

Missile Concept Optimization for Ballistic Missile Defense

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A fundamental trade in the development of a Ballistic Missile Defense interceptor missile concept is the quality of the engagement support system that provides threat state estimates versus the interceptor kinematic and terminal guidance capabilities. This article describes a methodology to optimally balance the conflicts among system performance goals, engagement support capabilities, and missile technology constraints. A key factor is the ability of the missile and the final-stage “kill vehicle” to remove the system errors caused by engagement support threat tracking and interceptor fly-out errors. The kill vehicle divert maneuver and guidance capabilities must be sized to remove system errors and accomplish intercept, but this need conflicts with the objective to maximize the missile kinematic capability to reach potential threat trajectories. An optimized missile configuration minimizes the time from launch to intercept while ensuring the seeker and divert maneuver capabilities needed to remove system errors. The methodology described here provides a unified high-fidelity approach to missile concept development.

INTRODUCTION

Air and missile defense weapon system designs are typically based on an architecture that integrates an acquisition and tracking sensor used for fire control, a battle management command and control system, and guided missiles. Figure 1 illustrates the major engagement components and events that may comprise a Ballistic Missile Defense (BMD) engagement. The

detection and tracking of a threat missile may involve several sensors, which could be space, land, and/or sea based. Remote sensor data may be received, processed, and transmitted to a launch platform via a battle management, command, control, and communications (BMC3) node. Upon determination of an engagement solution, the defending missile is launched and guided

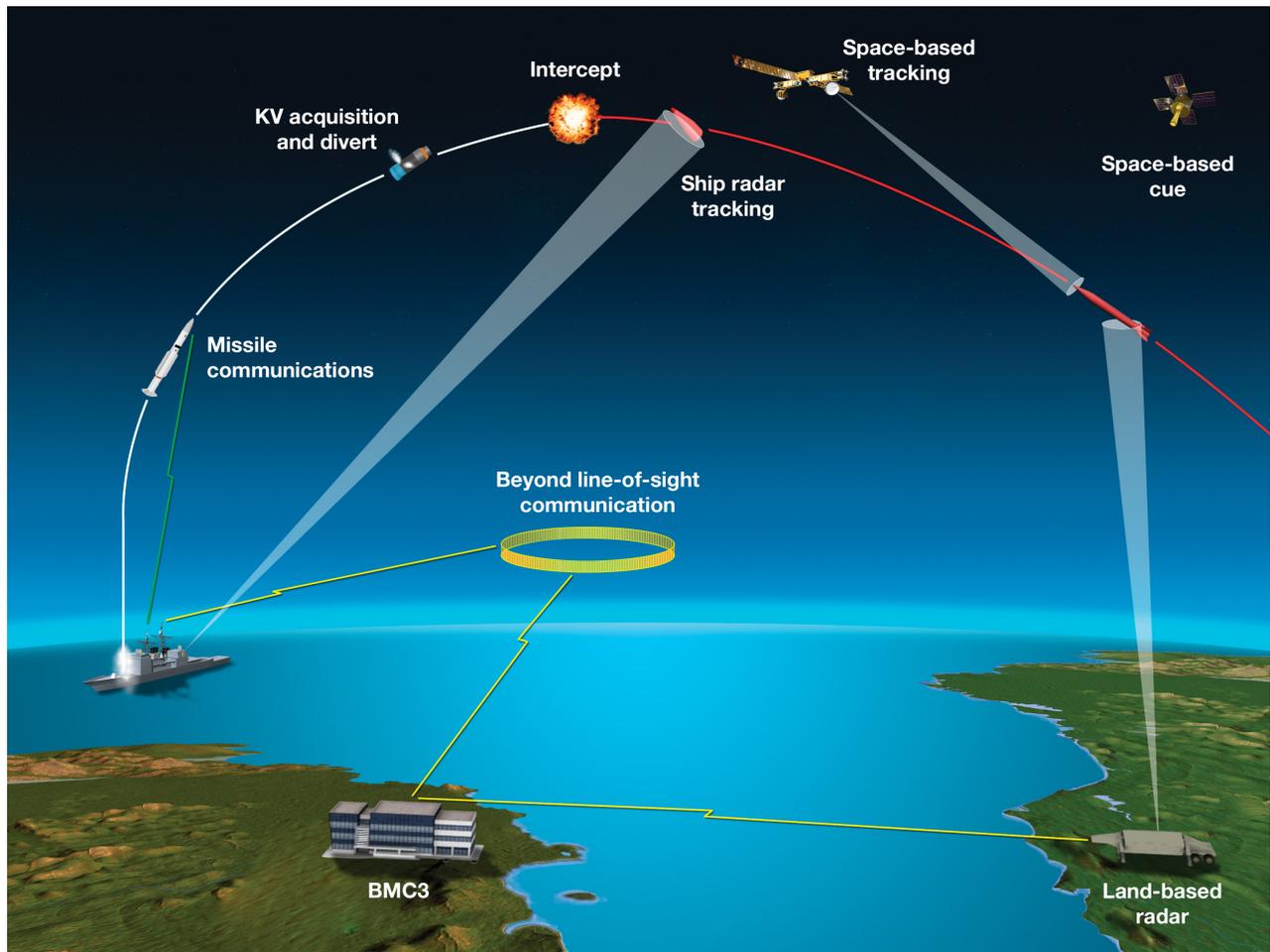


Figure 1. Notional BMD engagement.

on an intercept path until a kill vehicle (KV) is released for the final phase of the mission. The seeker on the KV acquires the threat lethal object and establishes a track for guidance. The KV's divert system removes the trajectory errors that remain after the earlier portions of flight and responds to guidance commands derived from seeker measurements. For exoatmospheric intercepts, the onboard sensor is typically an IR seeker, whereas a RF seeker is often used for endoatmospheric intercepts.

The development of a new weapon system concept typically involves a series of trades that derive fire control sensor, BMC3, and missile key performance parameters. These performance parameters characterize, for example, the detection range and track accuracy of the fire control sensor, communications time delay, the time of flight of the missile, and the ability of the missile terminal guidance to remove system errors. Depending on the particular weapon system needs, the tradable parameters may include all aspects of the fire control sensor, BMC3, and missile. In some cases, only missile parameters may be tradable as constrained by an existing launch system. In all cases, the starting point is the definition of a mission, the threat characteristics, oper-

ating constraints such as potential missile launch locations, and the portions of the system that must remain unchanged because of programmatic decisions.

Given a definition of the system context, the system engineering challenge is to appropriately balance the choice of key performance parameters with technology constraints, technical risk, program schedule, and cost. In addition, a system architecture that includes the participating components and the interfaces must be defined. The combination of key performance parameters and system architecture constitutes a system concept that ultimately evolves to a set of system and component requirements as more detailed analyses are conducted.

