Principles of Weapon Control Systems I

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Principles of Weapon Control Systems

- The Weapon Control System is the "engage" portion of the ***Detect, Control & Engage*** process
  - The decision to engage has already been made
  - Target information is provided
- WCS must prioritize engagements based upon
  - Mission
  - Threat
  - Resources required to support each engagement
- The Weapon Control System often relies upon the principle of the "least worst design" in order to create a balanced weapon system with the following characteristics
  - Robust
  - Simple
  - Predictable

WCS Design Must Balance the Requirements of Supporting Each Weapon While Making the Weapon System Robust, Simple, and Predictable

Robust

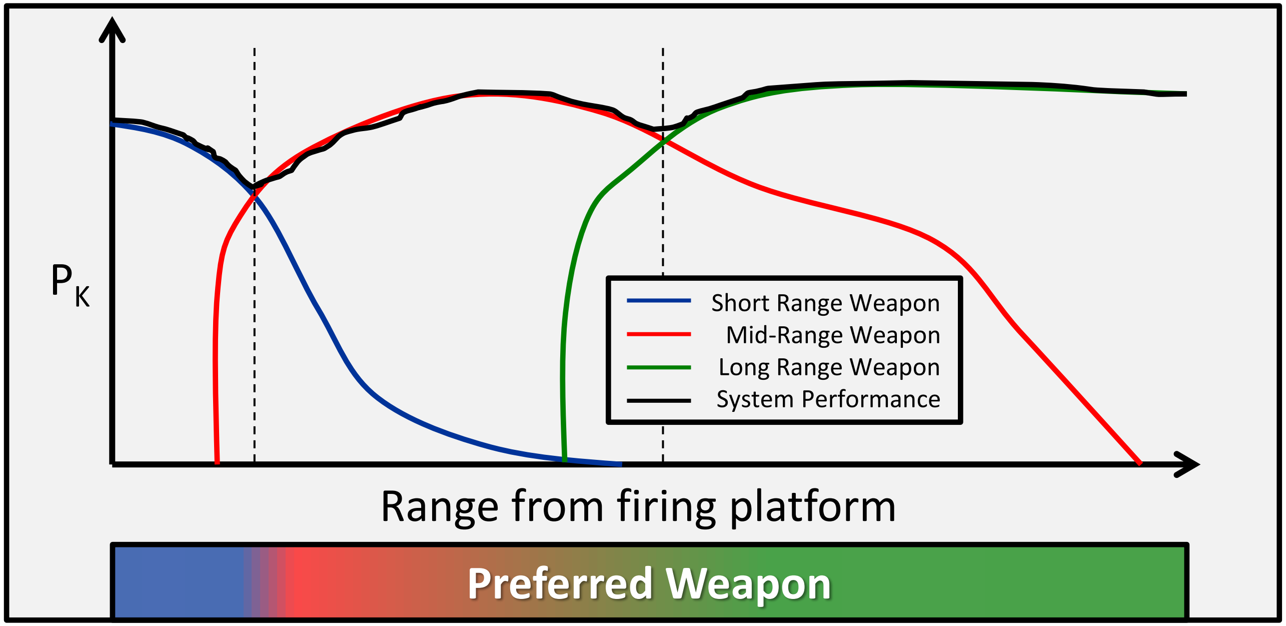
- Uniformly good system performance throughout the battle space
  - Optimum performance at each intercept point may not required
- Continuity
  - Performance “holes” for any weapon are unacceptable
  - Well-behaved performance regions for each weapon
  - Use different weapon capabilities to create a layered defense system
- Consistency across weapon system functions with regard to target assumptions
  - Track processing
  - Launch decision processing
  - Guidance processing

Combat System Effectiveness is More Important than an Individual Weapon’s Performance

Layered Defense

Example of a Robust WCS

- Having multiple weapons for a given mission area can provide a better chance for success
  - The region lethal performance of each weapon differs throughout the battle space
  - Selecting the proper weapon for the given intercept range creates a highly effective layered defense system



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Measures of Weapon Effectiveness

