RANGE OPTIMIZATION USING TRAJECTORY SHAPING ANALYSIS OF A SURFACE-LAUNCHED ROCKET

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ABSTRACT

This paper is outlined the design and flight performance of an advanced Surface-Launched Rocket. Brief descriptions of the technologies in the rocket design, parameters driving the rocket design & performance, the rocket performance prediction and examples of maximizing flight performance are presented. The structure of the written conceptual sizing computer code for the rocket design and optimizing the baseline configuration geometry, weight, and balance is described using a flowchart. Some examples in the rocket technology state-of-art advancement including maneuverability, supersonic air breathing and enhance tactical rocket performance are given.

The initial furnished properties of the project were one launch system and one target. Conceptual design modeling vs preliminary design modeling is briefly discussed for a rocket configuration and it follows by the configuration sizing criteria for maximizing flight performance. In this design theory, the range calculation using Breguét method is discussed in depth

Among the major outcomes of the rocket design theory and the flight performance analysis used for a reference rocket with certain specifications are wing skin friction drag is more important than shock wave drag for a thin wing of the rocket, high specific impulse provides higher thrust and reduces fuel consumption, flight trajectory shaping modifies extended range, and flight envelope should have large max range, small min range, and large off boresight.

INTRODUCTION

The primary purpose of the paper is to distill the technical knowledge into an integrated approach for a step-by-step rocket design. Initially, the objective of the project was 'Hands-on-Learning' of the design and flight mechanics of a specific rocket based on *Design-Build-Fly* concept.

This design method generally uses simple closed-form analytical expressions that are physics-based, to provide insight into the primary drivers. Closed-form analytical expressions are used in lieu of computers - a throwback to the way rocket design was conducted over thirty years ago. The paper also provides example calculations of rocket-powered and ramjet-powered baseline rockets, typical values of rocket parameters, examples of the characteristics of current operational rockets, discussion of the enabling subsystems and technologies of tactical rockets, and the current/projected state-of-the-art of tactical rockets.

The cruise range is driven by L/D, I_{SP}, velocity and propellant or fuel weight fraction, drag, static margin, thrust, and zero-lift drag coefficient. The theory starts with the initial requirements and specifications of the rocket and the step-by-step design procedure mainly covers the design body and tails for maximum flight range, and for accurate and stable flight; calculation of aerodynamic drag coefficient; calculation of thrust and thrust duration; measurement of weight (± 1% accuracy); prediction of flight range and altitude for proscribed; proscribed target location, launch location, launch pressure, and launch angle; discussion reasons for performance of alternative concepts; initial sizing and flight performance analysis; aerodynamics parameters estimation; propulsion parameters estimation; flight performance parameters' estimation; and integrating flight performance envelope. Some examples of the current operational tactical rockets are:

- Loading rockets on rail and ejection launchers and rocket carriage on launch platforms
- Pilot actions prior to launching rockets
- Store separation trajectories (safe as well as unsafe)
- Flight trajectories, intercepts and detonations of warheads for air and surface targets
- Plume observable of high smoke, reduced smoke, and minimum smoke motors
- Rocket countermeasures and counter-countermeasures
- Development facilities, development testing, and manufacturing processes.

In recent years, the increased usage of tactical rocket systems has been seen for military operations. Moreover, tactical rockets are expected to have an even larger share of military operations in the future. A key contributor to the increased effectiveness is the advancement in technology. Examples of advancement in rocket system effectiveness include improved range, firepower, maneuverability, accuracy, lethality, and adverse weather capability. A historical example of the value of guided weapons is Thanh Hoa Bridge in Vietnam. For over six years, a total of 871 aircraft sorties dropped unguided bombs but failed to close the bridge. However, the first operational application of laser-guided bombs on 13 May 1972 resulted in direct hits on the supporting piers, dropping the center span and closing the bridge. It is noted that eleven aircraft were lost using unguided munitions in the 871 previous sorties. No aircraft were lost in the four sorties using precision-guided munitions.

The complexity of the design equations and the number of parameters involved make it difficult to appreciate how a change to the specification of a rocket alters the final design. The analysis in this paper gives readers an insight into the interaction between the many important parameters in the rocket design. Due to limited length for the paper, the authors have to eliminate nearly all equations and the step-by-step mathematical procedure to be able to keep the paper within the allowed number of pages.