System concepts are often developed in an iterative fashion, with relatively simple performance models of system components. Depending on the operational context, measures of effectiveness are selected to ensure that the derived concept meets an operational need. For example, a common BMD measure is the defended area versus the threat launch area denied. The ship operating area or locations of land-based missile launchers are other important operational considerations. A system performance model can then be applied to determine

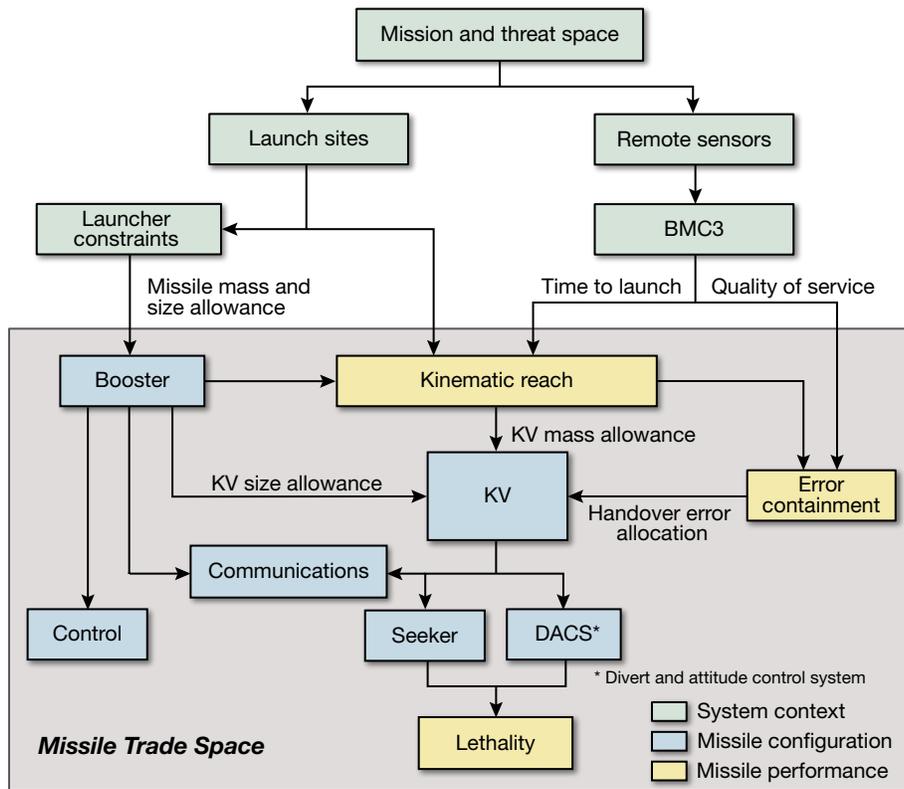


Figure 2. BMD system and missile dependencies.

the system parameters that provide the needed system performance while satisfying technology capability limits. Because of the many parameters involved, this can become a very complex and iterative process that crosses many disciplines.

This article describes an integrated multidisciplinary optimization approach that is based on a flow-down of the key component characteristics from the operational needs and constraints. The focus is on the defending missile. The other portions of the system are treated in a simpler way, but the approach covers all of the critical performance parameters across the entire system.

Figure 2 illustrates the basic dependencies for the missile concept development. The missile trade space is bounded by a system context definition including the mission, threat, launch sites, launcher constraints, sensor capabilities, and BMC3 assumptions. The major components of the missile concept are (i) the booster propulsion stack, (ii) the control systems used for each booster stage, (iii) the communications with the ground weapon control system, (iv) the KV propulsion for divert and attitude control, and (v) the KV seeker. Each of these major components is described by a set of key performance parameters, which are discussed in later sections.

Besides the five major missile components, Fig. 2 also highlights the principal performance attributes. “Kinematic reach” refers to the ability of the missile to reach a threat in time and space after launch of the threat. The

collection of possible intercept points will be referred to as the “kinematic battle space.” The kinematic capability of the missile is mostly constrained by missile mass and dimension limits defined by the launcher system. Given these constraints, the booster can be optimized to minimize time of flight to a space point as a function of staging, control options, and KV mass. In addition to the basic kinematic capability of the missile, kinematic reach is also constrained by the minimum timeline to missile launch after threat launch, which is dictated by remote sensor and BMC3 capabilities.

“Error containment” refers to the ability of the missile to remove the predicted intercept point error caused by sensor track error, system time delays, and missile guidance and navigation errors.

It also includes the missile pointing error, which must be contained by the seeker field of view (FOV) for initial acquisition of a threat object. Some of these errors can be managed by the upper stage of the booster stack, but much of the error, called handover error, must be removed by the KV. The required probability of error containment is allocated from an overall probability of single-shot kill.

The final performance attribute, “lethality,” refers to the endgame guidance accuracy of the KV to effect a lethal hit. The probability of lethal hit is also allocated from a total probability of single-shot kill.

MISSILE CONCEPT OPTIMIZATION

Paralleling the performance attributes in Fig. 2, optimization of the missile concept can be separated into three loosely coupled subproblems as shown in Fig. 3: (i) kinematic reach, (ii) error containment, and (iii) lethality. Decoupling is possible because optimization of the booster configuration to minimize flight time depends on KV mass but not the specific KV configuration. Kinematic reach is the most fundamental performance criterion because the threat trajectory must be within both the missile range and speed capabilities for the intercept to be possible. For specified missile launcher and system timeline constraints, the booster can be optimized to maximize the reach to threat trajectories for a

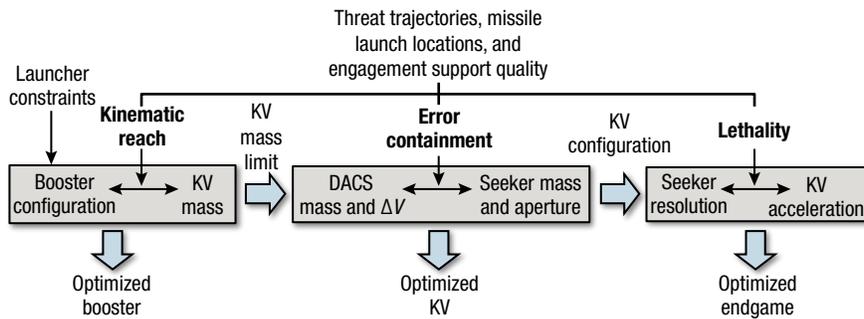


Figure 3. Key missile trade flow.

KV mass limit. Optimization of the booster configuration for a given KV mass is discussed in the next section.

Given kinematic reach, the system errors must be removed to intercept the threat. A larger KV mass degrades missile kinematic reach but allows more capable seeker and divert and attitude control system (DACs) capabilities to remove handover error. Thus, the second optimization is to minimize KV mass while still achieving error containment. This optimization mostly becomes a trade between the DACs mass and the seeker mass. DACs mass translates to KV divert maneuver performance (i.e., acceleration or velocity change, ΔV), whereas seeker mass translates to seeker acquisition range. As seeker acquisition range is increased, less divert performance is needed because more time is available to remove error.