Robust

- Every weapon system has a unique way of grading success. However, there are some standard metrics that are used
- Circular Error Probability (CEP_{XX})
  - Most often used for artillery
  - Describes the size of the area about the intended aim point in which XX percent of the artillery will land (i.e. CEP_{50})
- Probability of Mission Kill (P_{MK})
  - Probability that the threat's ability to deliver its payload has been neutralized
  - Abstract metric that is difficult to measure outside of a high fidelity simulation
- Probability of Guidance (P_G)
  - Probability the weapon can be guided within a specific radius of the threat
  - Threshold radius is a weapon system specificity
- Probability of Hit, Damage, or Kill (P_H, P_D, P_K)
  - Probability of placing a specific amount of energy on the target
  - Different energy levels correspond to hitting the target, damaging the target, or a target kill

Predictable

- Predictability is required for launch decision processing
  - Understanding of missile capability as a function of
    - Target kinematics
    - Battlespace
    - Knowledge of missile behavior throughout flight
  - Scheduling requirements
    - Resource (illumination, launcher) support
    - An understanding of depth of fire (DOF) to aid resolving scheduling conflicts
    - Accurate, well-behaved time of flight estimates over the entire battle-space
- Required for post-launch functionality
  - Being able to predict the missile trajectory
    - Inflight communications
    - Guidance computations
  - Resource allocation in raid environments
    - Scheduling

Simple

- Combat systems has many missions
  - Many functions are run simultaneously
  - Most combat system has “maximum weapon usage” requirements
- Closed form solutions and table look-up procedures are used in many support functions
  - Tabular data provides an easy way to update the system software with limited regression testing
  - Closed form solutions are highly desirable provided they aren’t overly complex
- Timing (computer processing) requirements hinder more complex designs

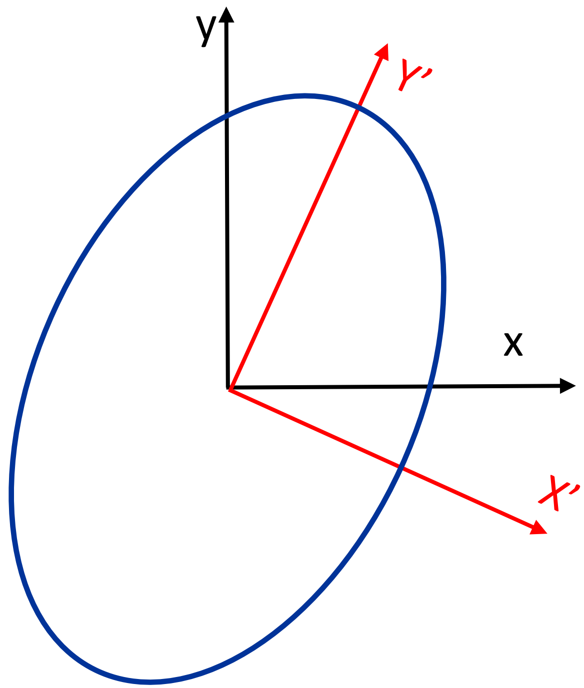
Simplicity Refers to Implementation, Not Assumptions or Capability

Coordinate Systems

- The weapon system uses a variety of coordinate systems
  - Most functions have a “native” coordinate system
- A native coordinate system allows for simplicity in certain functionality
  - Tracking/filtering object measurements
  - Defining weapon capability
  - Categorizing target criticality (severity of threat)
  - Communications

Coordinate Systems

- The concept of a native coordinate system is best explained through example
- Think of it as describing an ellipse in a coordinate system that reduces mathematical complexity
- In the illustration to the left, it is easier to describe the ellipse in the prime coordinate system
- Even though the prime system appears tilted to the casual observer, it best describes the semi-major and semi-minor axes of the ellipse



Let's Look at Some Coordinate Systems Used in the WCS…

ECEF / LLA

Coordinate Systems

- Usage: Communications with GPS aligned systems (combat system, missile, etc.)

