First-Order Conceptual Design for Turbojet Missiles and Guided Bombs

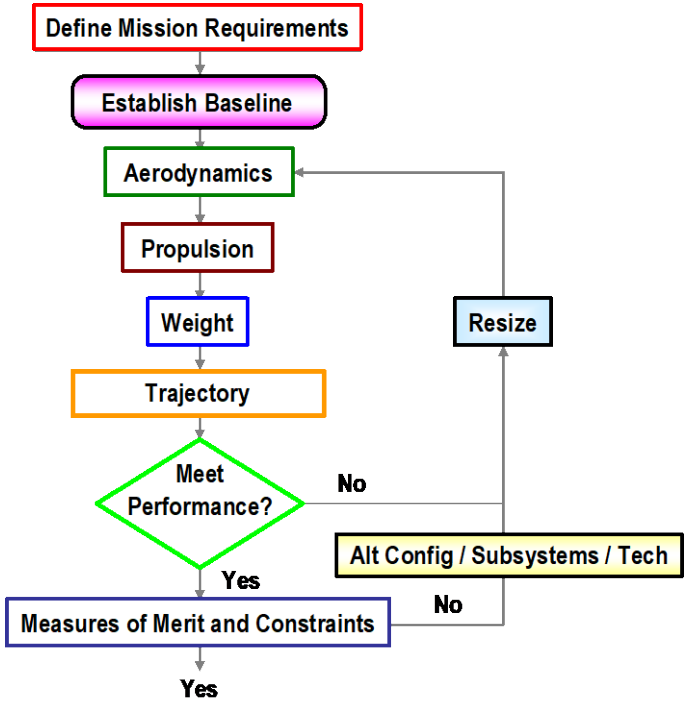
Seth Spears
Lone Star Analysis
2022 SciTech Forum, January 3-7

Agenda

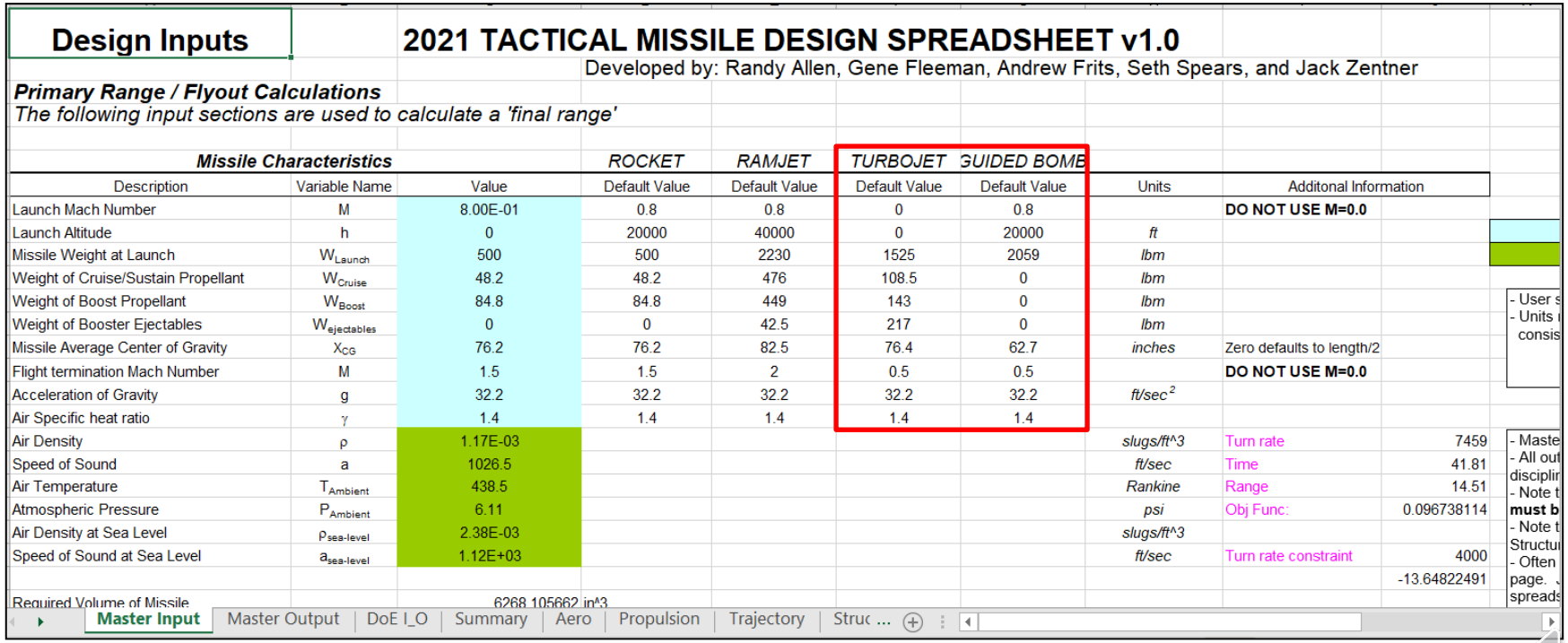
- Introduction
- Tactical Missile Design Spreadsheet
- Updates and New Baselines
- Use Case Example
- Verification and Validation