There is some coupling between the booster and KV optimization problems. The booster and KV capabilities are both optimized when the kinematic reach and error containment are brought into balance. If error containment cannot be achieved for certain trajectories given the KV mass limit, then some kinematic reach may need to be sacrificed to bring the concept into balance. The goal is to ensure that errors are contained for all potential intercept points. Conversely, if all of the mission threat trajectories are reached with excessive containment margin, then other portions of the system design such as engagement support quality or KV mass and missile size might be relaxed.

Once a basic KV configuration is determined, endgame lethality depends on the ability to determine and steer out remaining guidance errors. This is mostly a trade between seeker resolution and acceleration capability of the KV. The result of this trade can affect the KV optimization because both the seeker resolution and KV acceleration parameter selections might influence KV mass, which may require a rebalance of the KV DACs and seeker capabilities.

KINEMATIC REACH

To establish missile kinematic performance requirements for a given mission, the first step is to develop several optimized booster concepts that span the allow-

able missile size and mass trade space given launcher constraints. For each of these booster concepts, the mass and volume of the KV is allowed to vary parametrically. Once the configurations are developed, a coverage analysis identifies the maximum KV mass that can be tolerated for each concept and still meet the threat trajectory engagement goals. This analysis will establish missile kinematic and KV mass thresholds for each missile concept. The missile kinematic threshold can be expressed in terms of a minimum booster burnout velocity (V_{bo}).

Booster Optimization

The booster concept is developed with a multidisciplinary system-level missile design optimization tool called ORION (Optimization of Rockets for Intercept OperatioNs), which was written at the Johns Hopkins University Applied Physics Laboratory (APL). ORION integrates physics-based and empirically benchmarked models of propulsion, aerodynamics, payload packaging, and vehicle kinematics for single- or multiobjective booster optimization and relies primarily on genetic algorithms to determine the optimal solution.

Modern computational resources have now enabled multidisciplinary, system-level analysis and design optimization.¹ In a multidisciplinary design optimization approach, complex system models are developed by integrating detailed models of various subsystems early in the design phase. Subsystem design parameters are then varied, with their interactions observed at the system level, leading to truly optimized system designs. ORION, a multidisciplinary design optimization tool for missile propulsion systems, provides the capability to comprehensively observe the impacts of missile subsystem interactions earlier in the design evolution than previously possible.

ORION integrates detailed models for propulsion, nosecone design and payload packaging, aerodynamics, and vehicle kinematics to facilitate system-level optimization of the missile component design parameters. Coupling of the integrated missile model to various optimization algorithms provides the capability for multi-variable, multiobjective optimization. Figure 4 illustrates the basic approach used in ORION and a three-stage missile example. The optimization variables include the length, L_g , outer diameter, D_{go} , and inner diameter, D_{gi} , of the propellant grains for each stage; the length, L_n , exit diameter, D_e , and throat diameter, D_t , of the nozzles; the length, L_{nose} , and radius, R_{nose} , of the nosecone; and the outer diameter, D_{GS} , of the guidance system. The

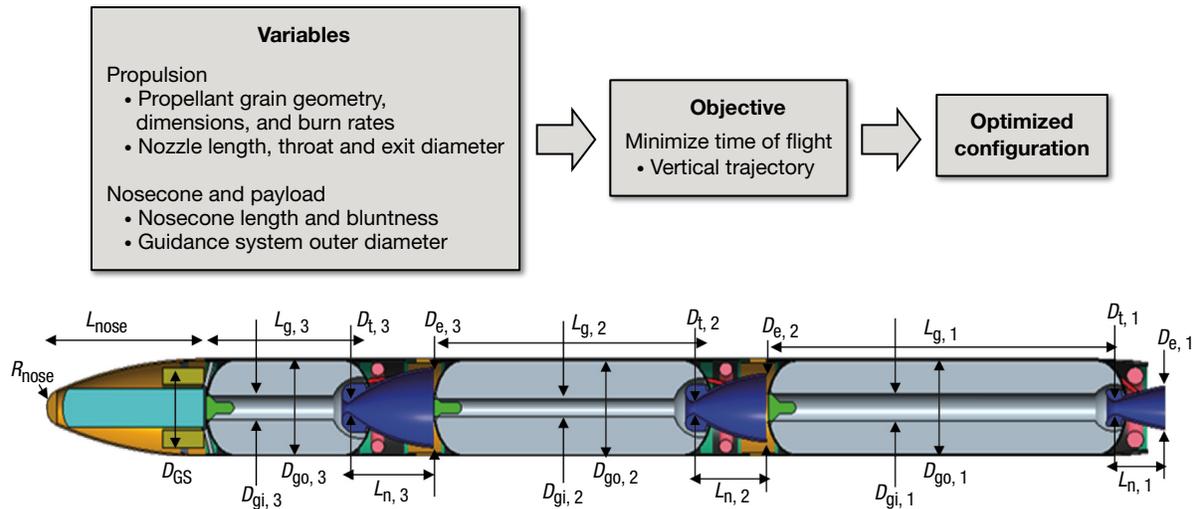


Figure 4. ORION booster optimization.

total number of design variables is 15 for a two-stage missile and 21 for a three-stage missile.

Propulsion Model

The propulsion system model uses physics-based and empirically benchmarked calculations to provide the capability for medium-fidelity stage and motor characterization. A solid rocket motor modeling and design tool developed by APL, called ARIES (Analysis of Rockets for Initial Exploratory Studies), is used for this purpose. The motor/stage model accepts an input list whose components generally fall into one of four categories: (i) propellant; (ii) nozzle assembly; (iii) case assembly; or (iv) stage assembly. The inputs consist of propellant formulation and ballistic properties, as well as certain dimensions, masses, and material properties of various components. ARIES calculates motor component dimensions and masses and, in addition, calculates motor interior ballistics, producing time traces of chamber pressure, thrust, and expelled propellant mass. ARIES primarily follows textbook principles for design calculations and performance predictions. Motor performance is calculated on the basis of a lumped-parameter ballistics code developed at APL.

Nosecone and Aerodynamics

The nosecone model in ORION allows the user to choose from five different standard nosecone shapes: conical, tangent ogive, Kármán ogive, LV-Haack, and power law. Nosecone length, base diameter, bluntness, thickness, and material density are input. ORION then solves for the outer mold line, surface area, and mass of the nosecone. Thermal analysis is performed separately to ensure the nosecone provides adequate thermal protection of the KV.