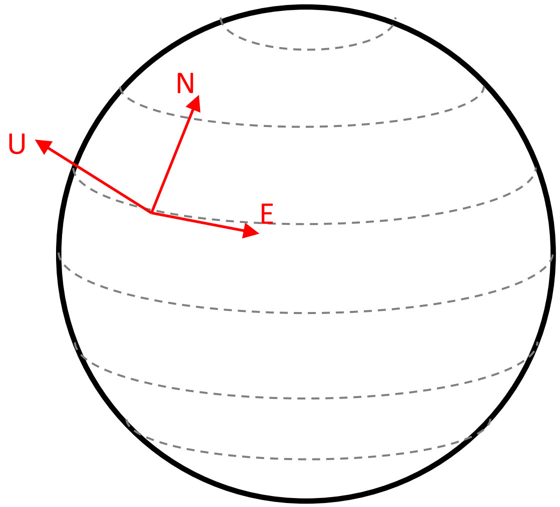
  Determine earth rotational effects on trajectories/guidance
- Origin: Center of the earth
- Description:
  - LLA
    - Latitude
    - Longitude
    - Altitude
  - ECEF
    - X axis is from center of the earth to a point at 0° latitude and 0° longitude
    - Z axis is from center of the earth to a point at 90° latitude
    - Y axis completed the right hand coordinate system

East North UP – ENU

Coordinate Systems

- Usage: The default coordinate system for many weapon systems
- Origin: Local Reference Point (typically fixed to a location on the platform)
- Description:
  - Defined by geographic North and geographic East, both tangent to the surface of the earth
  - The third component of the points up, and completes the right hand coordinate system

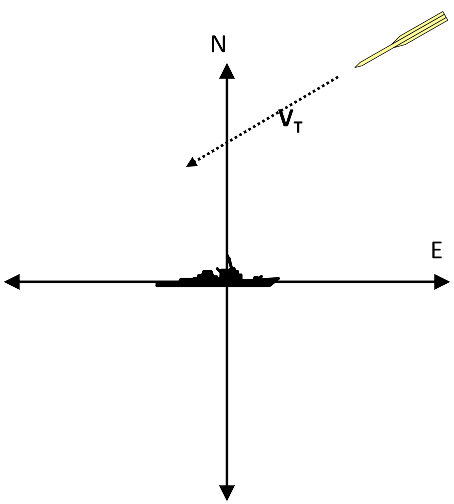
Note that many aircraft systems use a NED (north, east, down) coordinate system rather than ENU

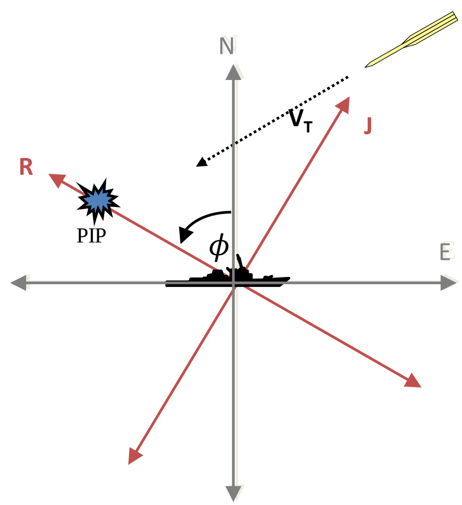


Missile Communications - JRU

Coordinate Systems

- Usage: Missile communications
- Origin: Local Reference Point offset by location of the missile at initialization
- Description:
  - Formed by rotating the ENU coordinate system by angle ϕ about the U axis
  - ϕ can be a launch angle, or define the angle from north and the downrange direction for the specific engagement

