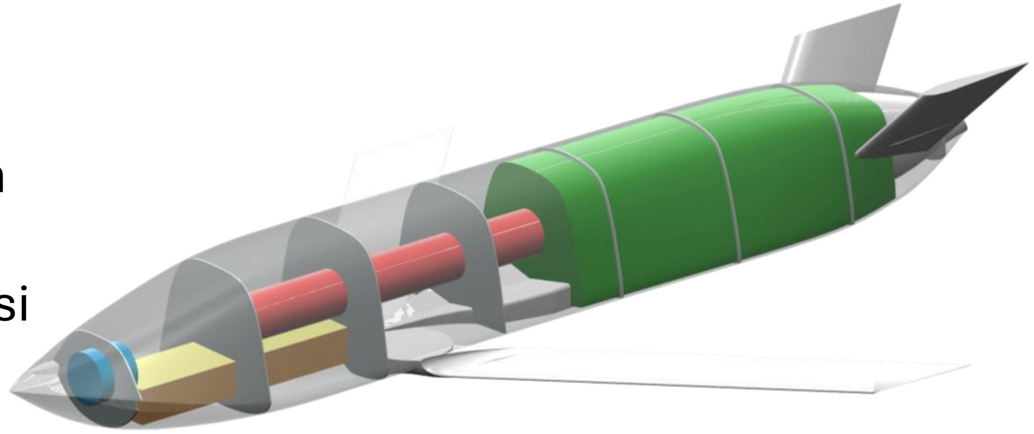
Component Weight Breakdown

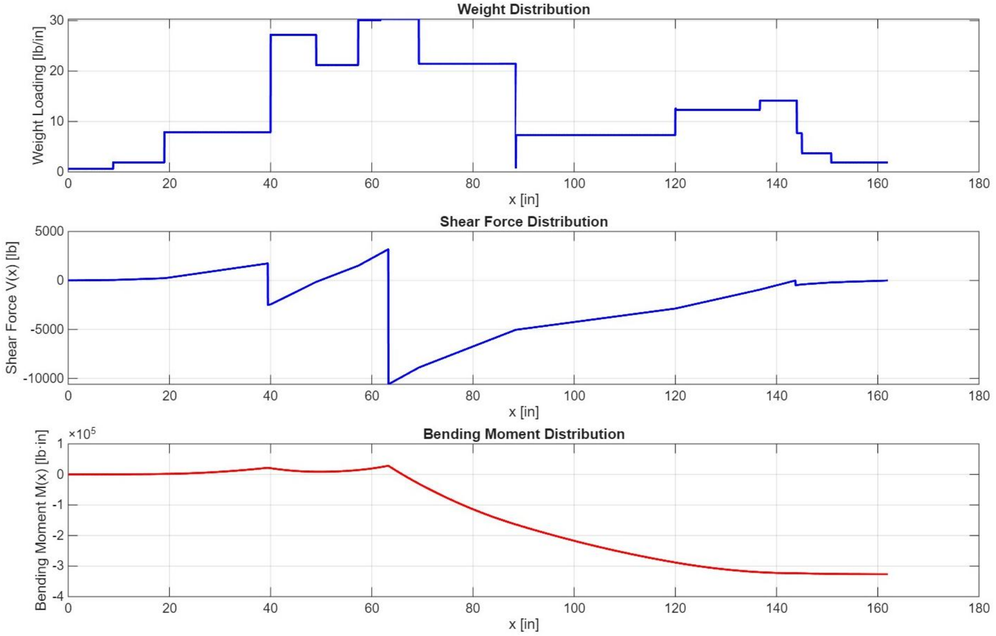
Total Weight: 1975 lbs



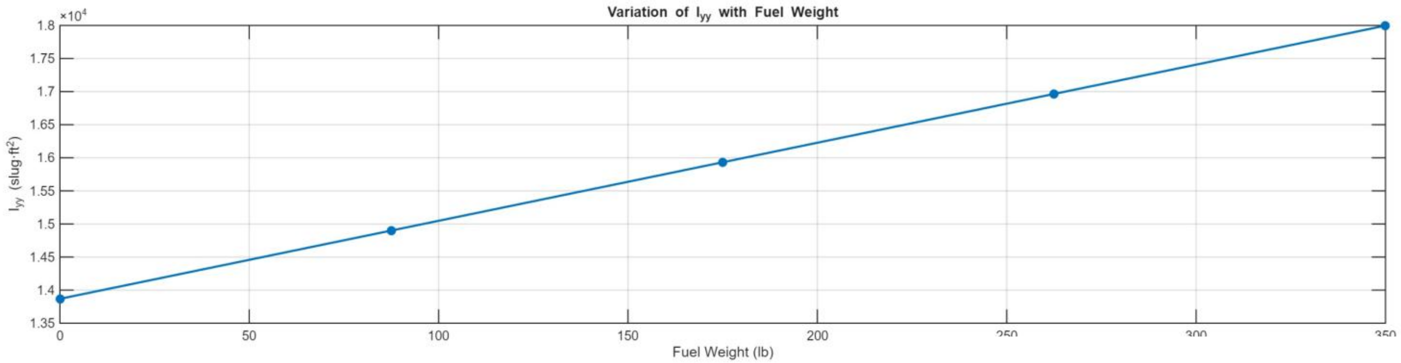
WRAITH Structure

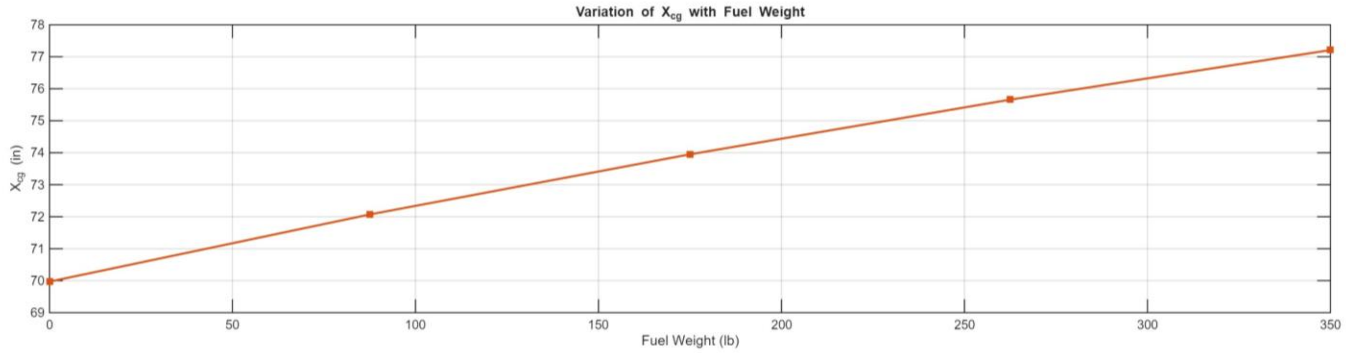
- High-grade, M55J Carbon Fiber
  - $E = 49$ Msi, $F_t = 291$ ksi $F_c = 127$ ksi
- Fuselage Skin: 0.11 inch thick
- Wing: Solid Carbon Fiber
- V-Tail: Solid Carbon Fiber
- Bulkheads: 0.22 inch thick
- Maximum Vertical Load Factor: 9.3