Aerodynamic calculations are performed using Missile DATCOM, an industry standard for preliminary

aerodynamic analysis. The geometry and dimensions of the nosecone and propulsion stages, as well as fins or other aerodynamic surfaces that exist in the design space, are flowed to DATCOM. DATCOM then returns sets of tables of aerodynamic coefficients (e.g., axial or normal force coefficient versus Mach number) for use in the flight model.

Optimization Algorithms

To perform optimization, ORION primarily relies on a genetic algorithm (GA), which is a non-gradient-based method capable of evaluating continuous and discontinuous systems. GAs have been shown to be successful in the single- and multiobjective design optimization of various types of aerospace systems and their components. GAs have been applied to the design of airfoil and nosecone shapes,² unmanned aerial vehicles,³ spacecraft orbital dynamics,⁴ hybrid rockets, space launch vehicles,⁵ and missiles.⁶ The GA does not use gradients to determine the direction of parameter variation for a single design point but instead evaluates a population distributed over the entire parameter space. Thus, compared with gradient-based optimization algorithms, the GA is more likely to avoid local optima and find the global optimum. However, the evaluation of so many more points leads to increased convergence times. In addition, because the process of population evolution is stochastic, the exactness of the converged solution, as well as repeatability of the algorithm execution, cannot be guaranteed. Each time the algorithm is executed, a slightly different solution could be obtained.

In addition to the GA, the pattern search algorithm (PSA), another nongradient-based optimization method, can also be used. The PSA requires a starting point and evaluates multiple nearby design points to find one where the objective function is improved compared with the current point. That point then becomes the

starting point for the next iteration, and the process is repeated until no improvement is observed. Compared with the GA, the PSA typically requires fewer function evaluations to converge to a solution, leading to faster convergence times, and the solution is sometimes more accurate. However, the PSA is sensitive to the choice of initial point and can be less likely to find global optima than the GA.

Hybrid algorithms can combine the advantages of various algorithms while avoiding some of their disadvantages. In ORION, a hybrid algorithm, consisting of a combination of the GA and PSA, can also be executed. In this hybrid, the GA is executed first and the result becomes the starting point for the PSA. In this sense, the GA, which is highly likely to converge to a point very close to the global optimum, is used to find a very good starting point for the PSA, which is in most cases capable of higher local accuracy. This type of strategy is excellent for highly nonlinear systems with many variables in which many local optima exist.

Inert Mass Growth

Following typical U.S. engineering practices, inert mass growth is observed during the evolution of aerospace system designs, and this growth adversely affects the performance of those systems. Frequently, initial estimates of component masses are aggressively low, resulting in overly optimistic preliminary performance estimates. As the component and system designs mature and designers better understand the impacts of the component requirements, mass inevitably increases and is accompanied by decreasing performance. To avoid overly aggressive performance estimates, mass growth projections must be included early in the design. To account for inert mass growth, ORION uses a standard developed by the American Institute of Aeronautics and Astronautics (AIAA).⁷ In the methodology provided by this standard, mass growth allowance is included at any time in the system design phase by accurately assessing the current maturity of the individual components and assigning a certain percentage of additional mass to the current component mass estimate. The value of the percentage depends on both the type of component (i.e., electrical, structural, thermal, propulsion, etc.) and the maturity of that component (i.e., early estimate, layout, preliminary design, released design, existing hardware, and actual mass). This mass growth allowance accounts for component mass increases necessary to meet existing requirements. However, the standard also calls for the inclusion of additional mass margin to account for potential omissions or revisions of existing requirements. The assigned percentages for mass growth allowance and mass margin decrease as the program matures. ORION accounts for inert mass growth by assigning a user-input percentage increase to the masses determined by physical calculations.

Boost Control

The design of the system used to maintain airframe stability throughout flight has a significant impact on the overall missile concept. Traditional types of control systems include aerodynamic surfaces, attitude control systems (ACSs), thrust vector control systems, or some combination thereof. The level of control required will determine the actuator type, size, and mass, which in turn will impact the overall missile kinematic performance. Thus, control system design is coupled to the booster optimization process described above.

Key events that drive the design of the control system are stage separation, coast periods, and upper-stage maneuvers. A stage separation occurs when a spent stage separates from the rest of the missile, which induces destabilizing conditions in the form of tip-off angles and angular rates. The control system must maintain airframe control during stage separation. This function is called capture.

First-stage separation occurs during a portion of flight when the dynamic pressure is near its highest and is particularly stressing on the actuators. They must provide a high force in a short time to maintain stability. This is especially important if the airframe is aerodynamically unstable, because unchecked tip-off angles and rates can quickly lead to a loss of control. Other events that drive control system requirements are wind gust disturbance rejection and upper-stage maneuvers such as nosecone deployment.

Both operating conditions and key event times are needed to define the control system requirements. Missile flight is simulated to characterize each event, and analyses are parametrically run to develop control performance requirements. A control system is chosen and sized for each stage, and its mass is added to the missile in the appropriate locations. This mass addition will change the missile flight characteristics, which in turn modify the control requirements, making the determination of control system requirements a highly iterative and coupled problem.

Once the control requirements are established, it is then necessary to parametrically define the control performance requirements and associated hardware size and mass versus dynamic pressure. With those relationships defined, ORION can generate missile staging concepts that reflect a properly controlled missile.

An example of this coupled process can be seen on the sizing of the second-stage ACS. Total impulse is driven by the control required during capture and the second-stage coast. The second-stage coast occurs after the motor has burned out, and the ACS must provide control without the aid of the thrust vector control system. For each possible missile trajectory, coast time and the corresponding required impulse is determined. Combined with the impulse required for capture, ACS mass is estimated as a function of total impulse. That

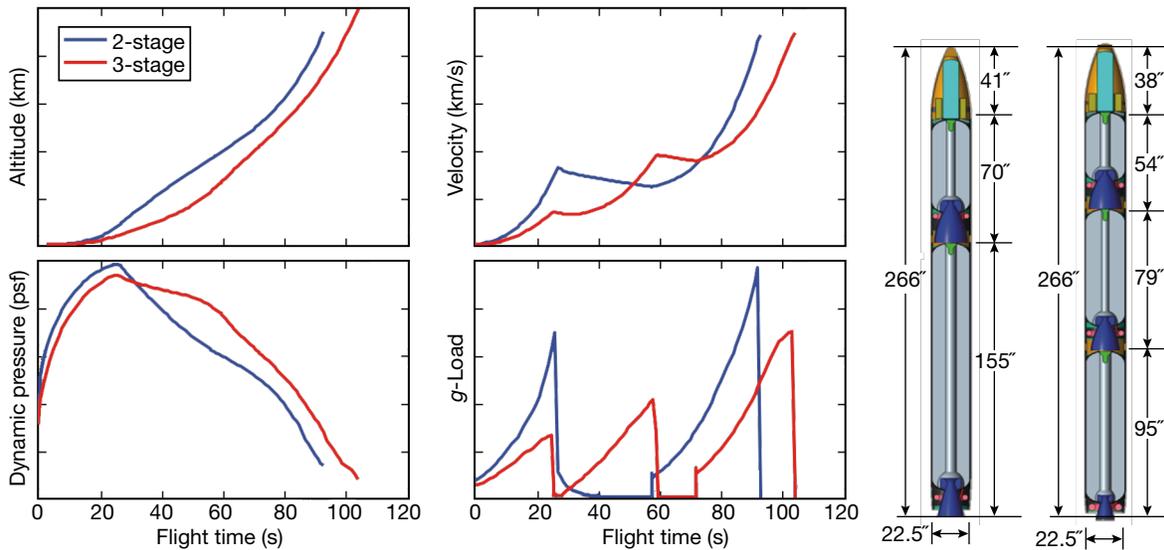


Figure 5. Vertical flight model results for the two- and three-stage optimized concepts.

relationship is used in ORION to model the interaction of missile performance and control system design in the booster optimization.