DEFINITIONS

The followings are the major parameters that initially drive rocket design and its flight performance. These are the aerodynamic configuration sizing parameters emphasized in this paper.

- Stabilizer geometry/size
- Flight control geometry/size
- Length
- Thrust profile
- Flight conditions (α, M, h)
- Nose fineness
- Diameter
- Propellant/fuel type and weight
- Wing geometry/size

Flight condition parameters that are most important in the design of tactical rockets are angle of attack (α), Mach number (M), and altitude (h). For the aerodynamic configuration, the rocket diameter and length have a first order effect on characteristics such as rocket drag, subsystem packaging available volume, launch platform integration, seeker and warhead effectiveness, and body bending. Another configuration driver is nose fineness, an important contributor to rocket drag for supersonic rockets. Also, nose fineness affects seeker performance, available propellant length, and rocket observables. Another example is rocket propellant/fuel type and weight, which drive flight performance range and velocity. The aerodynamic configuration wing geometry and size are often set by maneuverability requirements and aerodynamic efficiency. Stabilizer geometry and size are often established by static margin requirements. In the flight control area, the geometry and size of the flight control surfaces determine the maximum achievable angle of attack and the resulting maneuverability. Finally, the thrust profile determines the rocket velocity time history.

CRUISE RANGE EQUATION

The cruise range is driven by L/D, I_{sp}, velocity and propellant or fuel weight fraction. As a good estimation for a conceptual design, it is calculated from the Breguét Range Equation.

$$R = (L/D) \cdot I_{SP} \cdot V \cdot ln[W_L/(W_L - W_P)] \quad \textbf{(Eq. 1)}$$

where,

W_L = launch weight
W_P = propellant weight
R = cruise range
L/D = lift-to-drag ratio
I_{SP} = specific impulse

Based on an examination of the Breguét range equation, new technology development has payoff in the areas of higher cruise velocity, aerodynamic efficiency (lift/drag), specific impulse, lightweight structure, lightweight/low volume subsystems, and higher density fuel/propellant.

Table 1 compares four propulsion alternatives for a long range precision strike rocket. The propulsion alternatives are subsonic cruise turbojet, supersonic cruise liquid hydrocarbon fuel ramjet, hypersonic cruise liquid hydrocarbon fuel scramjet, and supersonic cruise solid propellant rocket. All four

propulsion types are held to a rocket launch weight of 2,000 pounds, a representative weight limit for carriage on a small fighter aircraft such as the F-18C.

Table 1 - Typical Values for Precision Strike Rocket

Parameter	Total Rocket Weight of 2,000 lb			
	Subsonic Turbojet Rocket	Liquid Fuel Ramjet Rocket	Hydrocarbon Fuel Scramjet Rocket	Solid Rocket
L / D, Lift / Drag	10	5	3	5
Specific Impulse (I_{SP})	3,000 sec	1,300 sec	1,000 sec	250 sec
Average Velocity (V_{AVG})	1,000 ft / sec	3,500 ft / sec	6,000 ft / sec	3,000 ft / sec
Cruise Propellant or Fuel Weight / Launch Weight (W_P/W_L)	0.3	0.2	0.1	0.4
Cruise Range (R)	1,800 nm	830 nm	310 nm	250 nm

As it can be seen from the table, ramjet and scramjet rockets booster propellant for Machs 2.5 to 4 take over speed not included in W_P for cruise. Rockets require thrust magnitude control (e.g., pintle, pulse, or gel motor) for effective cruise. The maximum range for a rocket is usually attained by semi-ballistic flight profile, instead of cruise flight. It can be also noticed from the table that the subsonic cruise turbojet propulsion is the preferred approach for long-range strike against targets that are not time-critical. Subsonic cruise turbojet propulsion has 120 percent greater range than the next best alternative, a supersonic cruise liquid fuel ramjet (1,800 nautical miles versus 830 nautical miles).

An examination of the Breguét range equation explains the difference in performance. The subsonic cruise turbojet rocket is superior to the supersonic cruise ramjet rocket in the maximum lift-to-drag ratio (L/D = 10 versus 5), specific impulse (I_{SP} = 3,000 seconds versus 1,300 seconds), and available fuel for a rocket launch weight limited to 2,000 pounds (600 pounds of fuel versus 400 pounds of fuel).