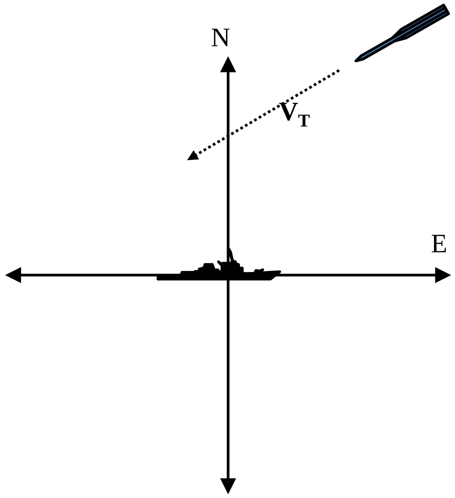


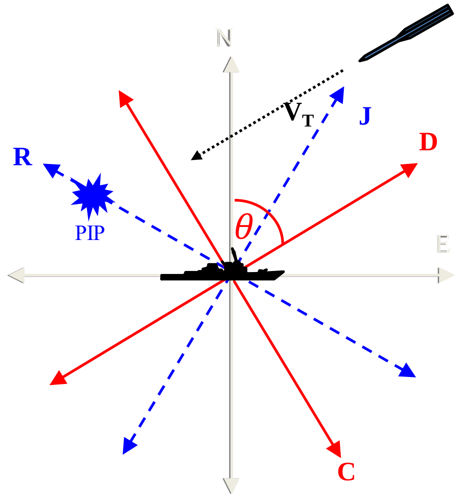


Crossrange Downrange Vertical – CDV

Coordinate Systems

- Usage: Describing missile capability against a threat
- Origin: Local Reference Point
- Description:
  - Formed by rotating the ENU coordinate system about the U axis by angle θ so that the target velocity vector is anti-parallel to the D direction