Introduction

- TMD spreadsheet follows the same process as this proven conceptual design flowchart
- Desired range, Mach number, and maneuverability determine the baseline
- Expedites design convergence



Tactical Missile Design Spreedsheet



Design Inputs

2021 TACTICAL MISSILE DESIGN SPREADSHEET v1.0

Developed by: Randy Allen, Gene Fleeman, Andrew Frits, Seth Spears, and Jack Zentner

Primary Range / Flyout Calculations

The following input sections are used to calculate a 'final range'

Missile Characteristics			*ROCKET*	*RAMJET*	*TURBOJET*	*GUIDED BOMB*			
Description	Variable Name	Value	Default Value	Default Value	Default Value	Default Value	Units	Additonal Information	
Launch Mach Number	M	8.00E-01	0.8	0.8	0	0.8		**DO NOT USE M=0.0**	
Launch Altitude	h	0	20000	40000	0	20000	*ft*		
Missile Weight at Launch	W_{Launch}	500	500	2230	1525	2059	*lbm*		
Weight of Cruise/Sustain Propellant	W_{Cruise}	48.2	48.2	476	108.5	0	*lbm*		
Weight of Boost Propellant	W_{Boost}	84.8	84.8	449	143	0	*lbm*		
Weight of Booster Ejectables	$W_{ejectables}$	0	0	42.5	217	0	*lbm*		
Missile Average Center of Gravity	X_{CG}	76.2	76.2	82.5	76.4	62.7	*inches*	Zero defaults to length/2	
Flight termination Mach Number	M	1.5	1.5	2	0.5	0.5		**DO NOT USE M=0.0**	
Acceleration of Gravity	g	32.2	32.2	32.2	32.2	32.2	ft/sec^2		
Air Specific heat ratio	γ	1.4	1.4	1.4	1.4	1.4			
Air Density	ρ	1.17E-03					*slugs/ft^3*	Turn rate	7459
Speed of Sound	a	1026.5					*ft/sec*	Time	41.81
Air Temperature	$T_{Ambient}$	438.5					*Rankine*	Range	14.51
Atmospheric Pressure	$P_{Ambient}$	6.11					*psi*	Obj Func:	0.096738114
Air Density at Sea Level	$\rho_{sea-level}$	2.38E-03					*slugs/ft^3*		
Speed of Sound at Sea Level	$a_{sea-level}$	1.12E+03					*ft/sec*	Turn rate constraint	4000
									-13.64822491
Required Volume of Missile		6268.105662 in^3							

Master Input | Master Output | DoE I_O | Summary | Aero | Propulsion | Trajectory | Struc ...