Booster Optimization Example

In this example, the dimensions of the rocket motor propellant grains, nozzles, nosecone, and payload were considered to be the primary drivers of size and performance. These parameters were optimized with the objective of maximizing V_{bo} . Two- and three-stage missiles are considered. For each stage, the composite motor case, the submerged contoured nozzle, the ACS, and the thrust vector control system are assumed. The propellant is assumed to be a conventional aluminized composite with ballistic properties typical of such propellants and the grain geometry assumed to be an internal burn tube.

Figure 5 shows a comparison of flight performance for the two- and three-stage variants of a 22.5-in.-diameter configuration. Although the two configurations produced similar results for V_{bo} , the three-stage variant has lower peak dynamic pressure and lower axial acceleration. Consideration of lower-level requirements and kinematic performance throughout the battle space may lead to one choice or the other.

ERROR CONTAINMENT

Referring to Fig. 3, the optimized booster configuration and associated kinematic analysis provides a KV mass limit, which allows the interceptor to meet range and time-of-flight requirements. The next step in the optimization process is to balance the capability between the IR seeker (and associated avionics package) and a propulsion system that provides the maneuver capability.

DACS operation and capability are driven by several key events determined by the KV release time and seeker functions. These events can include a divert maneuver using remote sensor data before the operation of the seeker, a divert maneuver after seeker acquisition, a divert maneuver after seeker discrimination, and a divert maneuver just before intercept. Of these divert events, the discrimination divert can be the most demanding and can be reduced by the incorporation of a more capable IR seeker. One of the critical factors in the concept design is the allocation of impulse to the possible divert maneuvers.

KV Configuration

The most commonly used KV configuration consists of a hard-mounted seeker and a cruciform DACS. The divert system provides the lateral motion for the KV, and the ACS provides the angular control to stabilize seeker pointing and control divert direction. The design of the ACS can be simplified if the center of gravity of the KV is aligned with the divert thrusters and remains aligned throughout operation. This can generally be achieved by positioning some of the avionics components aft of the DACS. This is called a split KV configuration as opposed to a unitary layout. Here the trade is between DACS and KV packaging complexity. The split KV design is attractive because the DACS is often the highest-risk assembly on the KV, and the entire missile. An example configuration is illustrated in Fig. 6.

DACS Constraints

For the traditional DACS, the two primary propellant options are hypergolic liquids and solids. Hypergolic propellants typically consist of a fuel and an oxidizer

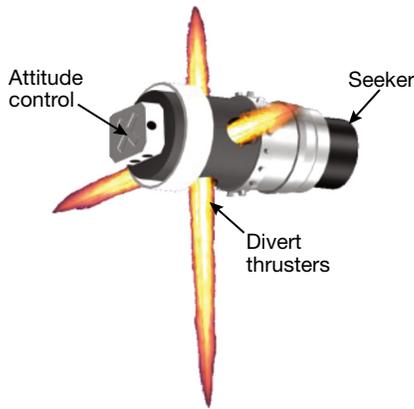


Figure 6. Example KV configuration.

that spontaneously ignite when they come into contact with each other. In addition, they are extremely toxic and/or corrosive, making them difficult to handle. Thus, liquid fuels have handling and safety concerns, which lead to higher infrastructure and leakage mitigation costs. On the other hand, a liquid-propellant DACS can be designed to ignite reliably and repeatedly, and it is a relatively mature technology.

There are four major types of solid-propellant DACSs (SDACS). The first is an extinguishable system, which can be stopped and started as required. Among the options, the extinguishable system is the least mature technology (lowest technology readiness level, or TRL) and highest risk. The second type SDACS uses multiple pulses. In this system, two or more divert pulses are contained in a single pressure vessel. This design is a medium TRL and risk option. The third option is a modular multiple gas generator design. The generators can be fired in pairs for each divert event to keep the center of gravity aligned with the divert plane as discussed in the previous section. For example, three divert events require six gas generators. This approach has a higher TRL and lower risk than the first two options. One of the drawbacks of this design is the low packaging efficiency, which results in a larger DACS space envelope compared with the other options. The fourth type, throttleable SDACS, is similar to the extinguishable system except the thrust can only be turned down to a lower level rather than completely turned on and off. This type of system has the highest TRL and lowest risk, but that can depend on the specific requirements. The final selection of a DACS configuration depends on the required operating time, divert capability, and mass while considering risk and cost.

Seeker Constraints

The IR seeker detects, acquires, and tracks objects of interest and selects which object should be intercepted. At a basic level, the IR sensor consists of optical com-

ponents that focus IR radiation, which is emitted or reflected from distant threats, onto an array of IR sensor elements, or pixels, that make up a focal plane array (FPA). There are several sensor and threat properties, or parameters, that will affect the design of the IR sensor. These parameters include:

- Aperture:** The physical aperture diameter is the diameter of the IR sensor. A larger aperture will improve seeker performance for two reasons. First, more IR radiation will be accepted into the sensor if the aperture is larger, increasing sensitivity. Second, the ability of an optical system to focus radiation onto a small spot will improve with larger aperture, so seeker resolution will also improve with larger aperture. However, a larger aperture will require a larger and more massive seeker and thereby a more massive KV. Note the design of the optical system may cause blockage, which reduces the effective size of the aperture.
- Waveband:** The IR sensor detects radiation in the IR region of the electromagnetic spectrum, which extends from ~2 microns to a few tens of microns. Threats will emit IR radiation according to the blackbody radiation equation, with the wavelength of the peak of the emission spectrum depending on the threat temperature. Colder threats will emit radiation that peaks at longer wavelengths. For example, room temperature threats, around 300 K, will emit a spectrum that peaks around 8–9 microns, so threat properties must be considered in selecting the seeker operating waveband.
- FOV:** The FOV is the angular extent observed by the seeker. A wider FOV allows the seeker to simultaneously observe objects with increased spacing or to find an object with increased location uncertainty. The former capability will affect the time at which threat selection must be accomplished, whereas the latter will affect the capability of the interceptor to contain a threat within its FOV at acquisition.
- Instantaneous FOV (IFOV):** The IFOV is the angular width observed by a single pixel of the sensor array. A smaller IFOV is generally better because it will allow increased resolution, which will enable the seeker to resolve multiple threats earlier, allowing more time for endgame guidance.
- Number of pixels or FPA format:** For a square array, the number of pixels in one dimension is given by the FOV divided by the IFOV: $N_{\text{pixels}} = \text{FOV} / \text{IFOV}$. Because it is desired to maximize FOV and minimize IFOV, a large number of pixels is advantageous. However, very-large-format IR arrays are more expensive to manufacture, so the maximum number

of pixels in one dimension is typically a few hundred. This means that balancing the requirements for large FOV and small IFOV is a critical factor in seeker design.