Missile Engagement Sequence

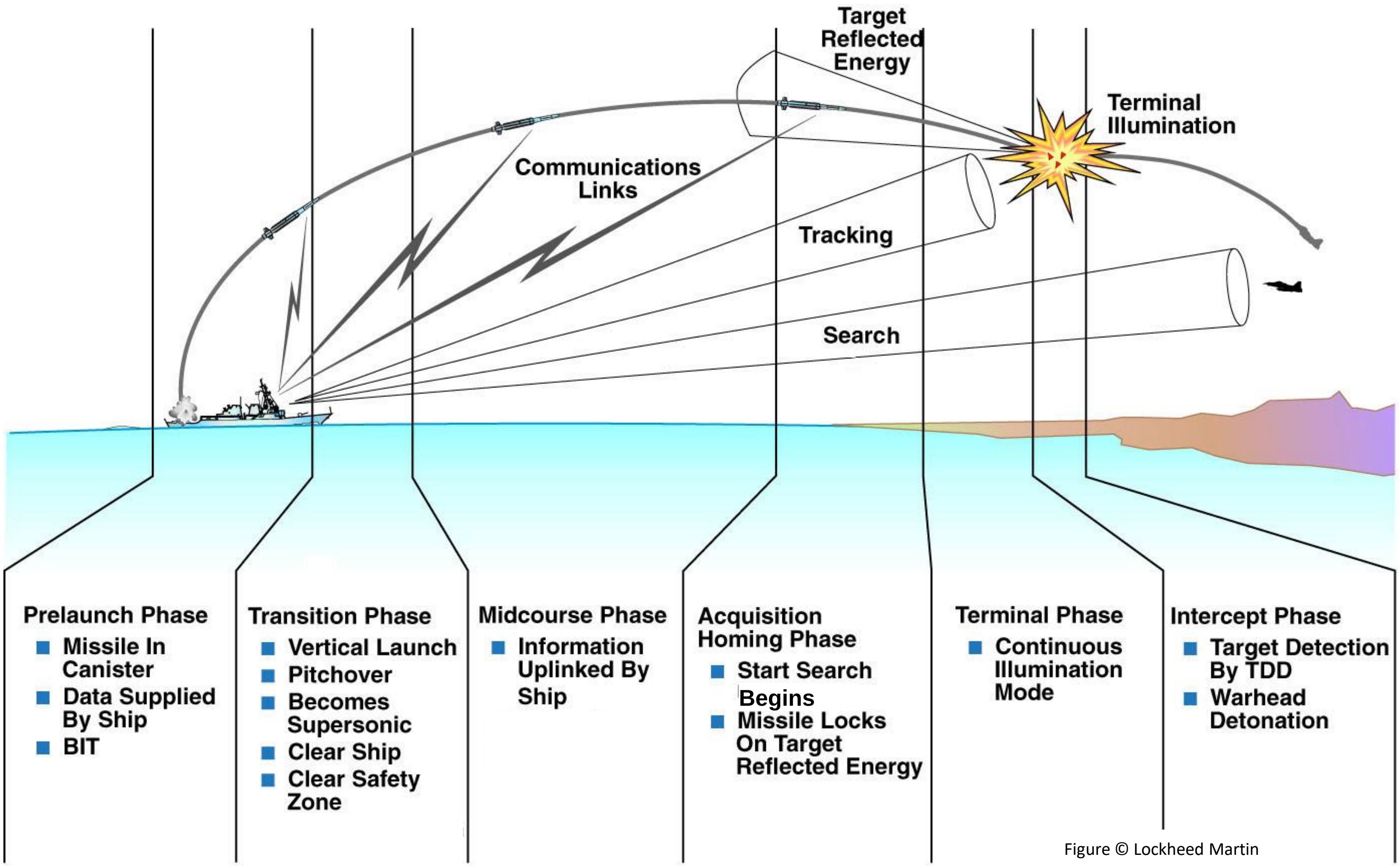


Figure © Lockheed Martin

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WCS Responsibilities

Pre-Firing Decision (Prelaunch) Processing

- Intercept Prediction
- Determining Weapon Capability
- Scheduling / Weapon Selection
- Weapon initialization

Post Intercept Processing

- Engagement Evaluation
- Kill Assessment

Post-Firing Decision (Inflight) Processing

- Guidance / Intercept Prediction
- Handover support
- Communication with Weapons
- Engagement Monitoring

Support Functionality

- Track Processing (filtering)
- Resource Management
- Scheduling
- Displays

Prelaunch Processing Responsibilities

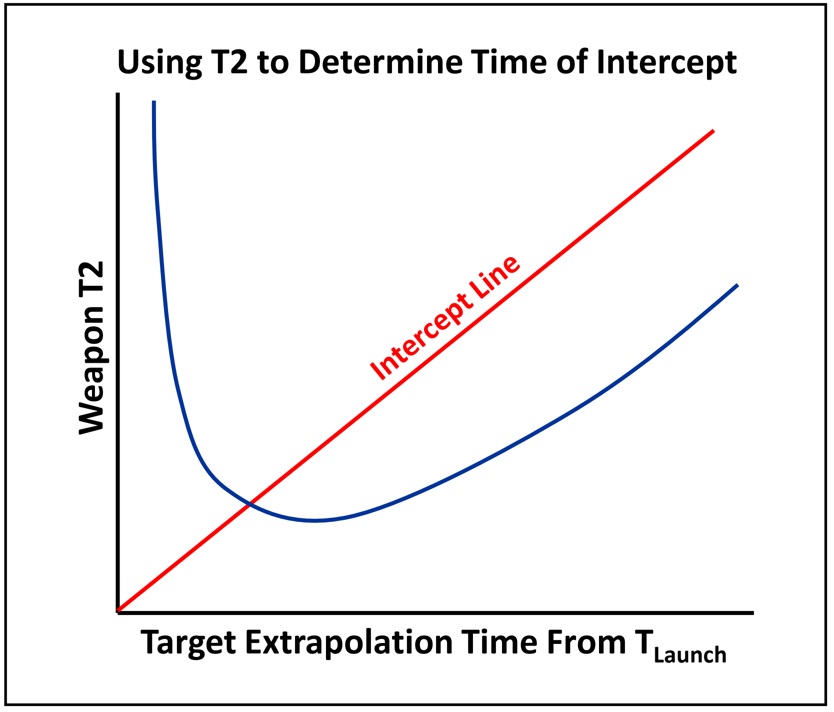
Prelaunch Decision Processing

- Determine if the weapon(s) are capable of having success against the threat
- Determine the window in which the threat can be engaged
  - Minimum and maximum ranges of intercept that satisfy performance criteria
- Schedule the engagement
  - Determine desired launch time and intercept point
  - Allocate additional resources needed during the engagement
    - Radar
    - Launcher
    - Illuminator (if needed)
  - Perform resource deconfliction if necessary
- Select the weapon (if more than one) to use
- Initialize the weapon (if needed)
- Fire the weapon