The ramjet rocket has less available weight for fuel because it requires a rocket to boost the rocket up to about Mach 2.5 for transition to ramjet propulsion. However, a ramjet rocket has an advantage of a shorter response time against time critical targets. It may also have an advantage in survivability due to the higher flight altitude and higher speed. If time critical targets are of utmost importance, scramjet propulsion may be preferred. As shown in the figure the scramjet rocket example is 70 percent faster than the ramjet (6,000 feet per second versus 3,500 feet per second).

However, the maximum range of a scramjet rocket that is limited to 2,000 pounds launch weight is only 37 percent that of a liquid fuel ramjet (310 nautical miles versus 830 nautical miles). Again, it is instructive to examine the Breguét range equation. The liquid fuel ramjet rocket is superior to the scramjet in the aerodynamic efficiency (L/D = 5 versus 3), specific impulse (I_{SP} = 1,300 seconds versus 1,000 seconds), and available fuel for a rocket limited to 2,000 pounds launch weight (400 pounds of fuel versus 200 pounds of fuel).
The scramjet rocket has less available weight for fuel because it requires a larger rocket booster for a higher takeover Mach number (Mach 4 versus 2.5), requires a longer combustor for efficient combustion, and requires more insulation. Finally, the supersonic cruise rocket has a maximum flight range of 250 nautical miles. The most efficient cruise condition for the long range rocket was found to be Mach 3 cruise at high altitude. The solid propellant rocket example uses thrust magnitude control from a pintle motor, for more efficient acceleration and cruise. Although it is not shown, a semi-ballistic flight

trajectory (e.g., launch, pitch-up, ballistic climb, glide) would have provided a more efficient flight trajectory for the rocket.

DESIGN SENSITIVITY METHOD

A flight performance sensitivity study was conducted of the rocket baseline configuration to determine the most significant parameters and the required accuracy for prediction methods. General information about design sensitivity studies and the available linear incremental methods for aerospace vehicle design are given by Saeedipour & Stevenson (1998) and Stevenson & Saeedipour (1996). Based on the incremental sensitivity method, it can be concluded that the flight range is most sensitive to specific impulse, propellant weight, zero-lift drag coefficient, drag-due-to-lift, and static margin (see Fig. 1 & 2).

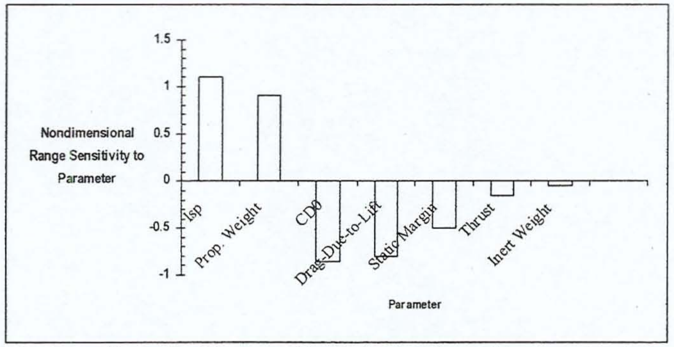

Figure 1. Rocket baseline configuration range driven by I_{SP}, propellant weight, drag and static margin

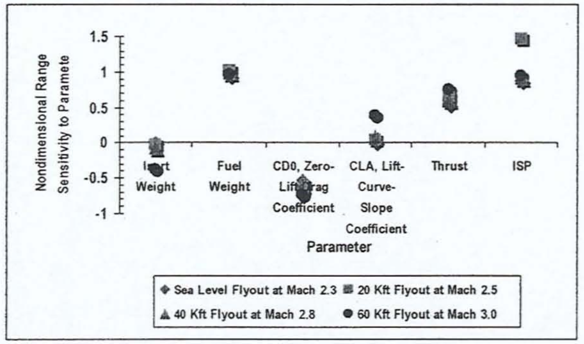

Figure 2. Ramjet-baseline range driven by I_{SP}, fuel weight, thrust, and zero-lift drag coefficient

A sensitivity study was conducted to define the ramjet baseline most significant parameters for flight range and the required accuracy for prediction methods. Note from the figure that flight range is most

sensitive to the ramjet specific impulse, fuel weight, zero-lift drag coefficient, and the ramjet thrust. The flight range is relatively insensitive to inert weight and lift curve slope, especially for low altitude flight (high dynamic pressure).