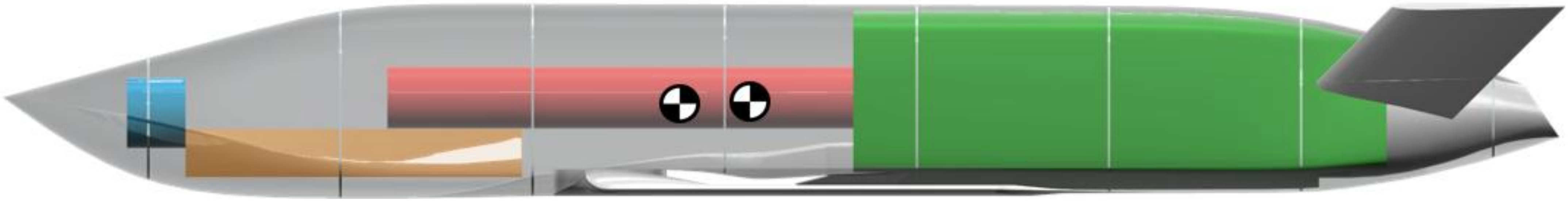




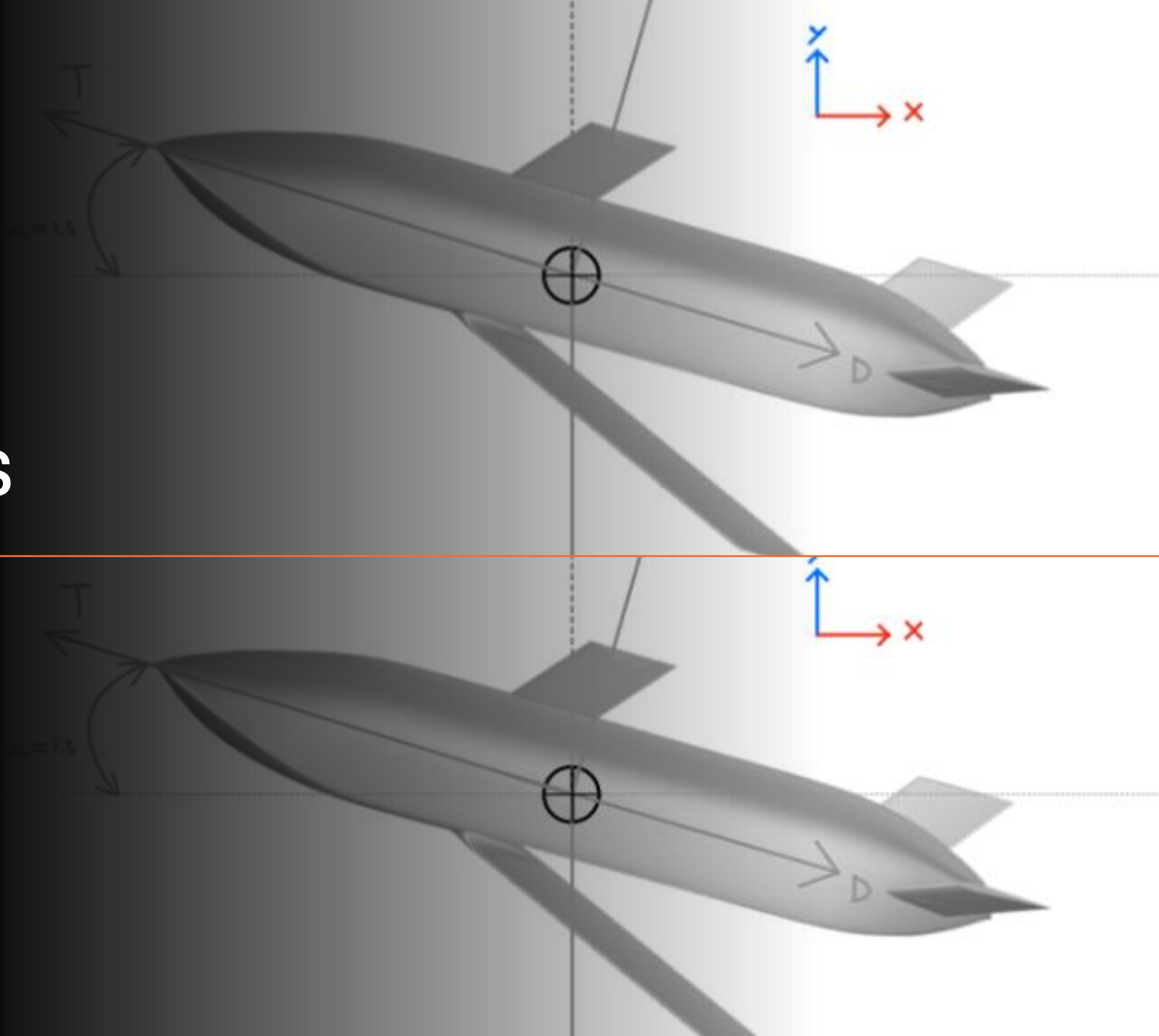
Center of Gravity



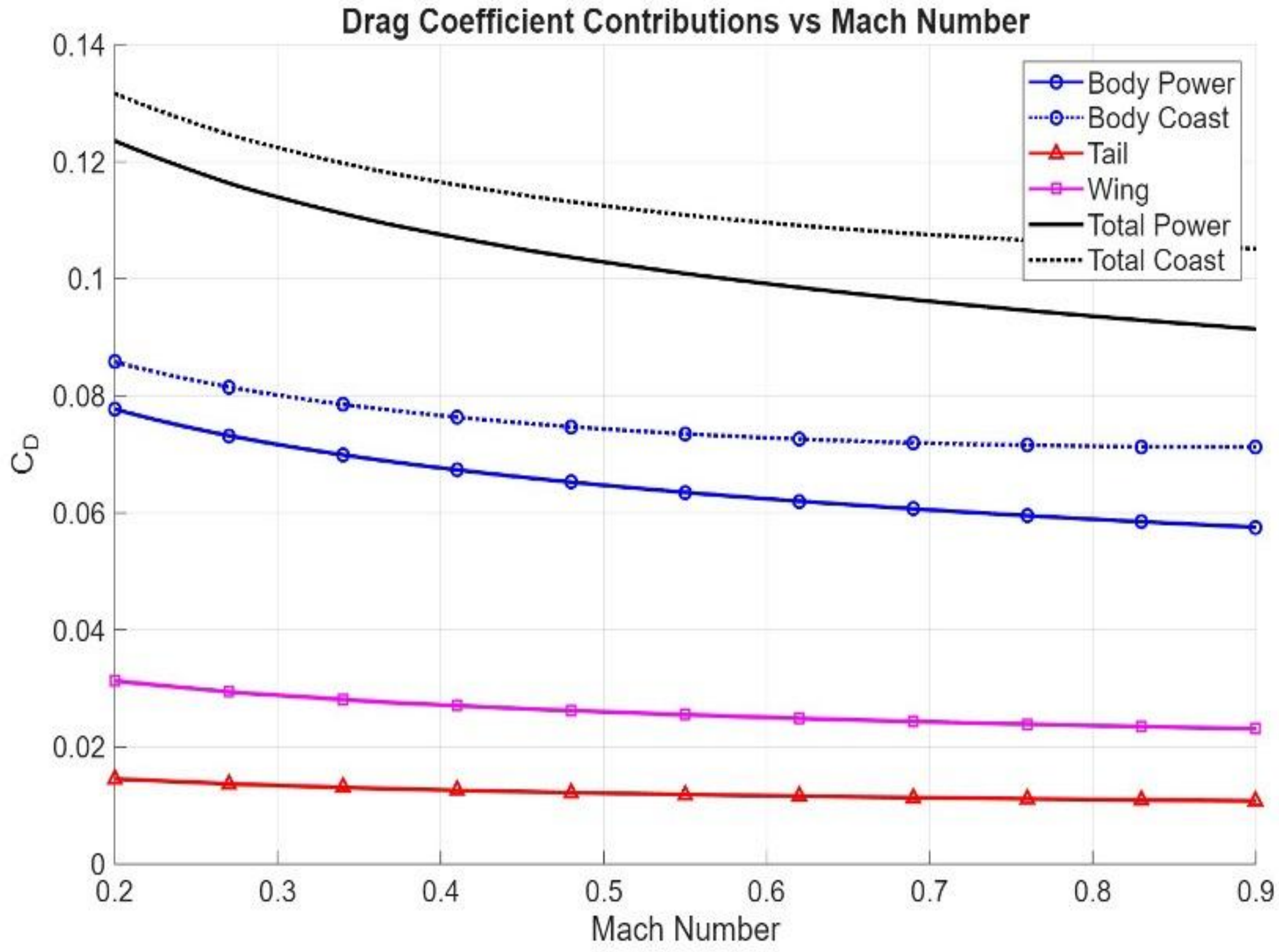




Aerodynamics

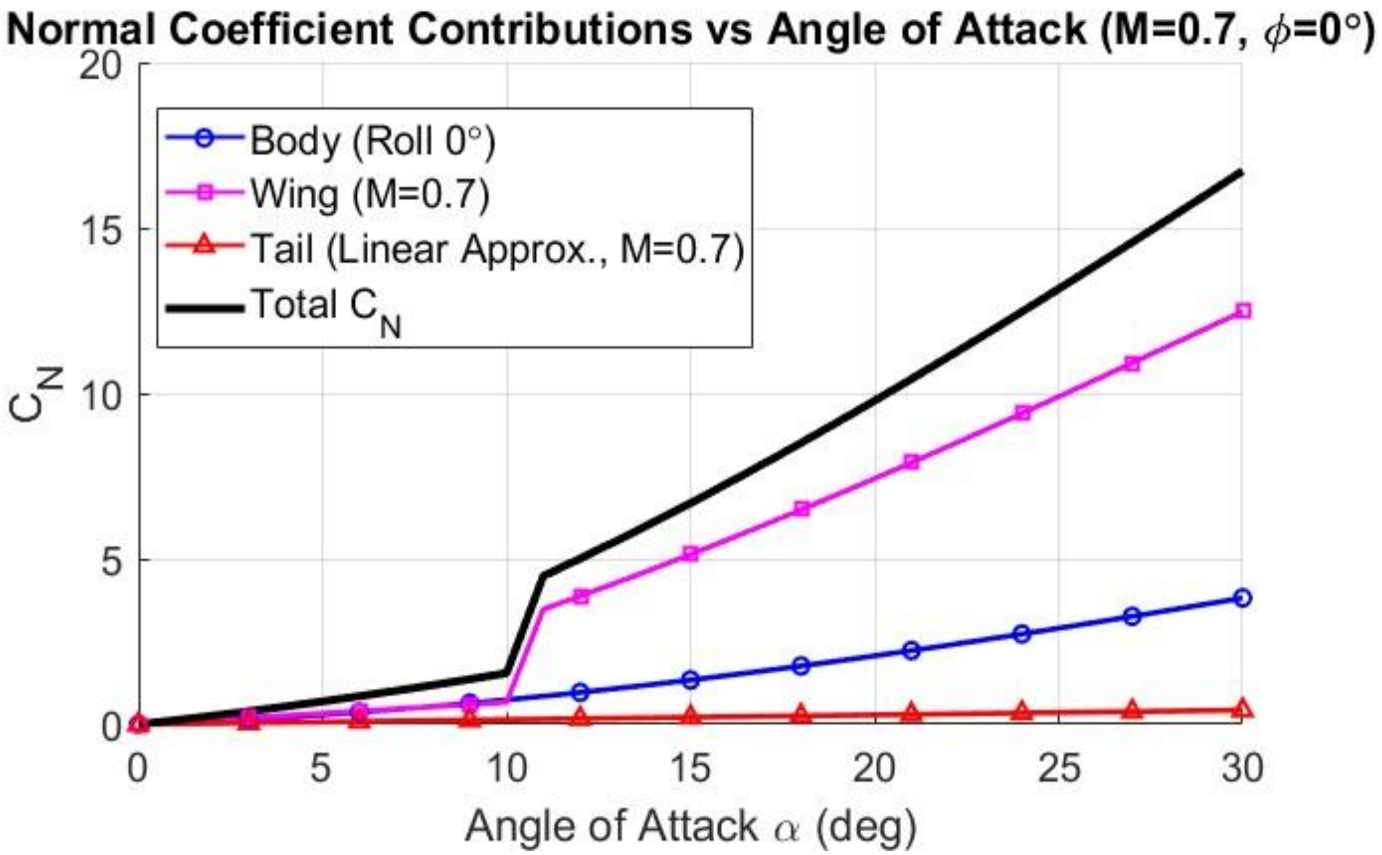


Drag



Drag Coefficient Contributions vs Mach Number
Body Power
Body Coast
Tail
Wing
Total Power
Total Coast
C_D
Mach Number
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

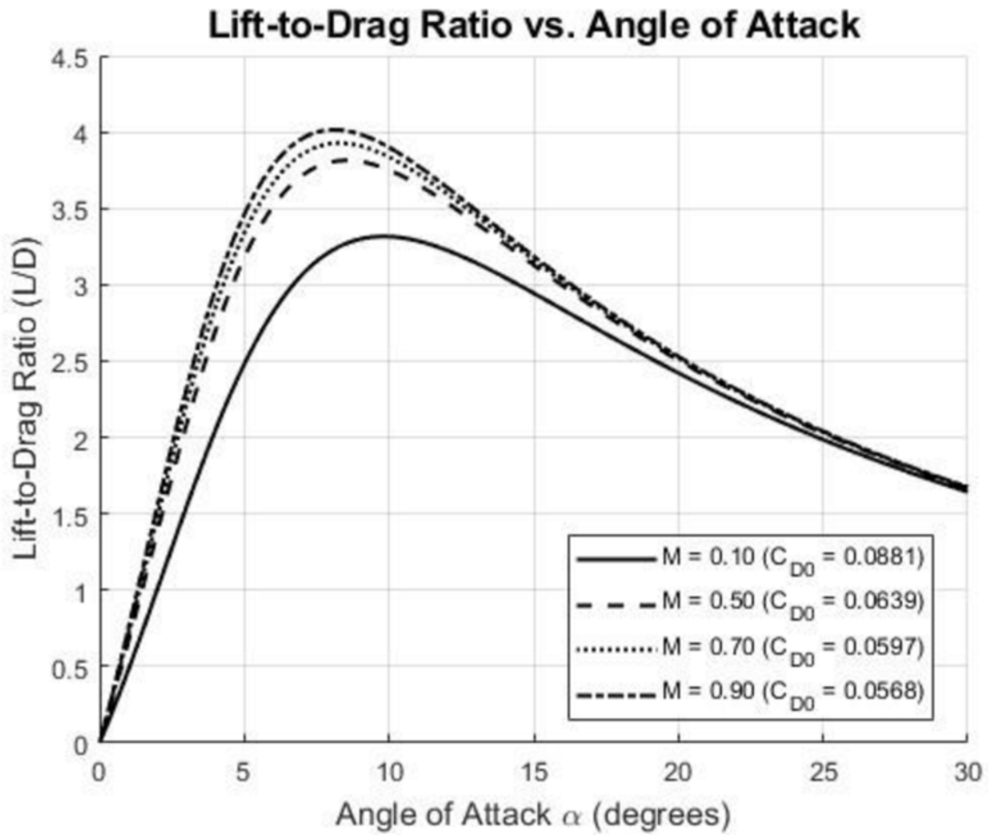
Lift



Normal Coefficient Contributions vs Angle of Attack (M=0.7, ϕ=0°)
Body (Roll 0°)
Wing (M=0.7)
Tail (Linear Approx., M=0.7)
Total C_N
C_N
Angle of Attack α (deg)
0
5
10
15
20
25
30