Prelaunch Intercept Point Prediction

Prelaunch Decision Processing

- One of the central themes of prelaunch processing is estimating the time it takes for a weapon to reach a given point in space from the time it is launch (T_{Launch})
- Virtually all weapons have non-constant speed profile which makes determining this time difficult without a simulation
- In lieu of a simulation, most systems rely upon a time of flight table that describes the time for the weapon to reach a given point in space
- The Navy refers to this as a T2 table
  - "T" for time
  - "2" indicates it is a predicted quantity
- When the T2 of the weapon to a particular point equals the extrapolation time of the target to the same point, an firing solution has been found



Using the T2 Table

Prelaunch Intercept Point Prediction

- There are two ways in which the T2 table can be used
  - Launch to satisfy a given intercept range
  - Launch to satisfy a given launch time
- Launch for a specific intercept range
  - Use the time to a given intercept range ($R2$) to determine the target range at which the weapon should be fired (ROF)
  - Simplifying this process for a 1-D scenario

$$ROF = R2 - (V_T)(T2)$$

- Launch for a given launch time
  - Use a recursive algorithm to determine the range at which the weapon T2 value and the target extrapolation time to a given point are equal
  - $T2 = FINDT2(RINT_M)$
  - $RINT_T = R_T - (V_T)(T2)$
  - Modify $RINT_M$ until $RINT_T = RINT_M$

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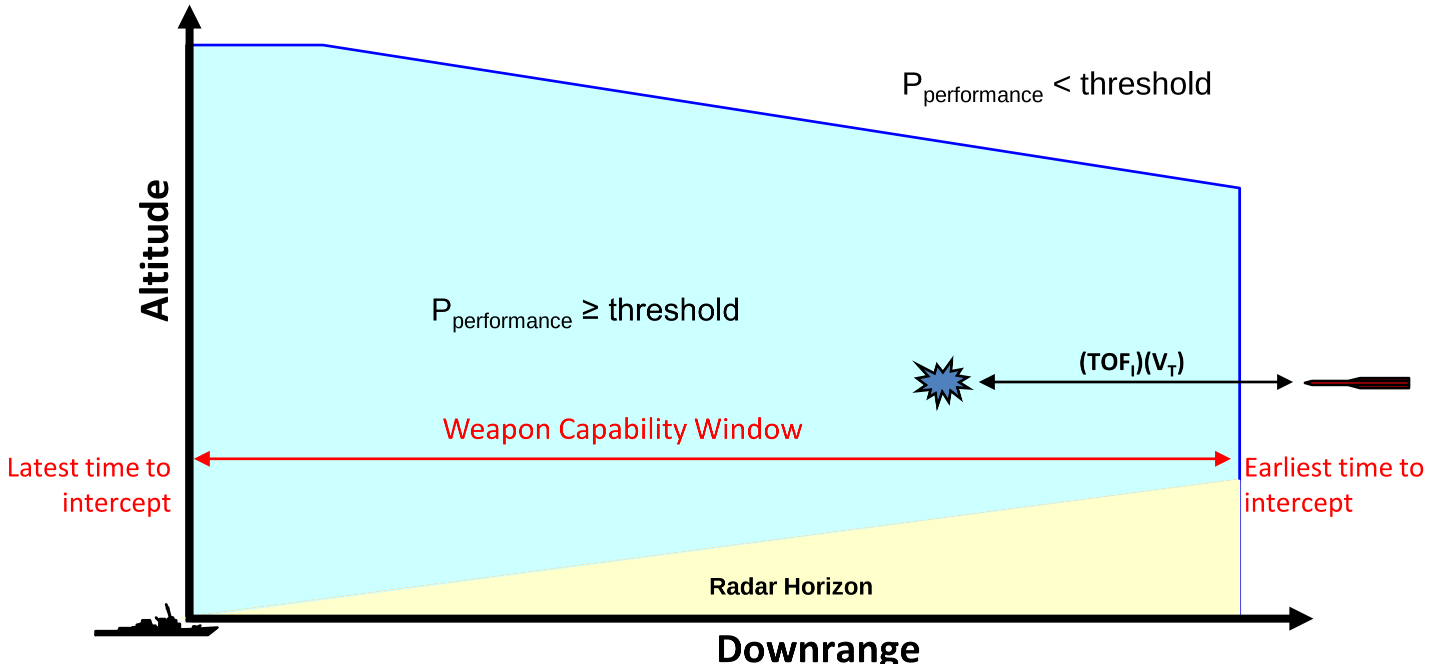
Weapon Capability Function