- Noise sensitivity:** The ability of an IR sensor to detect a given threat at a desired range will depend on its sensitivity, which is determined by its noise characteristics. There are several sources of noise that affect IR sensors, including shot (photon) noise, thermal emissions of the seeker mechanical and optical parts, detector dark current, stray light in the optical path, amplifier and readout noise, defective detector pixels, and quantization noise.

There are several figures of merit that are typically used to describe noise or sensitivity for IR sensors. One common measure is the noise equivalent irradiance (NEI), which is the flux density at the entrance of the optical system that produces an output with a signal-to-noise ratio (SNR) equal to 1.0 (output signal = system noise). NEI characterizes the sensitivity of the sensor system to a point (unresolved) source. NEI is expressed in watts per square centimeter or photons per second per square centimeter, and a lower number is better. To remove aperture dependency from the noise figure, a normalized parameter, $NCA = (NEI \times \text{clear aperture})$, may be used.

Seeker Acquisition Range

To optimize the KV configuration, the seeker performance parameter trade space must be characterized and related to the mass of the seeker. The relationships between the key seeker parameters, which determine acquisition range, are shown in nomograph in Fig. 7.

One begins at the lower left by specifying range requirements for acquisition and discrimination and ends at the upper right with an aperture requirement to meet the required ranges. To move from the start to the end of the Fig. 7 nomogram requires five steps.

In the first step, shown in the lower-left graph, the irradiance at the seeker aperture is calculated at the required range versus threat radiance. A proper choice of waveband to match the peak of the threat radiation spectrum will result in higher threat

radiance and thus greater irradiance at the seeker at a given range.

In the second step, shown in the middle-bottom graph, the irradiance found in the previous step is used to determine the first-stage aperture D_0 , which is the aperture required to meet the range requirement under the assumption of no translation or vibration motion and no frame summing. The input parameters at this stage are the SNR required to perform the considered seeker function (either acquisition or discrimination) and a noise figure for the sensor.

In the third step, shown in the middle-top graph, the effect of translational motion of objects in the seeker FOV is calculated. The major source of translational motion is typically a forced movement of the seeker to mitigate the effect of malfunctioning pixels in the FPA. Some may have no readout signal (dead pixels), and some may produce a very high readout signal at all times (hot pixels). The translational rate will affect how much energy is contained on a pixel in a frame time. The result of the calculation at this point is D_{Tr} , the required aperture with translation present, but with no vibration motion and no frame summing.

In the fourth step, shown in the lower right graph, the effect of vibrational motion, also known as jitter, is calculated. Jitter occurs because of high-frequency vibrational motion of the KV. The amount of jitter will depend on the DACS system used and associated pointing accuracy. Jitter is usually described in terms of peak-to-peak amplitude, in units of pixels. The result of the

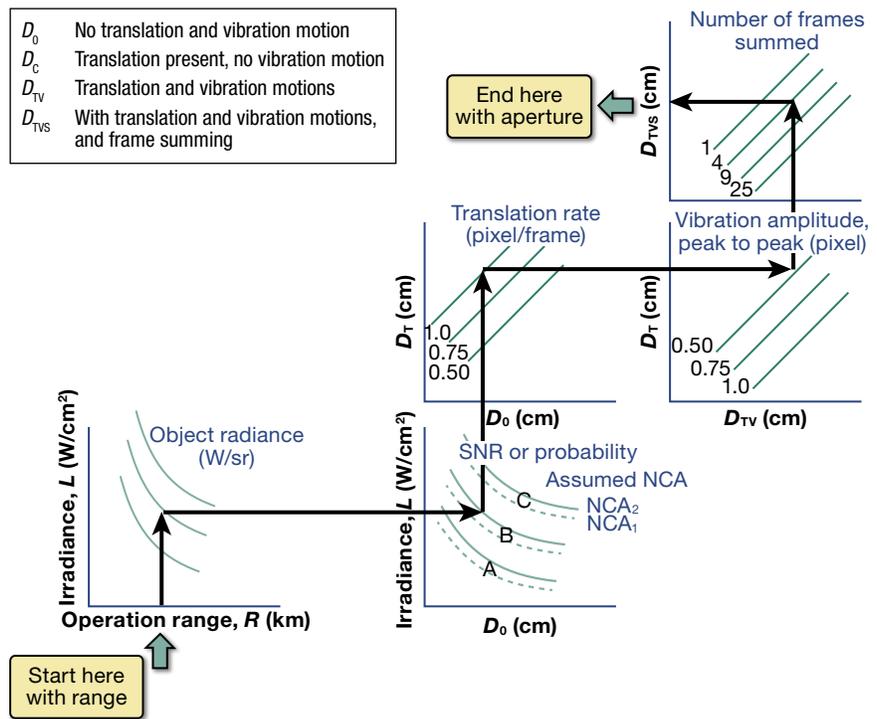


Figure 7. Seeker parameter nomogram.

calculation at this point is D_{TV} , the required aperture with translation and vibration present.

In the final step, the effect of frame summing to reduce noise is included. This has the effect of reducing the required aperture, depending on the number of frames summed for each measurement.

Seeker Field-of-Regard Containment

To acquire the threat object, the object must be within both the seeker detection range and the seeker FOV. The KV is commanded to point in the direction of the estimated threat object location as provided by the fire control sensor. However, pointing errors caused by threat tracking errors and KV navigation errors must be contained within the seeker FOV with high probability. The KV first attempts to acquire threats within its seeker FOV but may perform an angular search to achieve a larger field of regard (FOR).

The parameter relationships in developing the FOV/FOR containment requirement are expressed by the nomogram shown in Fig. 8. It begins with a roll-up of Fig. 7 in the lower-left corner to relate aperture to range.

The FOV/FOR that can be achieved for any aperture is limited by seeker design parameters such as FPA format and f -number. The f -number is the focal length divided by the effective aperture diameter. There are two commonly used formats, 256^2 and 512^2 , and practical f -numbers vary from 1.2 (expensive) to 3.0^+ (large and heavy seeker). The relationship of the FOV to these parameters is illustrated in the upper portion of Fig. 8.