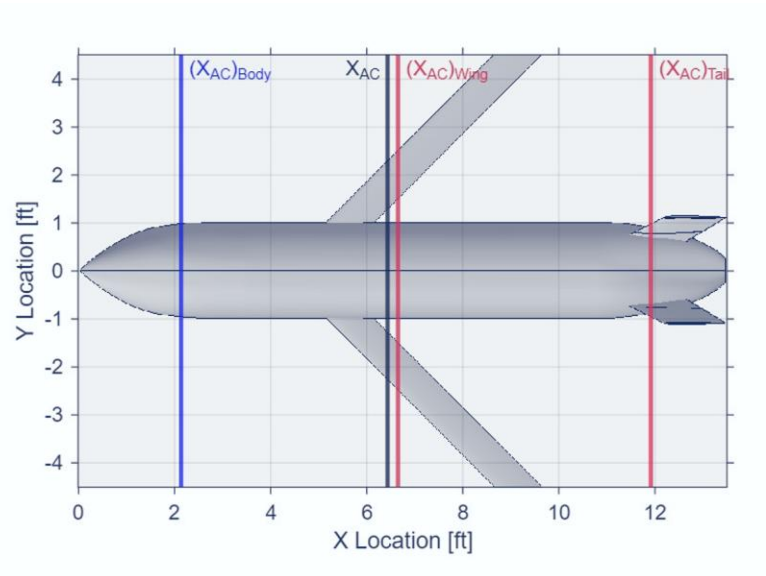
Lift to Drag Performance

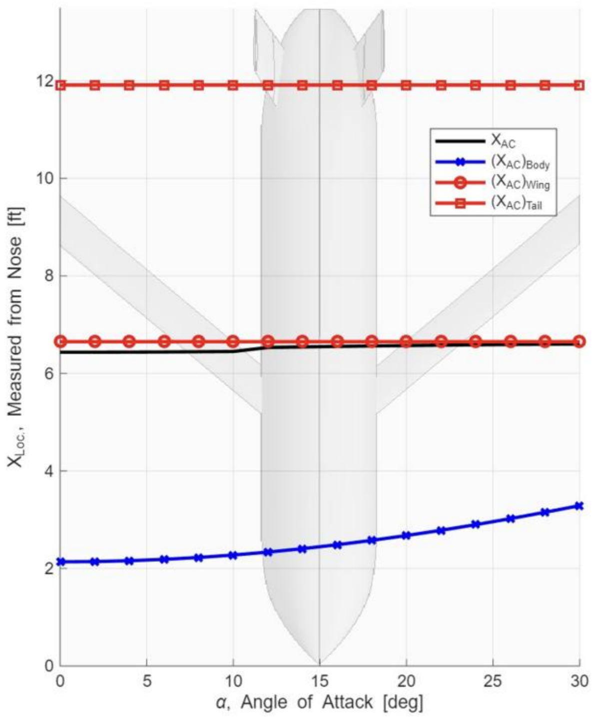
Mach Number	Values
0.1	3.29
0.5	3.65
0..7	3.73
0.9	3.78

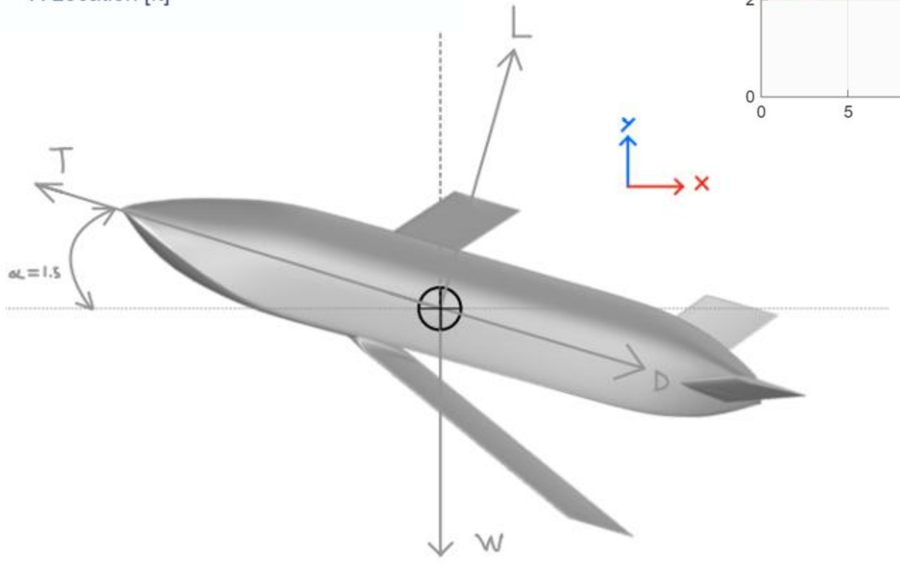


Cruise

Parameter	Values
Altitude	2,000 ft
Mach number	0.71
Weight (W)	1,975 lbf
Tail area	3.36 ft^2
Wing area	9 ft^2
Cruise satisfied at α	1.5 $^\circ$







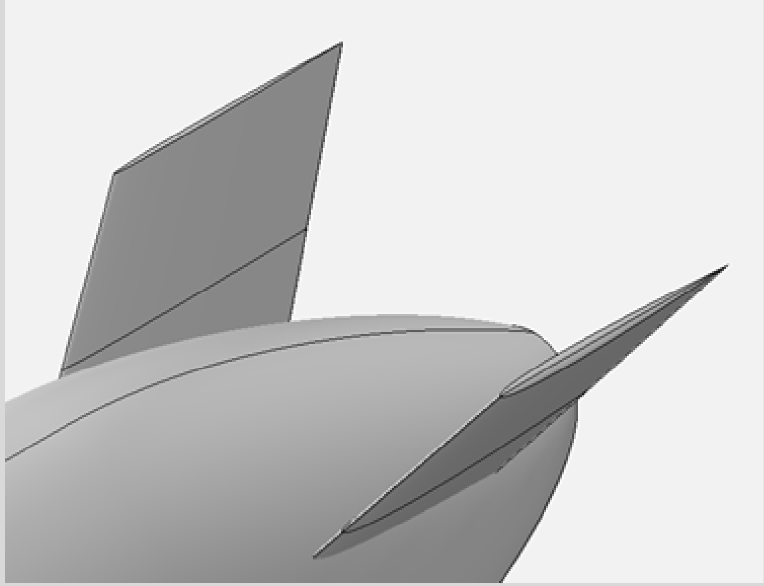
Tail sizing

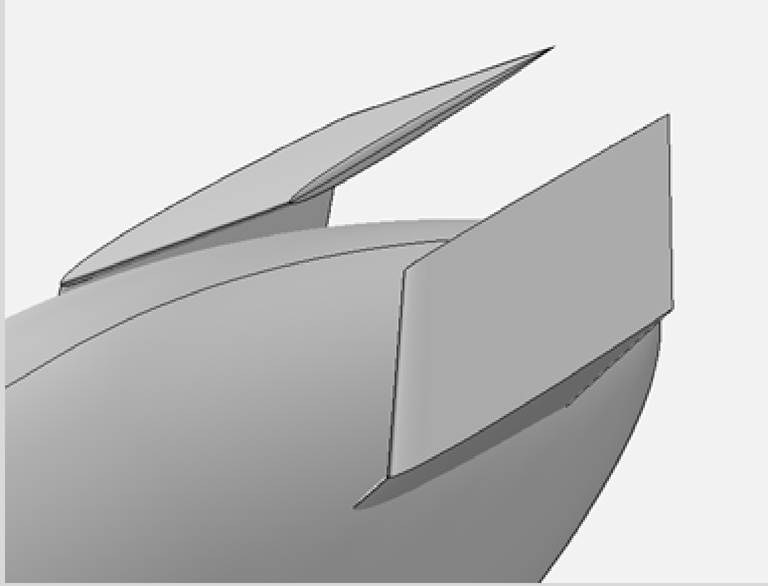
- **Old Tail :**

- **Span:** $b_{T,old} = 2.40$ **ft**
- **Root chord:** $c_{r,T} = 1.50$ **ft**
- **Tip chord:** $c_{t,T} = 1.30$ **ft**

- **New CG at 77.21 in**
- **New Tail :**

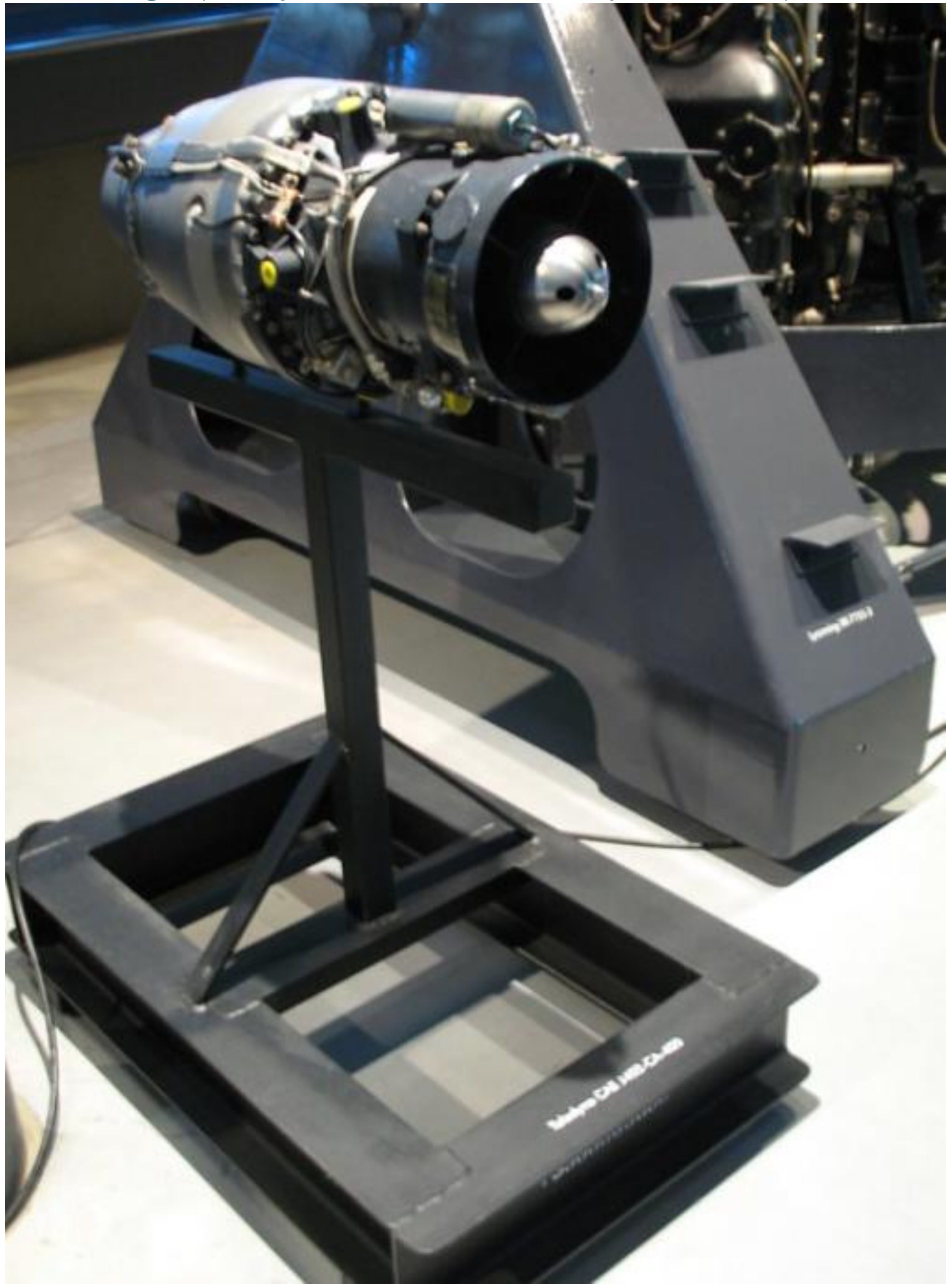
- **Span:** $b_{T,old} = 2.31$ **ft**
- **Root chord:** $c_{r,T} = 1.50$ **ft**
- **Tip chord:** $c_{t,T} = 1.30$ **ft**