- Used to determine the region in which a weapon has acceptable performance against a given threat
  - Unique function exists for each weapon
  - Results can be expressed as a region, contour, or a real time algorithm
  - Performance is a based upon
    - Intercept position & weapon/target geometry,
    - Track quality
    - Sufficient support of all required resources
- Weapon capability typically decreases as a function of crossrange
  - A straight and level target would be at the same crossrange throughout the engagement
  - The CDV coordinate system is typically used because of the ease in which performance is described by crossrange and downrange
- The function is only as accurate as the assumptions at the current time
  - The function is run on a periodic, or as new target data comes in

Weapon Capability

Polygons



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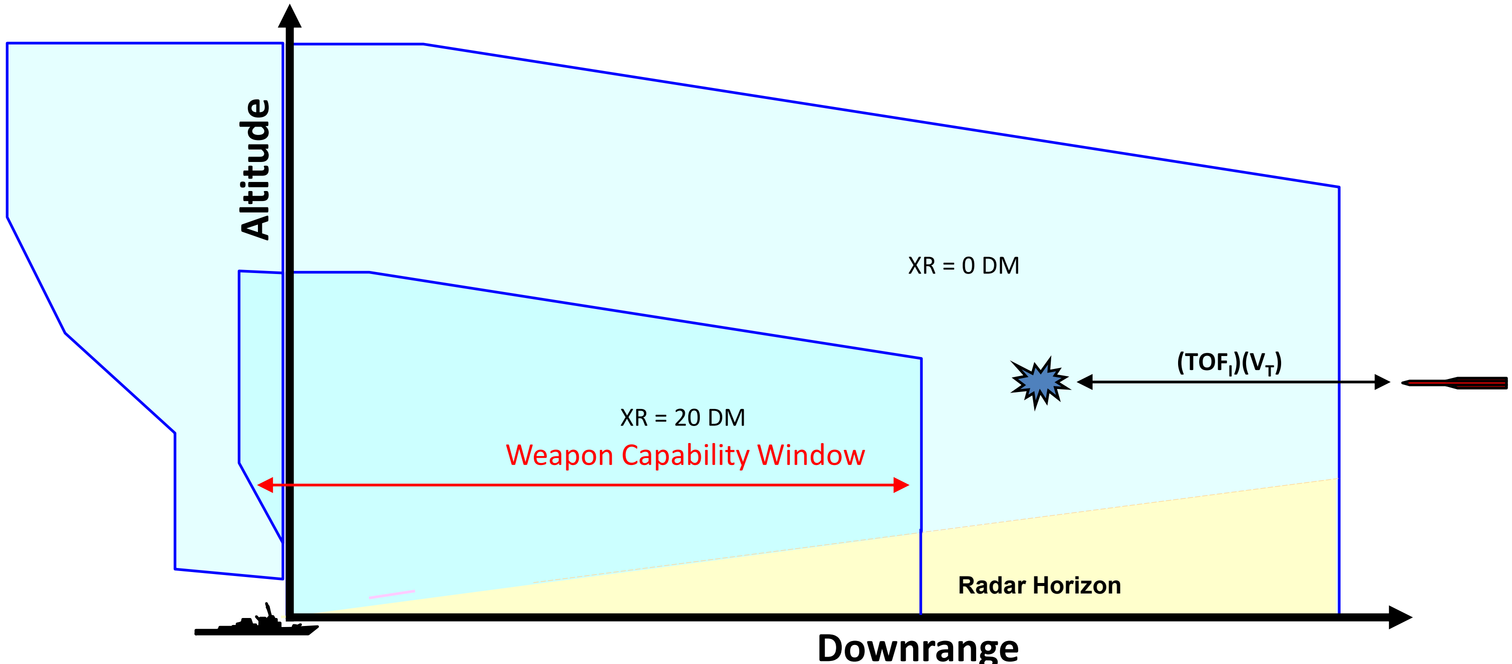
- Weapon capability contours define the boundary where the system has the capability to intercept a target with a specified kinematic characteristic (minimum acceptable P_G or P_K is inferred)
  - A target track quality must assumed
  - A contour is needed for each target speed to account for the changes in the missile/target geometry