The prediction methods for ramjet specific impulse, zero-lift drag coefficient, and ramjet thrust usually have sufficient accuracy (e.g., +/- 5%, 1 σ) for conceptual design. However, there is often large uncertainty in predicting the subsystem packaging volume available to package the fuel, providing uncertainty in the fuel weight. Inboard profile drawings are required to reduce the uncertainty.

FLIGHT TRAJECTORY AND PERFORMANCE ENVELOPE

Figure 3 illustrates the extended range advantage of rockets that use flight trajectory shaping. Flight trajectory shaping is particularly beneficial for high performance supersonic rockets, which have large propellant or fuel weight fraction. To take advantage of flight trajectory shaping, the rocket must rapidly pitch up and climb to an efficient cruise altitude. During the climb, the rocket angle-of-attack should be small, to minimize drag. The rocket initial thrust-to-weight ratio should be high ($\approx$ 10) for safe separation, followed by a relatively low thrust-to-weight ratio ($\approx$ 2) during the climb. A thrust-to-weight ratio greater than about two results in a high dynamic pressure, increasing drag. After reaching higher altitude, the rocket benefits from cruising at an improved lift-to-drag ratio, such as $(L/D)_{Max}$. Dynamic pressure for efficient cruise of a high performance supersonic rocket is of the order of 500 to 1,000 pounds per square foot. Following burnout, the rocket can have extended range through glide at a dynamic pressure of about 700 pounds per square foot, providing an aerodynamic efficiency approximately equal to $(L/D)_{Max}$.

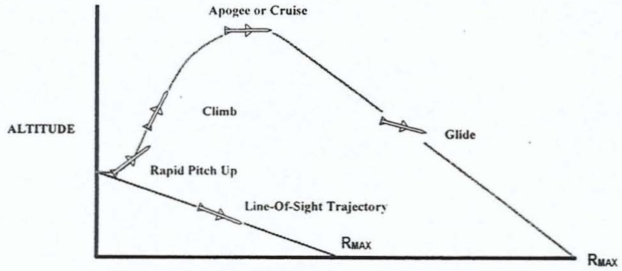

Figure 3. Flight trajectory shaping provides extended range

Based on the figure, design guidelines for horizontal launch are:

- High thrust-to-weight $\approx$ 10 for safe separation
- Rapid pitch up minimizes time / propellant to reach efficient altitude
- Climb at a $\approx$ 0 deg with thrust-to-weight $\approx$ 2 and q $\approx$ 700 psf minimizes drag / propellant to reach efficient cruise altitude for $(L / D)_{MAX}$
- High altitude cruise at $(L / D)_{MAX}$ and q $\approx$ 700 psf maximizes range
- Glide from high altitude at $(L / D)_{MAX}$ and q $\approx$ 700 psf provides extended range

The rocket flight envelope may be characterized by the maximum and the minimum flight ranges in forward and off boresight flight. In the example shown in the figure, the rocket has a large off boresight capability, up to +/- 180 degrees off boresight. Illustrated in the figure are the maximum and minimum ranges for straight-ahead flight, beam flight, and flight to the rear of the launch aircraft. It is noted that a supersonic rocket at 1 g flight and at low altitude flies near zero angle of attack. The maximum range for a supersonic rocket in straight-ahead flight is often driven by the zero-lift drag coefficient. The maximum range may be established by the speed and maneuverability required for an intercept. It was shown previously that higher rocket speed and higher maneuverability are required against a maneuvering target. This affects the maximum effective range for low miss distance. The maximum effective range against a maneuvering target is less than the maximum range against a non-maneuvering target. Also, the maximum effective range is a function of the intercept altitude.