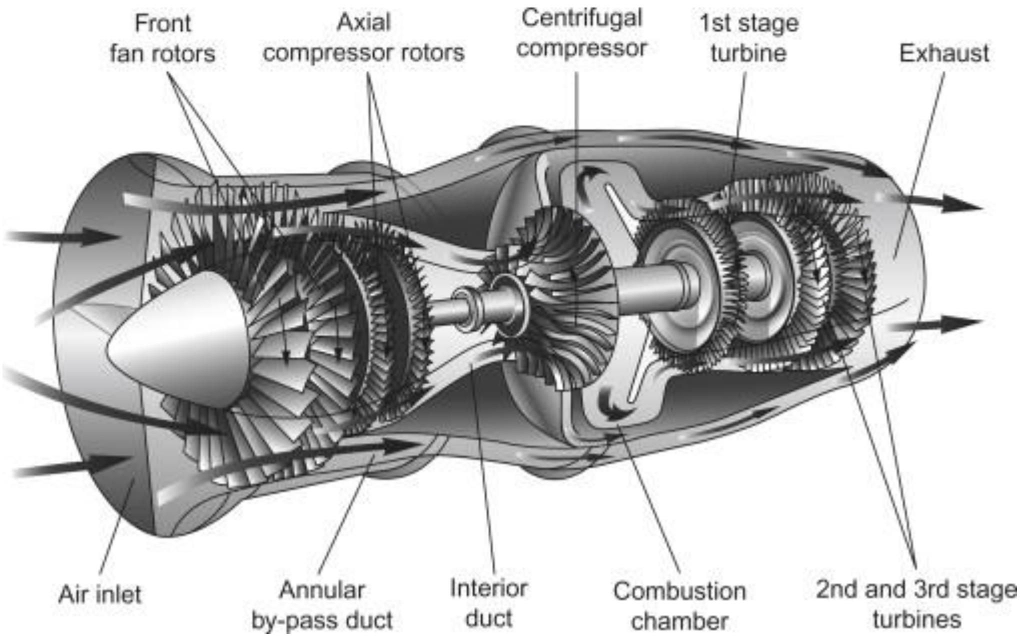


Propulsion

[Missile engine | Teledyne CAE J402-CA-400 turbojet missile e... | Flickr]



Teledyne J402

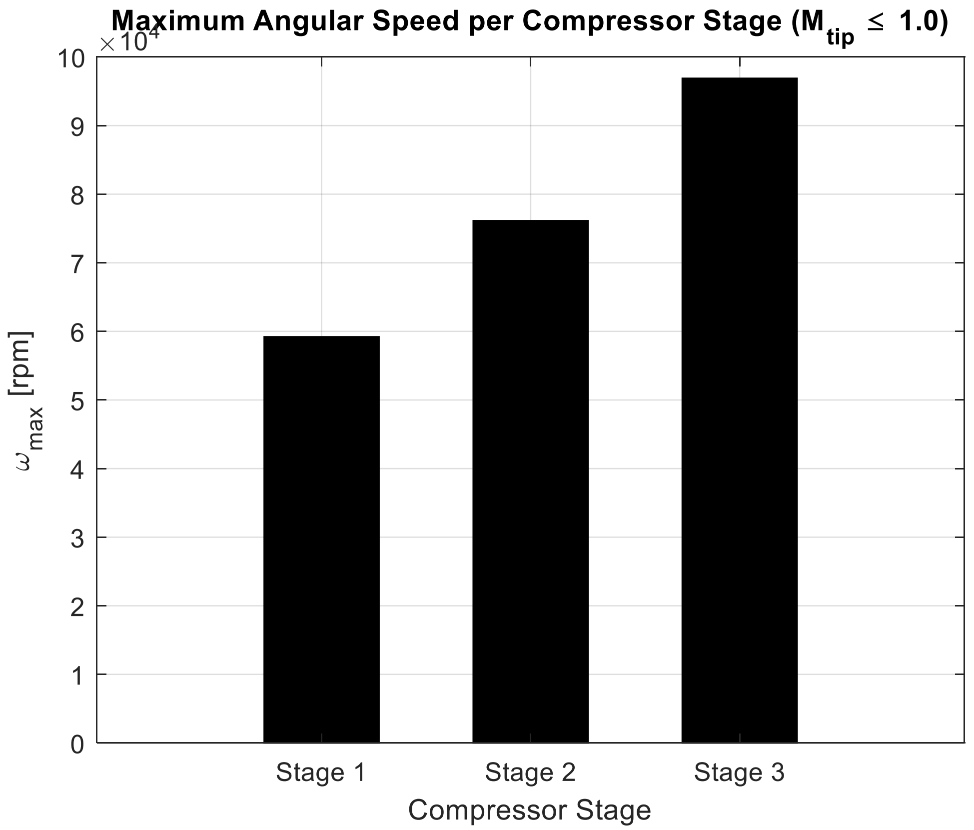


[Compressor Rotor - an overview | ScienceDirect Topics]

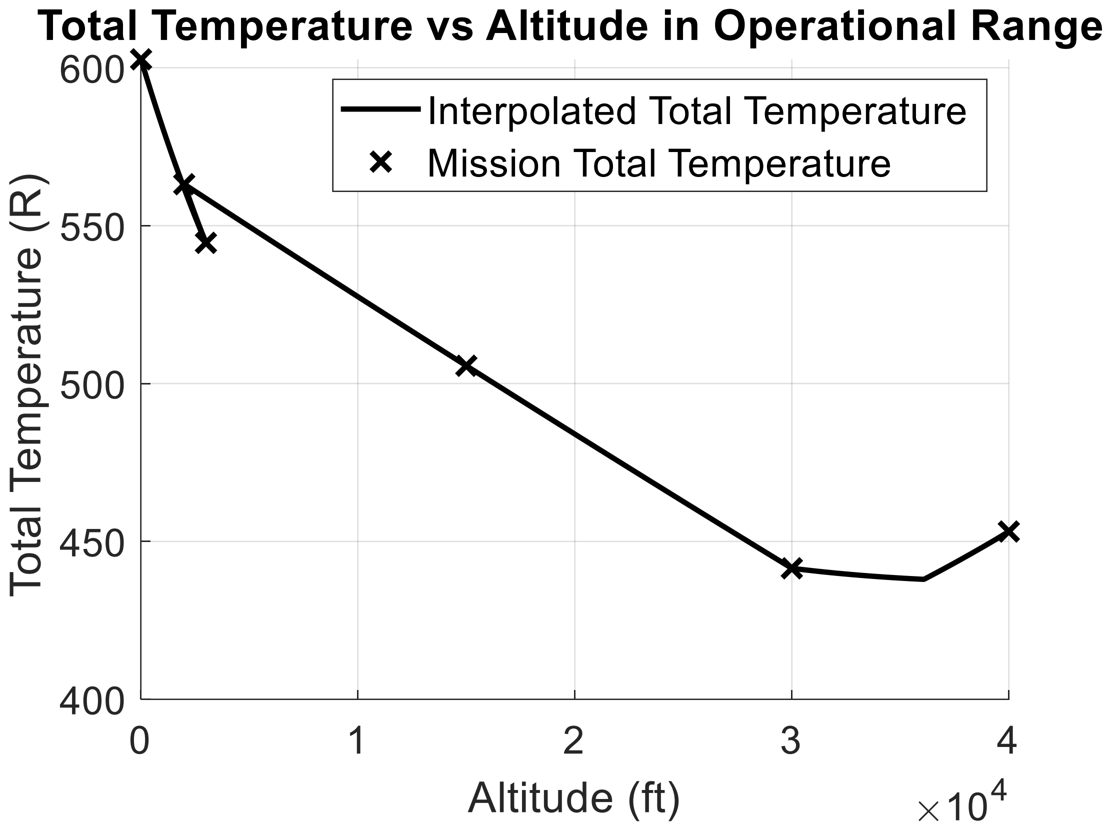
Axial Compressor 1 (C1) Diameter (ft)	**1.0118**
Axial Compressor 2 (C2) Diameter (ft)	1.1187
Centrifugal Compressor (C3) Diameter	1.3300

T2 (°R)	N (rpm)	PR_{C1} (~)	PR_{C2} (-)	PR_{C3} (-)	PR_{Tot} (-)
441.49	18667	1.8522	1.8853	2.8619	9.9934
505.62	19886	1.8424	1.8795	2.8863	9.995
563.11	20905	1.8342	1.8746	2.9068	9.9946
544.55	20583	1.8369	1.8761	2.9004	9.9952
602.65	21574	1.8291	1.8715	2.9213	9.9997

T_2 (°R)	$T_{2.3}$ (°R)	$T_{2.6}$ (°R)	T_3 (°R)
441.49	526.62	629.76	847.23
505.62	601.14	716.84	963.46
563.11	667.65	794.23	1066.5
544.55	646.2	769.3	1033.4
602.65	713.26	847.18	1137.1

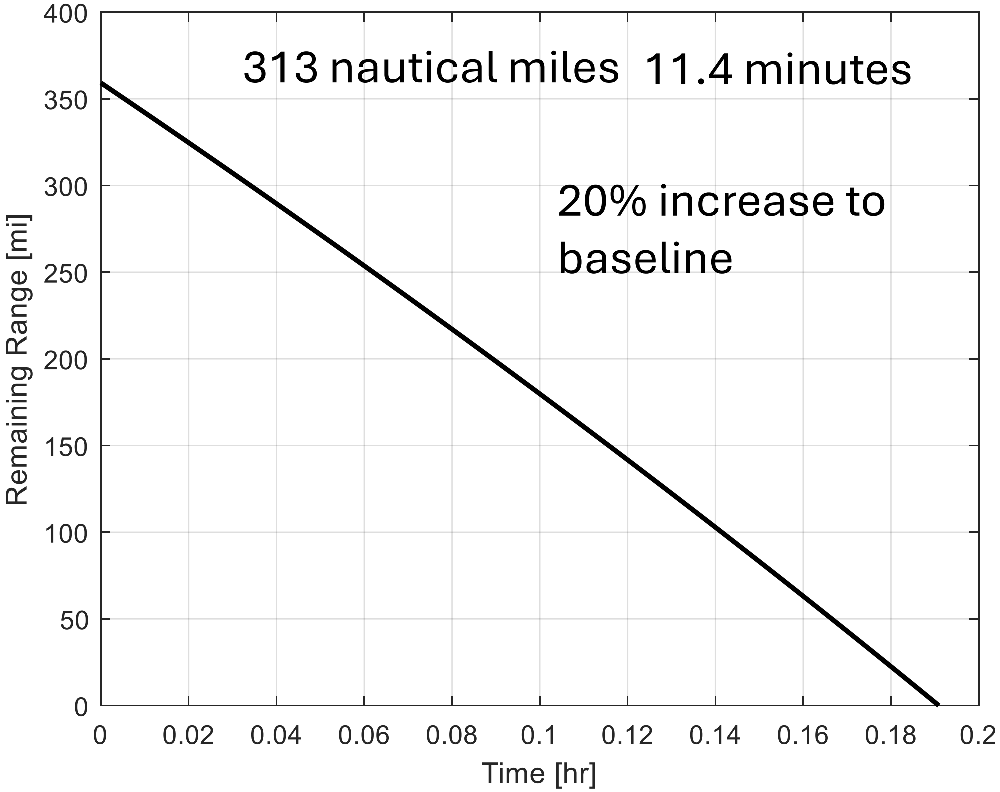


Maximum Angular Speed per Compressor Stage (M tip ≤ 1.0)
×10^4
10
9
8
7
6
5
4
3
2
1
0
ω max [rpm]
Stage 1
Stage 2
Stage 3
Compressor Stage