Tactical Missile Design Spreedsheet

Aerodynamics

	INPUTS			
	Description	Variable	Value	Units
	Missile Body Input			
	Nose Length	aero_len_nose	11.60	*inches*
	Missile Length	aero_length	182.70	*inches*
	Missile Major Dia (2a)	aero_2a	13.50	*inches*
	Missile Minor Dia (2b)	aero_2b	13.50	*inches*
	Nose Bluntness	aero_nose_blunt	0%	
	Missile Center of Gravity	aero_cg	76.4	*inches*
	Nozzle Exit Area	aero_exit_area	37.22	*inches*^{2}
	Air Density	aero_density	1.17E-03	*slugs/ft*^{3}
	Speed of Sound	aero_vsound	1026.5	*ft/sec*
	gamma	aero_gamma	1.40	
	Missile Wing Input			
	Number of Wings (0,1,2)	aero_num_wings	2	
	Wing Incident Angle	aero_wing_angle	0	*deg*
	Wing Planform Area	aero_wing_area	498.24	*inches*^{2}
	Thickness-to-Chord, max	aero_t_over_c	6.0%	
	Wing LE Thickness Angle	aero_le_thick_angle	45	*deg*
	Wing Aspect Ratio	aero_aspect_ratio	1.02	
	Station of Wing leading edge	aero_wing_le	73.1	*inches*
	Wing taper ratio	aero_wing_taper	0.512	
	Missile Tail Input			
	Number of Tail Wings (0,1,2)	aero_tail_wings	2	
	Tail Aspect Ratio	aero_tail_aspect	2.56	
	Tail Taper Ratio	aero_tail_taper	0.52	
	Station of Tail LE	aero_tail_le	134	*inches*
	Tail Thickness-to-Chord, max	aero_tail_t_over_c	0.09	
	Tail LE Thickness Angle	aero_tail_le_angle	45	*deg*
	AOA for Tail Sizing	aero_tsize_aoa	0	*deg*
	Description	Variable	Value	Units
	Flight Condition Input			

	OUTPUTS			
	Description	Variable	Value	Units
	Body Geometry Parameters			
	Nose Fineness Ratio	aero_fn	0.859259	
	Body Fineness Ratio	aero_fbody	13.5	
	Reference Area	aero_ref_area	143.139	*inches*^{2}
	Nose Hemispherical Dia.	aero_hemi_dia	0	*inches*
	Hemi Nose Ref Area	aero_hemi_ref	0.000	*inches*^{2}
	Semimajor Axis	aero_a	6.75	*inches*
	Semiminor Axis	aero_b	6.75	*inches*
	Missile Diameter	aero_ref_dia	13.5	*inches*
	Wing Geometry Paramaters			
	Wing Incident Angle (rad)	aero_wing_inc_rad	0.00	*rad*
8	Wing Semi-span (b/2)	aero_wing_span	11.25	*inches*
8	Wing Root Chord	aero_wing_root	29.30	*inches*
8	Wing Tip Chord	aero_wing_tip	15.00	*inches*
8	Wing Sweep	aero_wing_sweep	0.79	*rad*
	Wing Mean Aero Chord	aero_mean_chord	22.92	*inches*
	Wing Outboard (Y) Cp (from root)	aero_wing_y_cp	5.02	*inches*
	Station of Wing MAC LE	aero_wing_mac_le	79.48	*inches*
	Tail Geometry Parameters			
8	Tail Semi-Span (b/2)	aero_tail_span	11.25	*inches*
8	Tail Root Chord	aero_tail_root	11.60	*inches*
8	Tail Tip Chord	aero_tail_tip	6.00	*inches*
8	Tail Sweep	aero_tail_sweep	0.59	*rad*
	Tail Mean Aerodynamic Chord	aero_tail_mac	9.11	*inches*
	Tail Aerodynamic Center			
	(from tail MAC leading edge)	aero_tail_ac_le	2.28	*inches*
	(from nose)	aero_tail_ac_nose	140.70	*inches*
8	Tail Area	aero_tail_area	198.00	*inches*^{2}
	Tail Outboard (Y) Cp (from root)	aero_tail_y_cp	5.03	*inches*