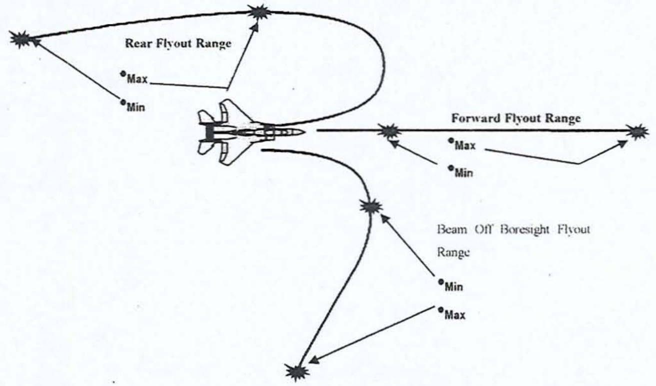

Figure 4. Flight performance envelope

A boost-coast rocket has less velocity and available maneuverability in a high altitude intercept than in a low altitude intercept. Other constraints on the maximum range include the fire control system maximum range and rocket time of flight limits (e.g., battery duration). The minimum range may be established by the maneuverability required to correct an initial heading error. For a beam flight (to the side of the launch platform), the rocket must operate at high angle of attack to rapidly turn the velocity vector to 90 degrees off boresight. The time to arm the warhead, based on establishing a safe standoff from the launch platform may also set the minimum range. Finally, the seeker gimble limit may set the minimum range in off boresght maneuvers. The maximum/minimum range for a beam intercept may be driven by a combination of parameters such as the seeker gimbal limit, maneuverability, stability, and the drag due to lift. For flight to the rear of the launch platform, the rocket must make a heading change of 180 degrees. The drivers for a rear intercept may be a combination of parameters such as zero-lift drag and the drag due to lift (see Figure 4).

ROCKET BASELINE CONFIGURATION

A configuration drawing of the rocket baseline configuration, which is similar to the Sparrow rocket, is shown in Figure 5 from Bithell & Stoner (1982). The rocket baseline is a radar-guided rocket. It has a design flight range of about 7 nautical miles when launched at an altitude of 20,000 feet. The rocket uses cruciform wings as control surfaces. Fixed cruciform tail surfaces provide static stability. Rocket launch weight is 500 pounds, including 133 pounds of propellant. The rocket motor has a boost-sustain thrust profile with 29,8000 lb-sec total impulse. The motor grain configuration is an internal burner type with

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three radial slots and aft end longitudinal slots. The nozzle has a 1.81 square inch throat area, and provides an expansion ratio of 6.2

Note from the Figure 5 that the diameter d = 8 inches, total wing span b_w = 40.2 inches, and length l = 143.9 inches. Shown are the length of the rocket motor and the section lengths/bulkhead locations. The rocket is divided into the nose, forebody, payload bay, midbody, aftbody, and the tailcone sections of the rocket. The wing geometry in the figure includes the wingspan, sweep angle, location of the mean aerodynamic chord, length of the root chord and its location, and the length of the tip chord. The tail geometry shown in the figure includes the tail span, sweep angle, location of the mean aerodynamic chord, length of the root chord and the location of the root chord.

- Body Fineness Ratio — $5 < l / d < 25$
- Nose Fineness Ratio — $l_N / d \approx 2$ if $M > 1$
- Efficient Cruise Dynamic Pressure — $q < 700$ psf
- Rocket Homing Velocity — $V_M / V_T > 1.5$
- Subsystems Packaging; Maximize available volume for fuel / propellant
- Trim Control Power — $\alpha / \delta > 1$
- Rocket Maneuverability — $n_M / n_T > 3$

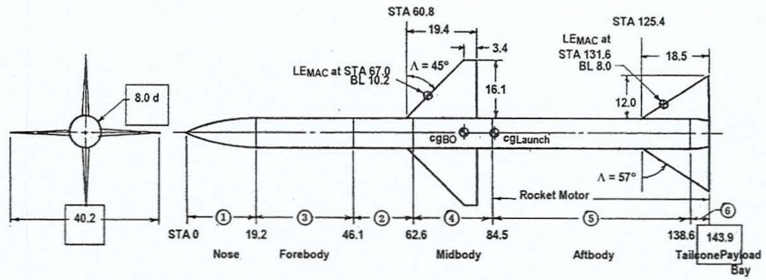

Figure 5. Rocket baseline configuration similar to the Sparrow rocket (dimensions in inches)

(Source: Bithell, R.A. and Stoner, R.C., "Rapid Approach for Rocket Synthesis, Vol. 1, Rocket Synthesis Handbook," AFWAL-TR-81-3022, Vol. 1, March 1982).

MAXIMUM FLIGHT RANGE OF BASELINE ROCKET

The rocket baseline configuration flight range is shown in the figure as a function of time. The launch conditions are Mach 0.8, 20K feet altitude. Note that the flight range at a time of flight t_f = 24.4 seconds exceeds the requirement by 15 percent (7.7 nautical miles versus 6.7 nautical miles). The rocket baseline achieves the required flight range of 6.7 nautical miles at a time that is 14 percent shorter than the required time-of-flight (21 seconds versus 24.4 seconds).