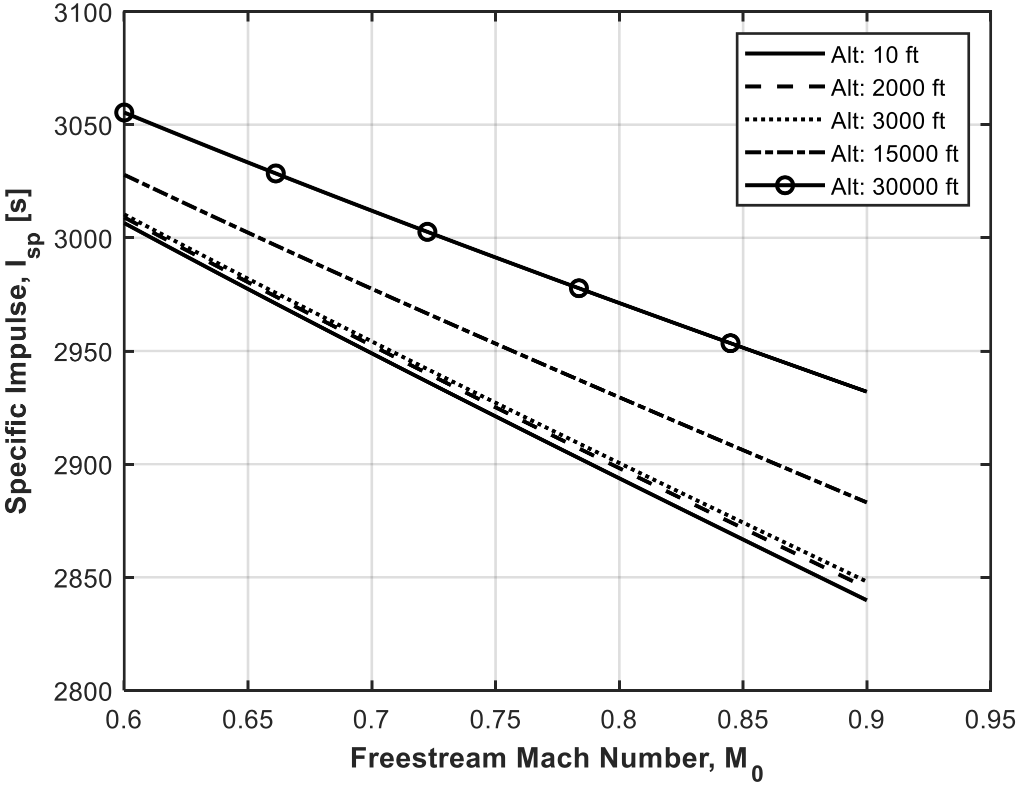


Total Temperature vs Altitude in Operational Range
600
550
500
450
400
Total Temperature (R)
Interpolated Total Temperature
Mission Total Temperature
0
1
2
3
4
Altitude (ft)
×10^4

Propulsion



313 nautical miles 11.4 minutes
20% increase to baseline
Remaining Range [mi]
Time [hr]
400
350
300
250
200
150
100
50
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

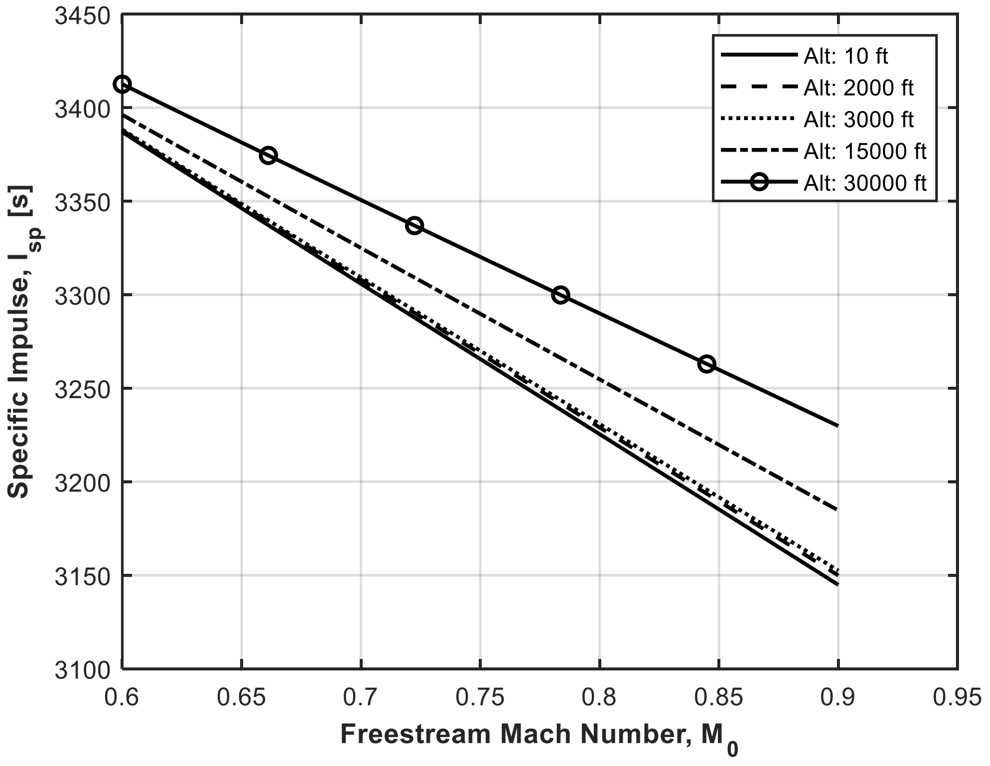


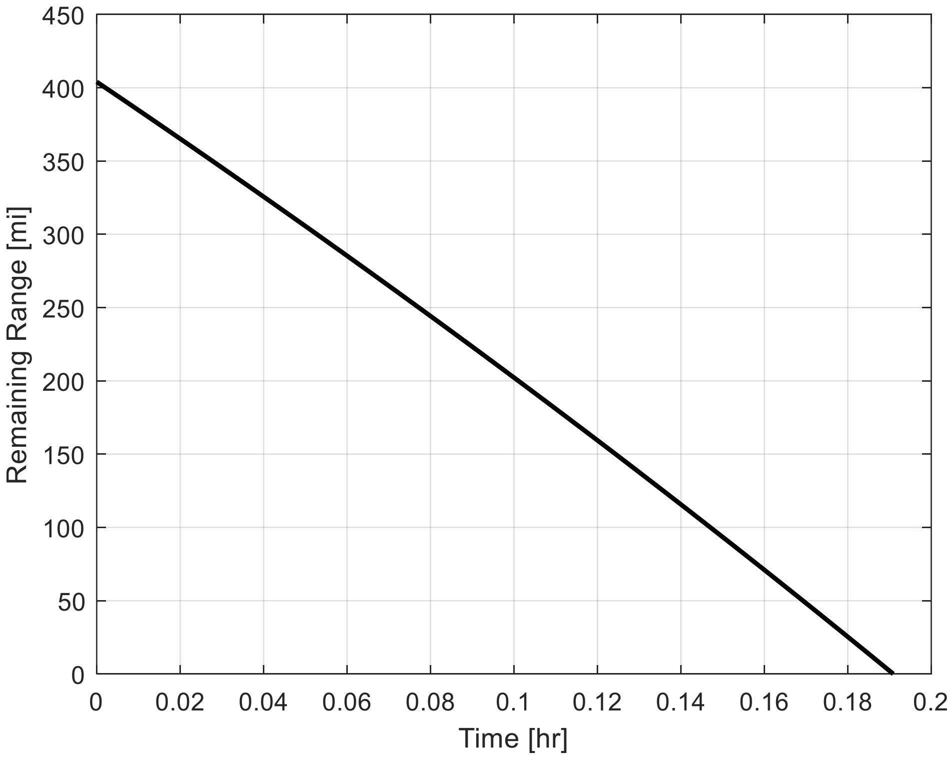
Alt: 10 ft
Alt: 2000 ft
Alt: 3000 ft
Alt: 15000 ft
Alt: 30000 ft
Specific Impulse, I_{sp} [s]
Freestream Mach Number, M_0
3100
3050
3000
2950
2900
2850
2800
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95

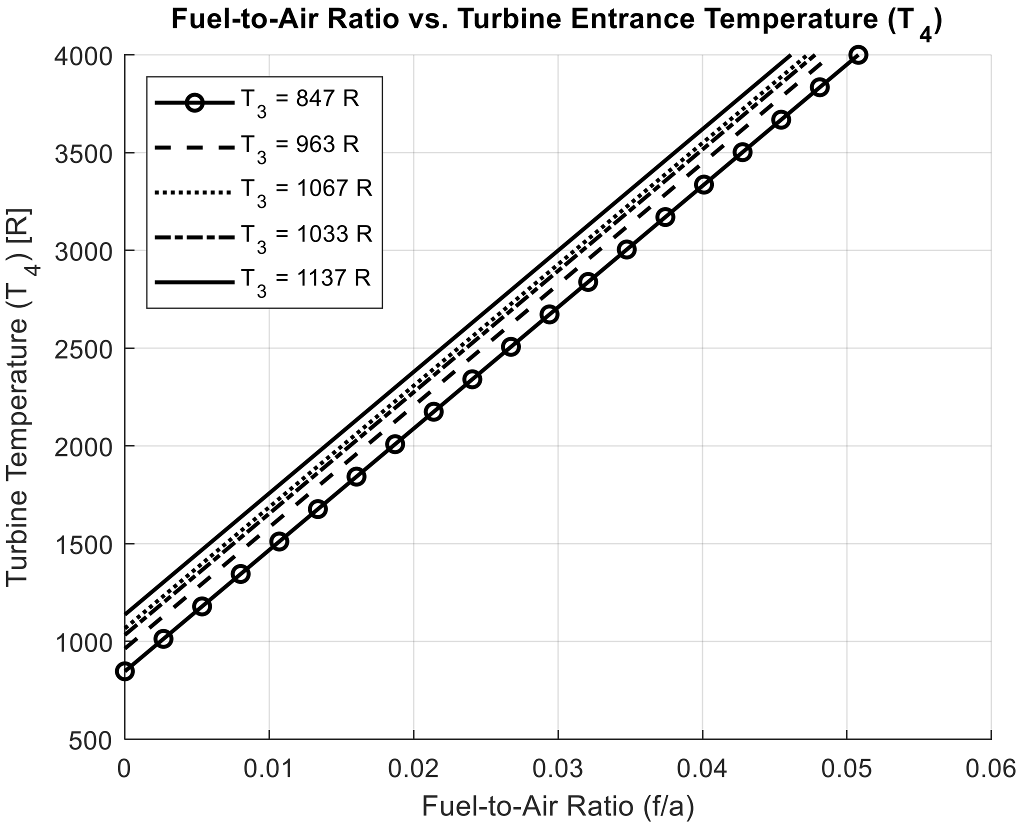
PR of 20

362 nautical miles

35% increase to baseline







Altitude (ft)	Tt2 (R)	Compressor Outlet Temperature (Tt3) in R
10	602.7	1,137
2,000	544.6	1,033
3,000	563.1	1,067
15,000	501.27	963
30,000	441.49	847