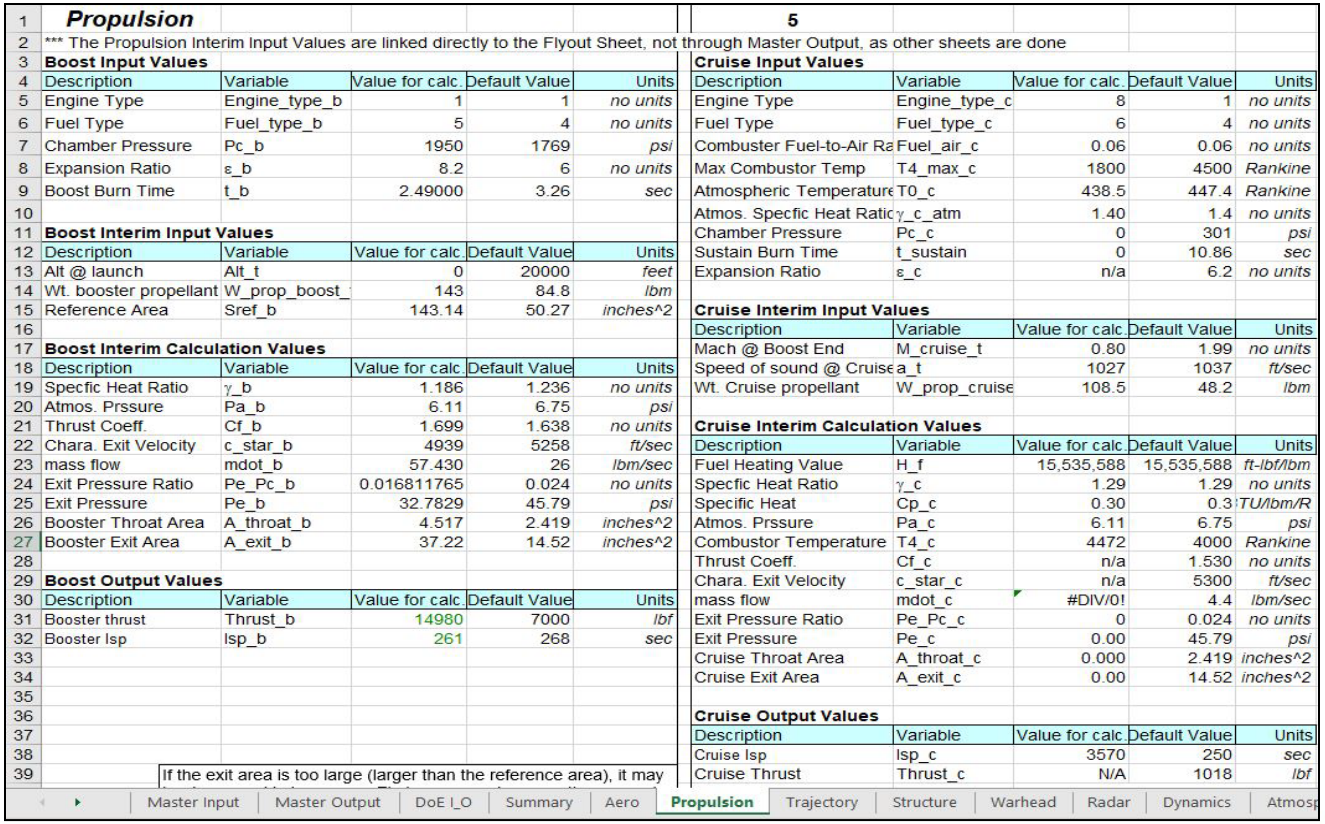
Note that the Tail is iteratively sized. It is sized to provide zero static margin at the "Tail Sizing Mach number", with the given geometry and leading edge position.