The FOV/FOR to contain KV pointing error and threat location uncertainty at a seeker acquisition range is shown in the KV seeker FOR containment calculations in the lower-right portion of the nomogram. The FOV/FOR requirement is evaluated for all kinematically feasible intercepts in the threat intercept battle space for a given seeker acquisition range.

KV Optimization

The previous sections described how DACS and seeker technology constraints can be related to the basic performance parameters of the KV trade space. As shown in Fig. 3, after the performance of the booster

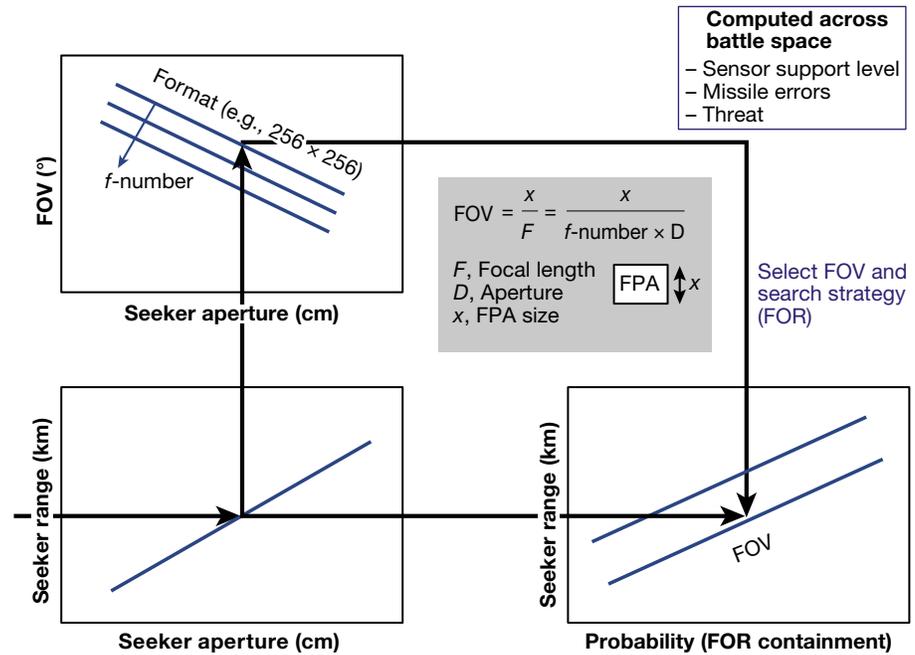


Figure 8. Seeker FOR containment relationships.

stack has been balanced with the mass of the KV, the next step is to balance the KV internally between the seeker and DACS. The objective is to ensure that error containment can be achieved given the KV mass limit or, if necessary, to rebalance KV mass with kinematic performance. The result is an optimized KV configuration.

Analyzing the Battle Space

Before KV optimization can be accomplished, key parameters related to the geometry between the intercepting missile and the threat must be determined. These parameters include: (i) handover error, expressed as initial zero effort miss; (ii) the closing velocity, which is the relative velocity between the intercepting missile and the threat; (iii) missile third stage burnout time; (iv) threat burnout time; and (v) missile time of flight. To extract these key engagement parameters, the battle space (all possible combinations of intercept, threat launch, and threat impact points) must be analyzed using an engagement simulation, which computes all possible intercepts where the intercepting missile can kinematically reach the threat. The simulation also determines the maximum possible time window during which the missile can be launched to have a successful intercept. This window is called the launch window.

For a given weapon system, there is usually a minimum acceptable launch window to allow for a successful engagement. For example, if the maximum launch window for a particular engagement is 120-s long and the minimum acceptable window is 45 s, then the engagement planner would find the best 45-s window within the 120-s time period. For this concept analysis,

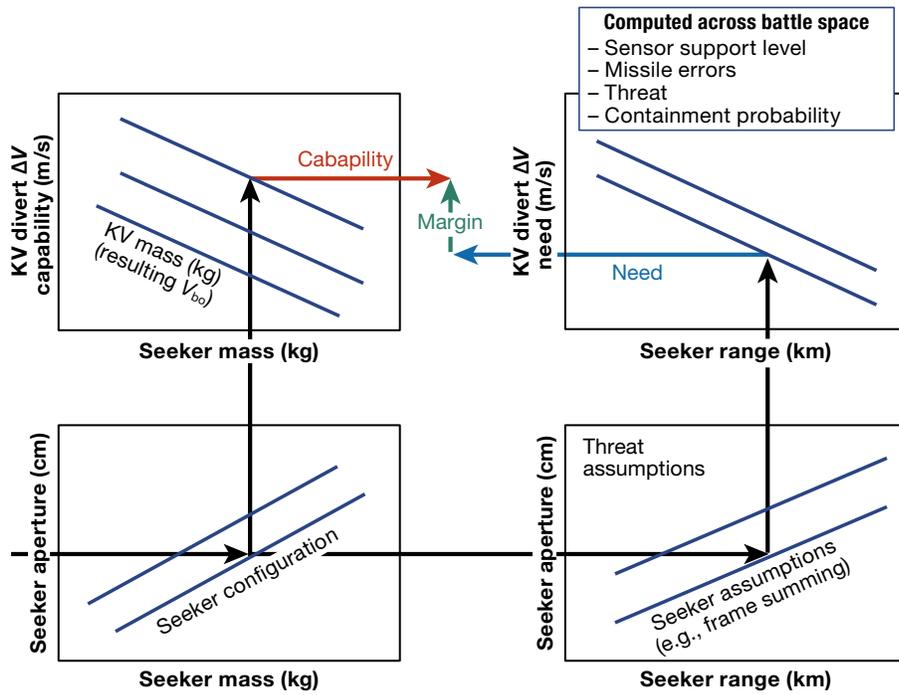


Figure 9. Divert containment relationships.

“best” is defined as the launch window that requires the minimum amount of divert. This methodology is used to select a minimum launch window for each and every engagement. Then, for the purpose of divert sizing, the single most stressing engagement is selected from all of the minimum launch windows. The key parameters that define this trajectory are used in the sizing of the required KV divert.

Seeker versus DACS

With the key parameters associated with the most stressing trajectory established, it is now possible to balance the KV mass between the seeker and DACS.

The relationships between the divert containment parameters are illustrated by the nomogram shown in Fig. 9. The seeker aperture size is first selected in the lower-left corner of the nomogram. The first plot relates the seeker mass to the aperture size. Multiple curves can be generated for different mass margin philosophies. Moving to the lower-right plot, the seeker performance is given as a function of aperture size. This is a roll-up of the nomogram shown in Fig. 7.