Trajectory and Simulation

2D Trajectory

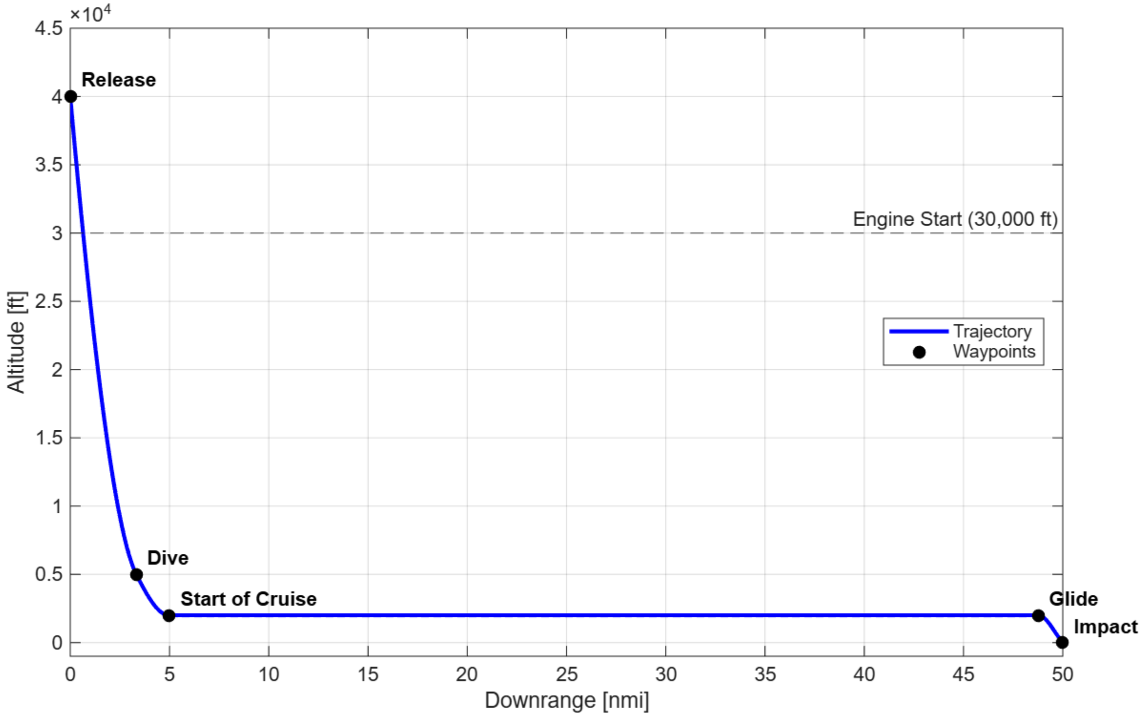
Trajectory Phases

- Launch/Dive
  - Rapidly decrease altitude
  - High-angle dive (> 30 deg)
- Cruise
  - Maneuver to target area
- Termination
  - Low-angle dive (< 30 deg) to target

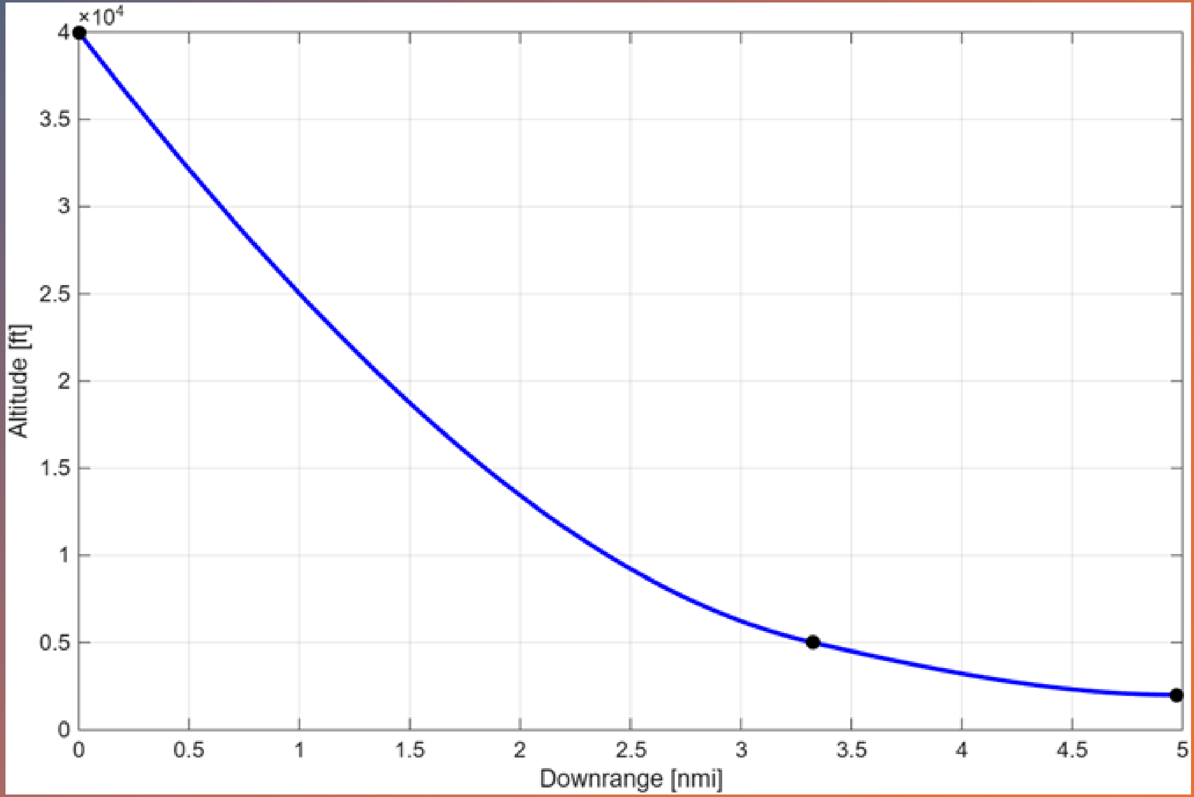
- Trajectory maximizes the survivability of the missile
- n-limit set 5 g's

(Range intentionally shortened for illustration)

Fig. 6.123 Options for Survivability Include Stealth, Altitude, Speed, Threat Avoidance, Terrain Masking, and Maneuverability. *Note*: See video supplement, Tomahawk Using Terrain Following and Jinking.



Lauch/Dive Phase



- After release
  - Wings and tail deploy
  - Missile enters a controlled 60-degree dive
- During dive
  - Engine starts at 30,000 ft
  - Missile maintains dive angle
- Approaching cruise
  - Missile initiates a flare maneuver
  - Pulls up to level flight

Cruise
Terrain Contour Matching and Radar Avoidance

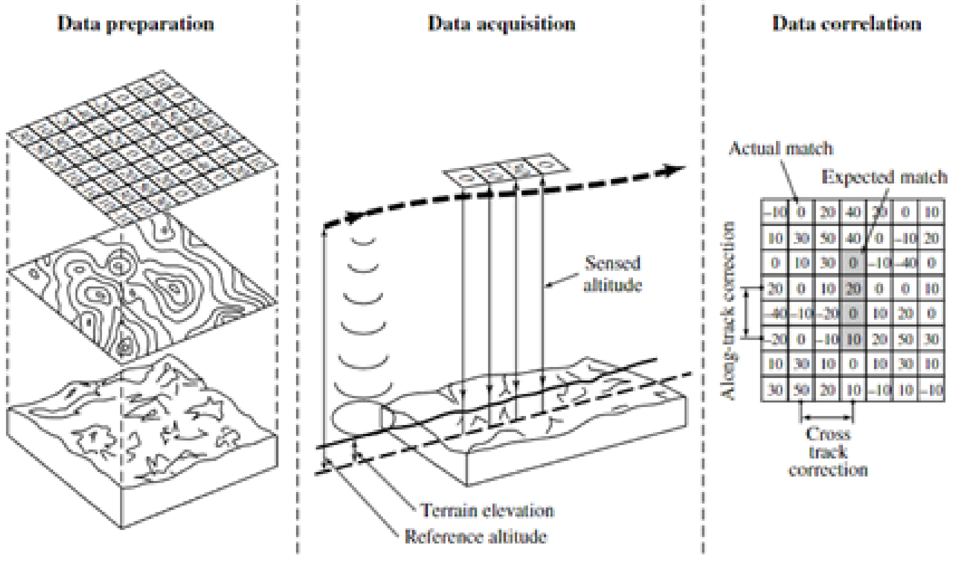
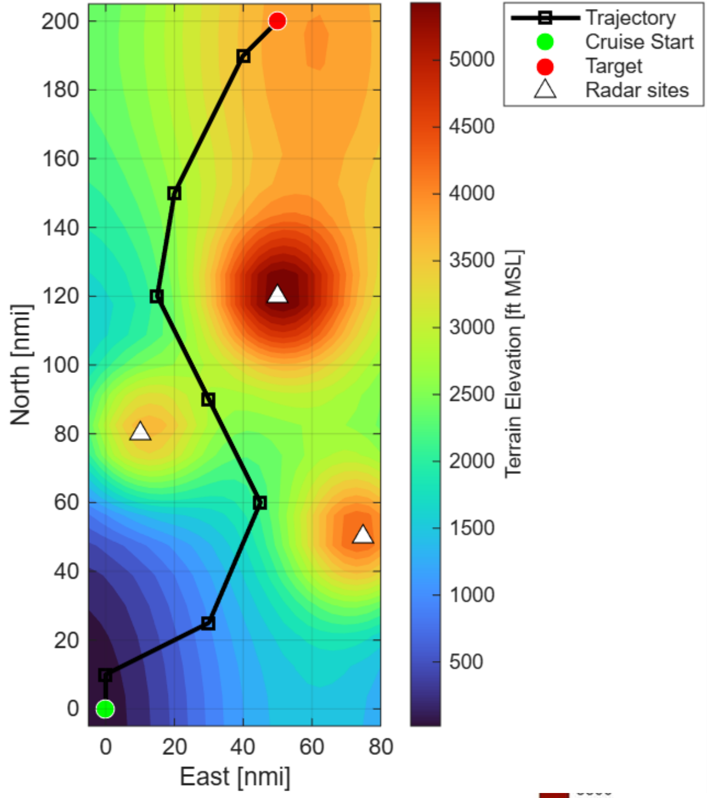
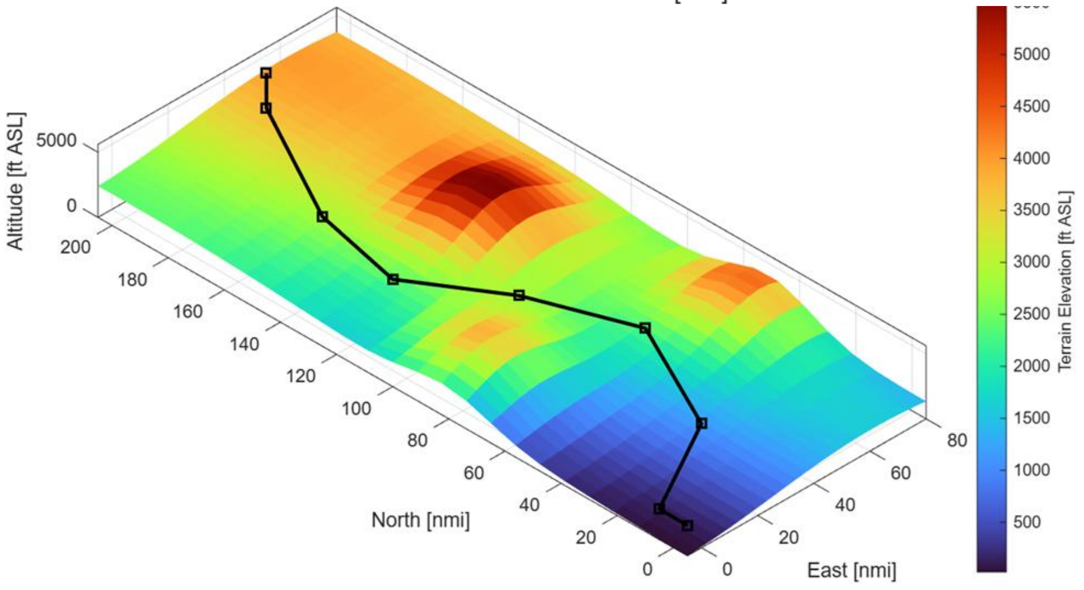


Fig. 7.11. *TERCOM* concept.