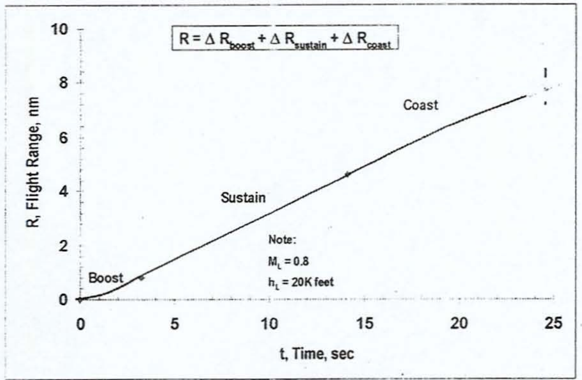

Figure 6. Flight range of baseline rocket

The total flight range is the sum of the incremental flight range during boost, the incremental range during sustain, and the incremental range during coast. The incremental range during boost is a function of the propellant weight; launch weight; specific impulse; thrust; average drag; launch velocity; and the boost time. The equation for the incremental range during boost is:

$$\Delta R_{boost} = (V_L + \Delta V/2)t_B = \{V_L + [-g_C I_{SP}(1 - D_{AVG}/T)\ln(1 - W_P/W_L)]/2\}(t_B) \qquad \text{(Eq. 2)}$$

where,

ΔR_{boost} = incremental range during boost
V_L = launch velocity
t_B = boost time
D_{AVG} = average drag
T = thrust

The incremental range during sustain is a function of the propellant weight (W_P), rocket weight at the begin of sustain, specific impulse, thrust, average drag, velocity at the begin of sustain, and the sustain burn time. The equation for the incremental velocity during sustain is:

$$\Delta R_{sustain} = (V_{BS} + \Delta V/2)t_s = \{V_{BS} + [-g_c I_{SP}(1 - D_{AVG}/T)\ln(1 - W_P/W_{BS})]/2\}(t_S) \qquad \text{(Eq. 3)}$$

where,

$\Delta R_{sustain}$ = incremental range during sustain
V_{BS} = velocity at the begin of sustain
t_S = sustain burn time
W_{BS} = rocket weight at the begin of sustain

The incremental range during coast is a function of the begin-of-coast velocity, burnout weight, atmospheric density, reference area, zero-lift drag coefficient, and the coast time. The equation for the incremental range during coast is:

$$\Delta R_{coast} = [2W/(g_c \rho S_{ref} C_{DO})]\ln\{1 + t_c/[2W\ (g_c \rho S_{ref} C_{DO} V_{BC})]\} \qquad \text{(Eq. 4)}$$

where,

ΔR_{coast} = incremental range during coast
V_{BC} = begin-of-coast velocity
W_{BO} = burnout weight
ρ = atmospheric density
S_{ref} = reference area
C_{D0} = zero-lift drag coefficient
t_C = coast time

CONCLUSION

The purpose of this paper has been to describe a simple method to originate the design effects in which the various rocket parameters interact. An iterative convergent rocket design program was used to validate the results of the method.

Flight performance consideration in tactical rocket design is oriented towards flight trajectory computation and comparison with the rocket flight performance requirements. Flight performance requirements include range, time-to-target, and off-bore sight capability. This paper presented equations of motion modeling, examples of flight performance drivers, typical flight performance for propulsion alternatives, steady state flight relationships, and proportional homing lead angle requirement. It also provided a method for predicting steady climb, steady glide, cruise, boost, coast, turn, and ballistic flight performance. Much of the impact of changes in the rocket aerodynamics, propulsion, and weight is in the area of flight performance. This design method that harmonizes the aerodynamics, propulsion, and weight while also satisfying the flight performance requirements is a primary activity in rocket configuration detailed design.

If practical, the rocket should have a long maximum range, a small minimum range, and a large off bore sight capability. This provides robustness for long range, short range, and off bore sight targets. It can be concluded that flight envelope should have large max range, small min range, and large off bore sight.

It is very easy to criticize the approximations made in this paper but it is hoped that it will form a basis for further discussion and development in rocket design methodologies.

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