Moving on to the upper-right plot, this is where the required divert is related to seeker performance. Of the four plots in this KV nomogram, the upper-right plot is the most complex to generate. This is where many of the system assumptions on target set, mission geometry, and engagement support quality are introduced. For these assumptions and throughout the battle space, the total divert (ΔV) needed to satisfy a containment probability

is computed as a function of seeker range capability. The containment probability is the product of divert and FOV containment probabilities.

Moving from the lower-left to the upper-left subplot, this is where the DACS performance versus mass is described. Multiple curves can be generated for different KV masses as a function of the seeker mass. The curves will depend on whether an SDACS or LDACS is assumed. The relationship between the upper-left and -right design points identifies how much margin, if any, exists between the required and delivered amount of divert.

Although the nomogram provides a useful tool for displaying different KV options versus system capabilities,

it does not directly provide an answer to the best split between optics and divert capability. From a performance perspective, the lightest KV that accomplishes the mission is desired. If margin is found, requirements on other portions of the system may be relaxed. To find the lowest mass KV, an automated tool was developed at APL that basically traces all possible paths around the nomogram in Fig. 9, with a specified margin between the required and delivered divert.

Each of the points along the x axis in Fig. 10 represents a different trace around the nomogram. The figure shows the subassembly masses of the seeker and avionics as well as the DACS. The KV mass is the summation

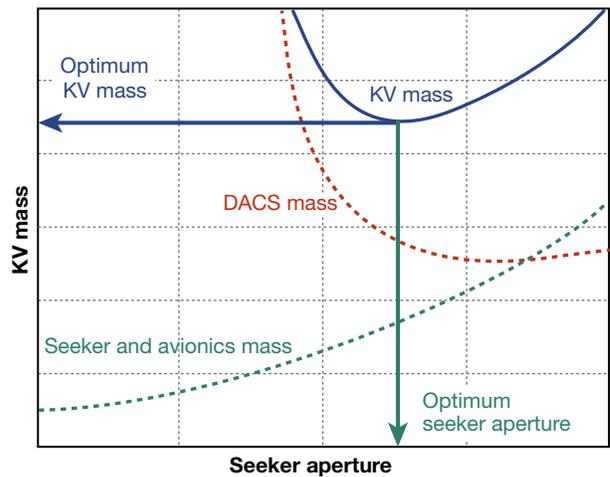


Figure 10. KV mass optimization.

of the two. From this plot, the optimum seeker aperture size and resulting minimum KV mass can easily be obtained. It is worth noting that the KV mass is highly dependent on the level of engagement system support and the required target set. Thus, a larger system balancing may consider the trade between engagement support parameters and the resulting missile configuration and performance.

Physical Packaging and ACS Sizing

Now that concepts for the major components of the KV have been developed, a physical layout of the KV must be realized to ensure a feasible KV size. This can be done using a solid modeling tool, such as Pro/ENGINEER or SolidWorks. In this way, the overall package is developed and visually checked and mass properties are determined. These mass properties are then applied in a simple six-degree-of-freedom simulation to size the ACS. The ACS is sized to maintain stability after the KV is ejected from the upper stage, perform the roll maneuvers before specific divert events, maintain control during divert events, and perform the seeker pointing functions.

LETHALITY CONSTRAINTS

The final trade area in Fig. 3 is the seeker resolution (IFOV) versus KV acceleration needed to ensure a hit accuracy that provides the desired level of lethality.

Figure 11 shows the form of the nomograph that illustrates the trades between IFOV and KV acceleration versus probability of hit. Given the FOV that is determined by handover error containment analysis, the lower left plot of Fig. 11 shows the relationship between FOV and IFOV versus FPA format. Given IFOV, the upper-left plot of Fig. 11 defines the angular extent of the threat object as a function of seeker aperture and the number of pixels, N , needed for recognition. The aimpoint recognition range for an engagement is the target projected length perpendicular to the line of sight divided by angular resolution required for aimpoint selection. Given the closing velocity of the encounter and the aimpoint selection range, the time-to-go at aimpoint selection is calculated. The acceleration needed to accurately hit the threat is estimated from the projected

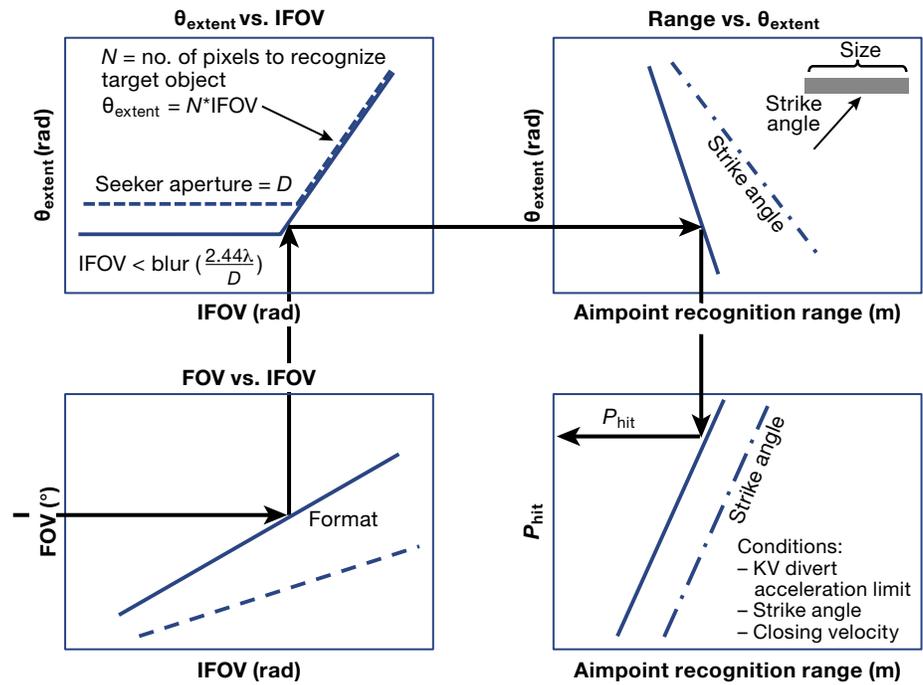


Figure 11. Lethality trade space.

miss and the time-to-go at aimpoint selection less processing delays. Finally, a terminal guidance simulation is used to calculate the probability of hit (P_{hit}) shown in the lower-right plot of Fig. 11.

CONCLUSIONS

Development of a missile concept in the context of a larger engagement support system involves a complex set of highly coupled trades. We have defined a systematic process that is logically decoupled and allows an overall performance optimization and balancing of conflicting constraints. Currently, the methodology is split into three major steps. The first is the optimization of booster kinematics, the second is optimization of KV mass to remove system errors, and finally, the third optimizes endgame lethality. Future research can explore ways to integrate these steps and include more detailed representations of the external sensors, command and control architecture, and engagement support functions. This can then lead to a more automated and simultaneous optimization of both engagement support and missile parameters.

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