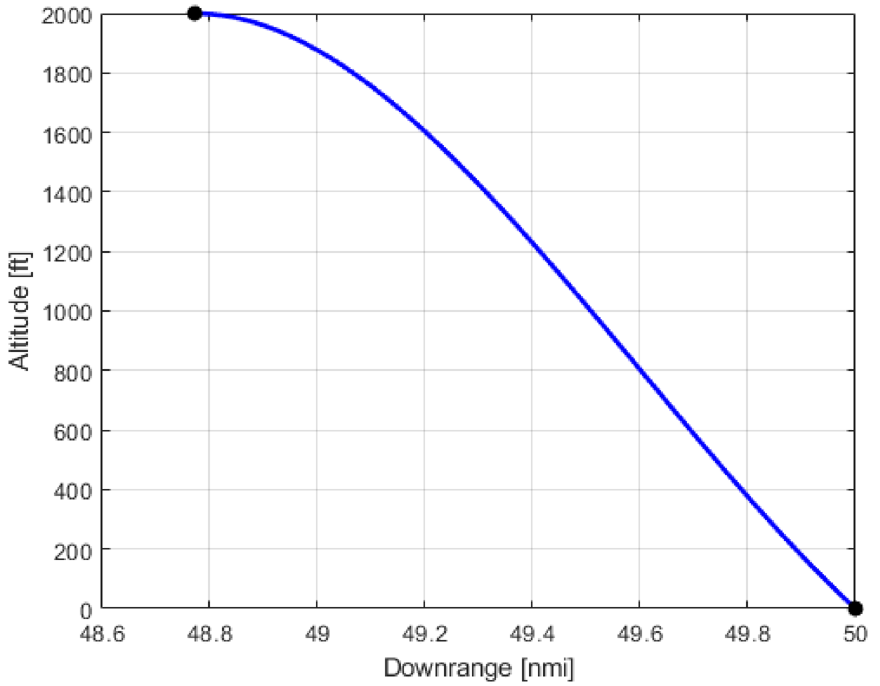


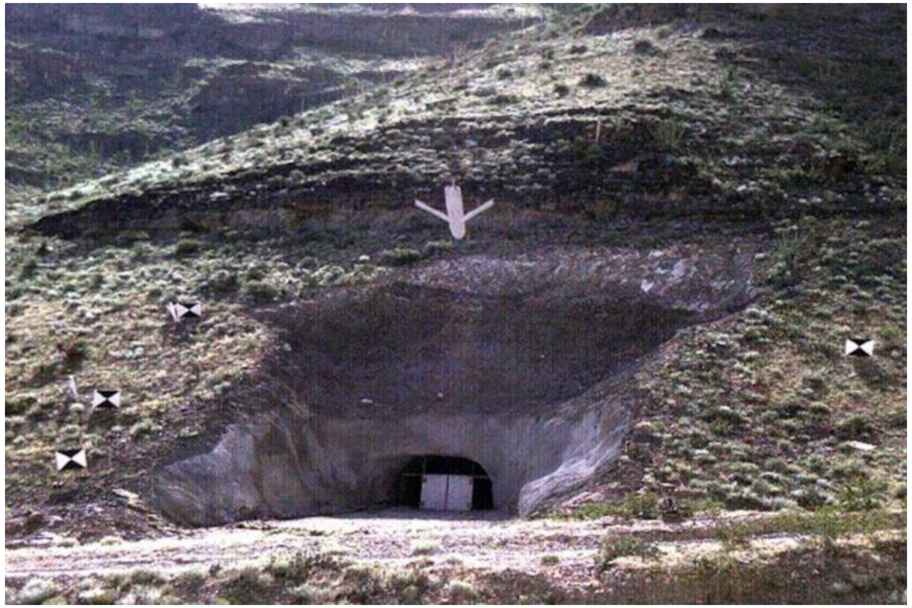
- Missile maintains low-altitude above ground altitude
  - Using pre-collected terrain data to maintain the correct altitude
  - Terrain Contour Matching (TERCOM) strategy
- Guidance towards stationary target
  - Lateral maneuvers to avoid radar
  - Terrain masking



Termination

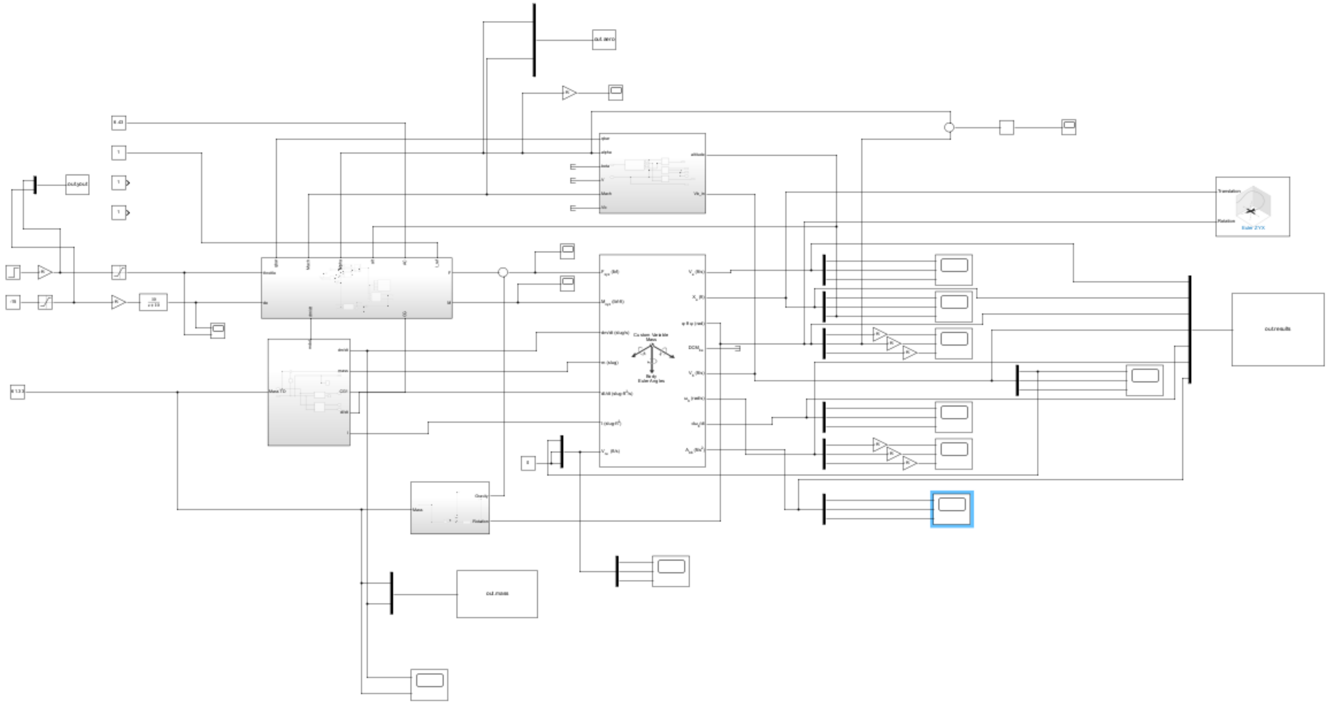
- Missile enters a low-angle dive from level cruise at to 0 ft AGL
- Small maneuvering towards ground target
- Trajectory is designed to ensure high precision

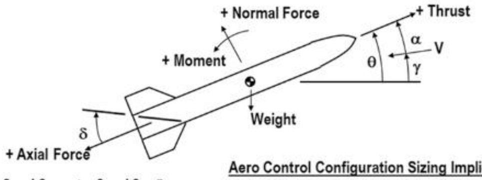




2D
3 DOF
Simulation

- Translation: X, Z
- Rotation: Θ
- Simulator created using MATLAB/Simulink
- Aerodynamic forces (N, A) modeled in body coordinates
- Engine modeled with fuel consumption lowering overall weight
- Atmosphere model decreases air density and temperature with altitude
- Controls
  - Thrust input
  - Ruddervator deflection





$$I_y \ddot{\theta} \approx I_y \ddot{\alpha} \approx q\, S_{Ref}\, d\, C_{m_\alpha}\, \alpha + q\, S_{Ref}\, d\, C_{m_\delta}\, \delta$$

$$(W / g_c)\, \dot{\gamma} \approx S_{Ref}\, \rho\, V\, C_{N_\alpha}\, \alpha / 2 + S_{Ref}\, \rho\, V\, C_{N_\delta}\, \delta / 2 + (T \sin \alpha) / V - (W / V) \cos \gamma$$

$$(W / g_c)\, \dot{V} \approx T - C_A\, S_{Ref}\, q - C_N\, S_{Ref}\, q \sin \alpha - W \sin \gamma$$

Aero Control Configuration Sizing Implication*

High Agility / Fast Rotation ⇒ $C_{m_\delta} > C_{m_\alpha}$, I_y small (W small), q large

Large / Fast Heading Change ⇒ C_N large ($C_{N_\alpha}\, \alpha$ or $C_{N_\delta}\, \delta$ large), W small, ρ large (low alt), V large, T / V large

High Speed / Long Range ⇒ Total Impulse ($\int T\, dt$) large, C_A small, q small