If the Baseline wing/tail parameters are preferred, place the number 1 in the corresponding row 13 cell, e.g., for the Turbojet,

Rocket	Ramjet	Turbojet	GB
		1	
16.1		11.25	
19.4		29.3	
3.4		15	
0.7854		0.7854	
13.3		22.92	
6.20		5.02	
60.8		78.1	
12	11.5	11.25	12.50
18.5	16.5	11.60	19.73
0	11.5	6.00	9.53
0.9948	0.6458	0.5934	0.7854
12.3	14.2	9.11	15.22
6.2	4.9	2.28	3.81
131.6	150.3	140.70	133
221.76	322.56	198	365.76
4.00	5.4	5.03	4.96

Master Input | Master Output | DoE I_O | Summary | **Aero** | Propulsion | Trajectory | Structure | Warhead | Radar | Dynamics | Atmospher ...

Tactical Missile Design Spreedsheet



Propulsion — 5

*** The Propulsion Interim Input Values are linked directly to the Flyout Sheet, not through Master Output, as other sheets are done

Boost Input Values

Description	Variable	Value for calc.	Default Value	Units
Engine Type	Engine_type_b	1	1	no units
Fuel Type	Fuel_type_b	5	4	no units
Chamber Pressure	Pc_b	1950	1769	psi
Expansion Ratio	ε_b	8.2	6	no units
Boost Burn Time	t_b	2.49000	3.26	sec

Boost Interim Input Values

Description	Variable	Value for calc.	Default Value	Units
Alt @ launch	Alt_t	0	20000	feet
Wt. booster propellant	W_prop_boost_	143	84.8	lbm
Reference Area	Sref_b	143.14	50.27	inches^2

Boost Interim Calculation Values

Description	Variable	Value for calc.	Default Value	Units
Specfic Heat Ratio	γ_b	1.186	1.236	no units
Atmos. Prssure	Pa_b	6.11	6.75	psi
Thrust Coeff.	Cf_b	1.699	1.638	no units
Chara. Exit Velocity	c_star_b	4939	5258	ft/sec
mass flow	mdot_b	57.430	26	lbm/sec
Exit Pressure Ratio	Pe_Pc_b	0.016811765	0.024	no units
Exit Pressure	Pe_b	32.7829	45.79	psi
Booster Throat Area	A_throat_b	4.517	2.419	inches^2
Booster Exit Area	A_exit_b	37.22	14.52	inches^2

Boost Output Values

Description	Variable	Value for calc.	Default Value	Units
Booster thrust	Thrust_b	14980	7000	lbf
Booster Isp	Isp_b	261	268	sec

If the exit area is too large (larger than the reference area), it may

Cruise Input Values

Description	Variable	Value for calc.	Default Value	Units
Engine Type	Engine_type_c	8	1	no units
Fuel Type	Fuel_type_c	6	4	no units
Combuster Fuel-to-Air Ra	Fuel_air_c	0.06	0.06	no units
Max Combustor Temp	T4_max_c	1800	4500	Rankine
Atmospheric Temperature	T0_c	438.5	447.4	Rankine
Atmos. Specfic Heat Ratio	γ_c_atm	1.40	1.4	no units
Chamber Pressure	Pc_c	0	301	psi
Sustain Burn Time	t_sustain	0	10.86	sec
Expansion Ratio	ε_c	n/a	6.2	no units

Cruise Interim Input Values

Description	Variable	Value for calc.	Default Value	Units
Mach @ Boost End	M_cruise_t	0.80	1.99	no units
Speed of sound @ Cruise	a_t	1027	1037	ft/sec
Wt. Cruise propellant	W_prop_cruise	108.5	48.2	lbm