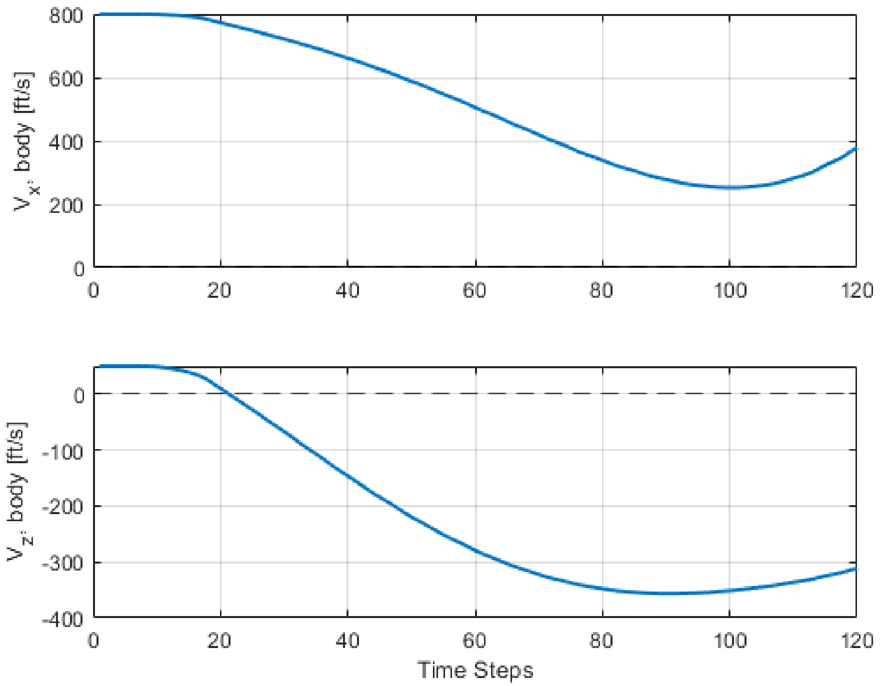
*Assumption: Angle of Attack α small ⇒ $C_m \approx C_{m_\alpha}\, \alpha + C_{m_\delta}\, \delta$ and $C_N \approx C_{N_\alpha}\, \alpha + C_{N_\delta}\, \delta$

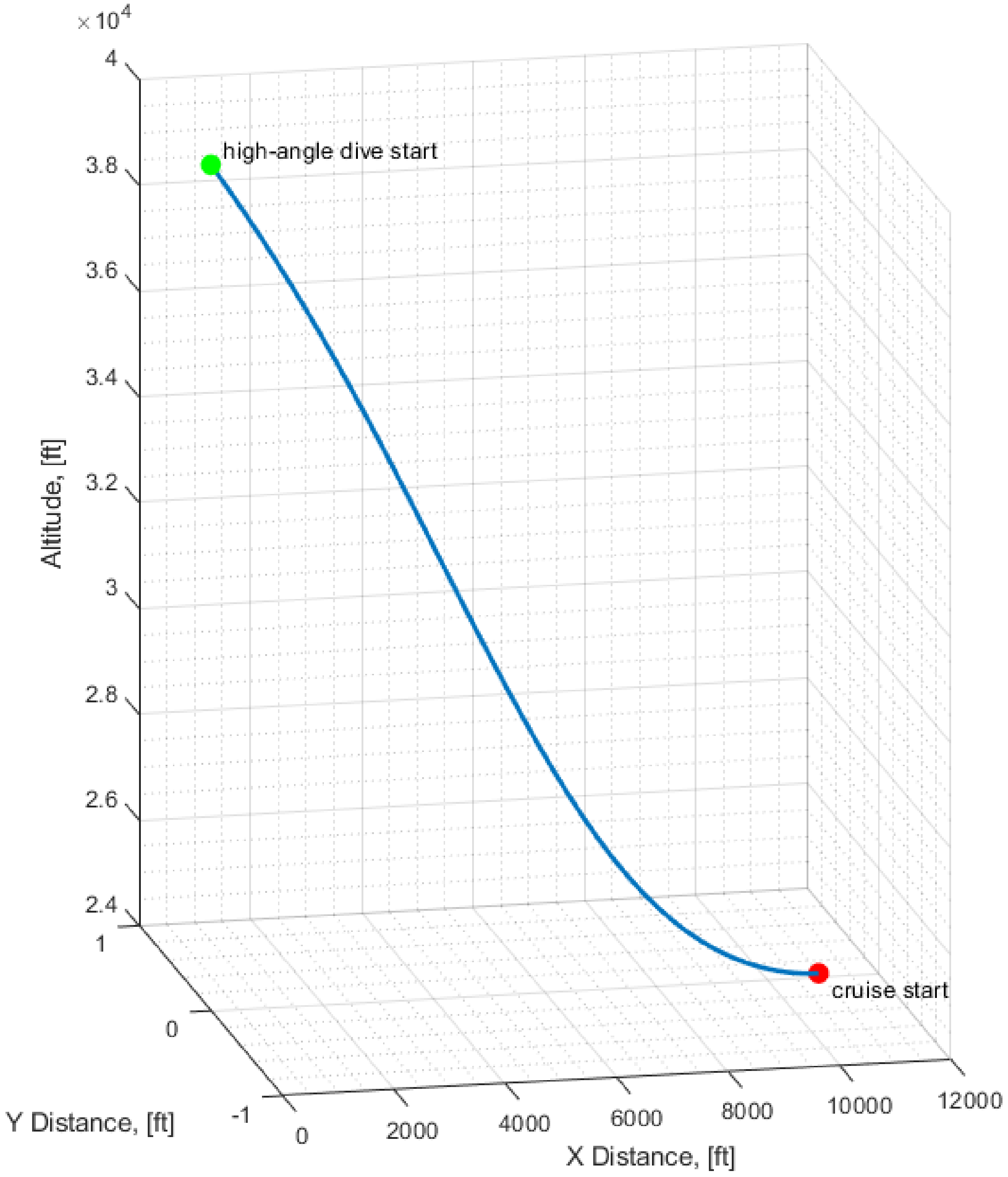
Nomenclature: I_y = pitch moment of inertia, θ = pitch attitude, q = dynamic pressure, S_{Ref} = reference area, C_N = normal force coefficient, C_{N_α} = normal force coefficient derivative with angle of attack, C_{N_δ} = normal force coefficient derivative with flight control deflection, C_m = pitch moment coefficient, C_{m_α} = pitch moment coefficient derivative with angle of attack, C_{m_δ} = pitch moment coefficient derivative with control deflection, ρ = atmospheric density, T = thrust, C_A = axial force coefficient, V = velocity, W = weight, t = time, α = angle of attack, δ = flight control deflection, g_c = gravitational constant, γ = flight path angle

Fig. 5.11a 3 Degrees of Freedom (3-DOF) Equations of Motion Show Drivers for Missile Configuration Sizing.

High-Angle Dive Simulation Results

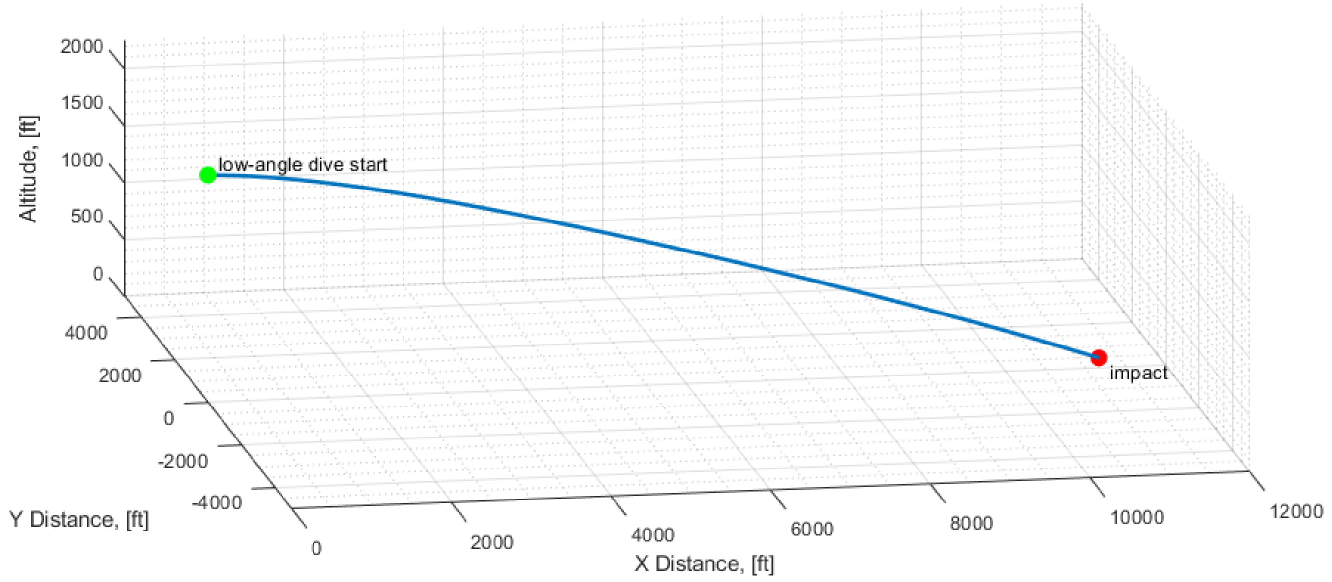
- Simulation starting states
  - 40,000 ft altitude
  - V = 800 ft/s
  - 60-degree dive
  - Simulation shows a controlled high-angle dive from cruise altitude to the target

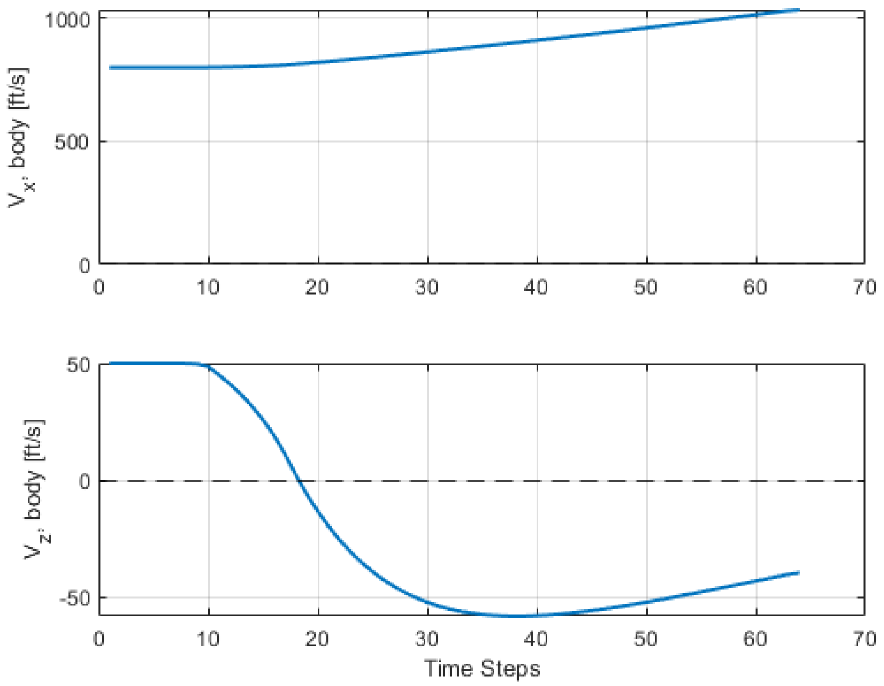




Low-Angle Dive Simulation Results

- Simulation starting states
  - 2,000 ft altitude
  - V = 800 ft/s
  - 5-degree dive
- Simulation shows a controlled low-angle dive from cruise altitude to the target
- Missile impact target at an altitude of 0 ft AGL





Rapid Dragon - YouTube

Conclusions

Range increased by 40%

Weight found to be 1975 lbs

Higher Lift to drag due to new wing

2 axial and 1 centrifugal compressor used to increase engine efficiency

Trajectory follows CONOP and uses terrain masking to avoid radar

Simulation shows missile was able to follow trajectory

Q/A