Cruise Interim Calculation Values

Description	Variable	Value for calc.	Default Value	Units
Fuel Heating Value	H_f	15,535,588	15,535,588	ft-lbf/lbm
Specfic Heat Ratio	γ_c	1.29	1.29	no units
Specific Heat	Cp_c	0.30	0.3	TU/lbm/R
Atmos. Prssure	Pa_c	6.11	6.75	psi
Combustor Temperature	T4_c	4472	4000	Rankine
Thrust Coeff.	Cf_c	n/a	1.530	no units
Chara. Exit Velocity	c_star_c	n/a	5300	ft/sec
mass flow	mdot_c	#DIV/0!	4.4	lbm/sec
Exit Pressure Ratio	Pe_Pc_c	0	0.024	no units
Exit Pressure	Pe_c	0.00	45.79	psi
Cruise Throat Area	A_throat_c	0.000	2.419	inches^2
Cruise Exit Area	A_exit_c	0.00	14.52	inches^2

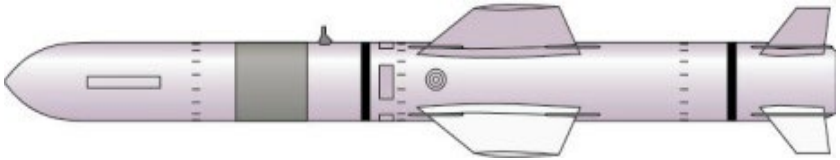
Cruise Output Values

Description	Variable	Value for calc.	Default Value	Units
Cruise Isp	Isp_c	3570	250	sec
Cruise Thrust	Thrust_c	N/A	1018	lbf

Master Input | Master Output | DoE I_O | Summary | Aero | Propulsion | Trajectory | Structure | Warhead | Radar | Dynamics | Atmosp

Updates and New Baselines

**Projectiles not to scale*



- Harpoon Missile, an all-weather, over the horizon, anti-ship missile

- MK-84 Joint Direct Attack Munition, a 2,000 lb., all-weather precision guided “smart bomb”

Updates and New Baselines

- Previously: Tail surface was iteratively sized to provide zero-static margin
  - Now: User has the option to utilize a specific tail configuration
- Previously: Detailed analysis of different flight paths were not fully incorporated
  - Now: Ballistic, loft, coast & glide trajectories
- Previously: A discrete atmospheric lookup table was required
  - Now: A linear interpolation of atmospheric conditions exists

Use Case Example

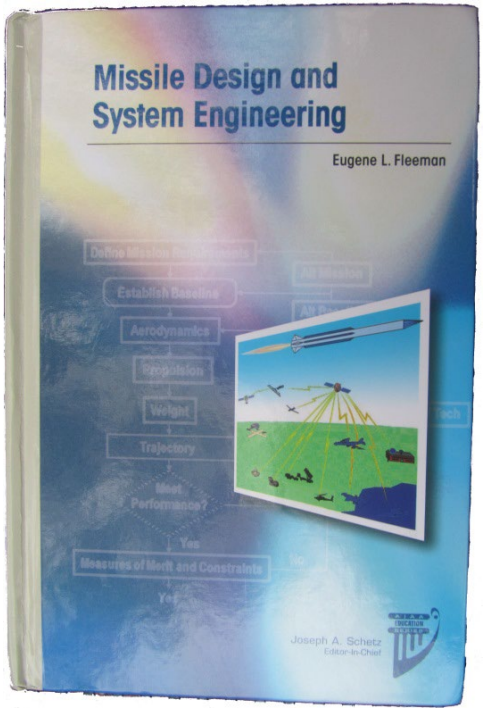
GBU-39

M982 Excalibur

- Attaching deployable wings (GBU-39) to an SDB (M982 Excalibur)
- Determine apogee of flight then maximum lift-to-drag ratio, using optimization, to then calculate glide range
- Result: an estimated range of 60.5 km (37.6 mi)

Verification and Validation

- Dissected every physics-based equation driving the TMD spreadsheet
- Developed an independent model from proprietary software
- Consulted with missile design expert, Eugene Fleeman



AMERICAN INSTITUTE OF
AERONAUTICS AND ASTRONAUTICS