Weapon Capability

Downrange-Crossrange View



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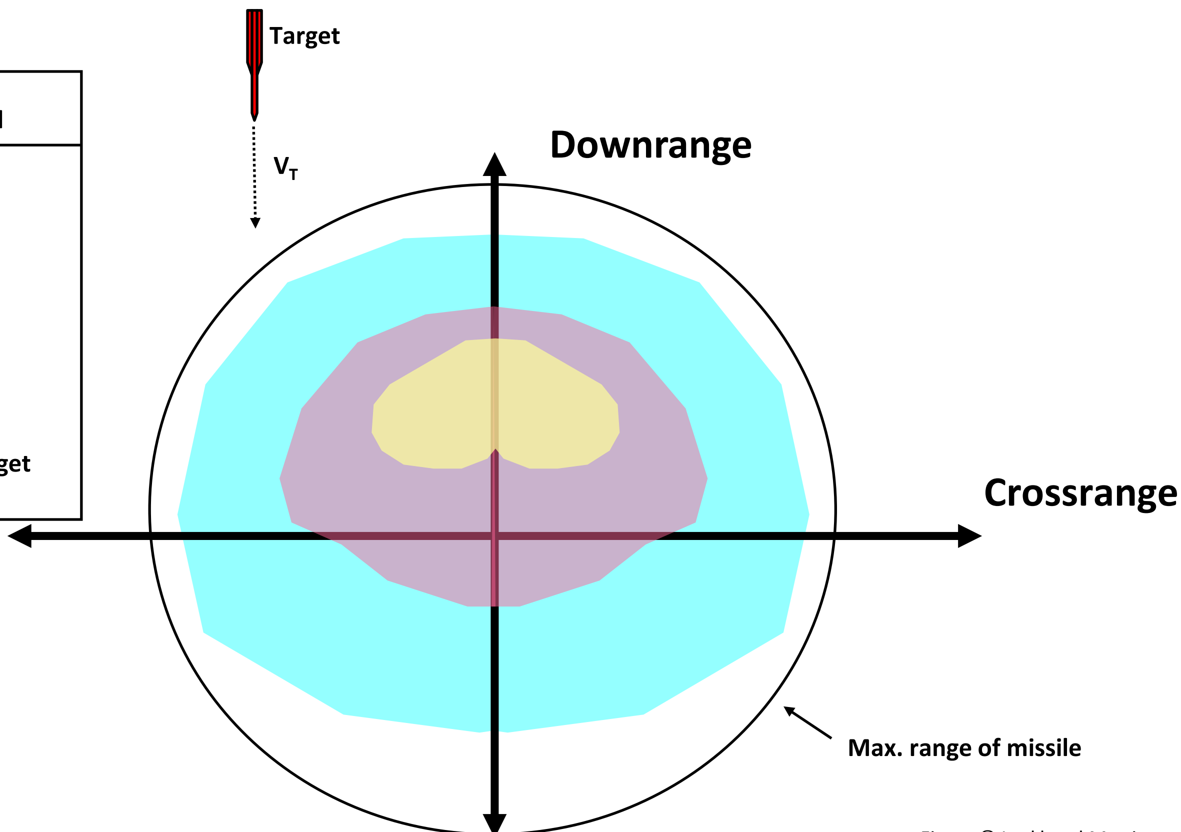
- The size of the capability contour will decrease as the crossing component of the intercept point increases

Weapon Capability

Top Down View

Color	Target Speed
	Mach 3 target
	Mach 2 target
	Mach 1 target
	Stationary target



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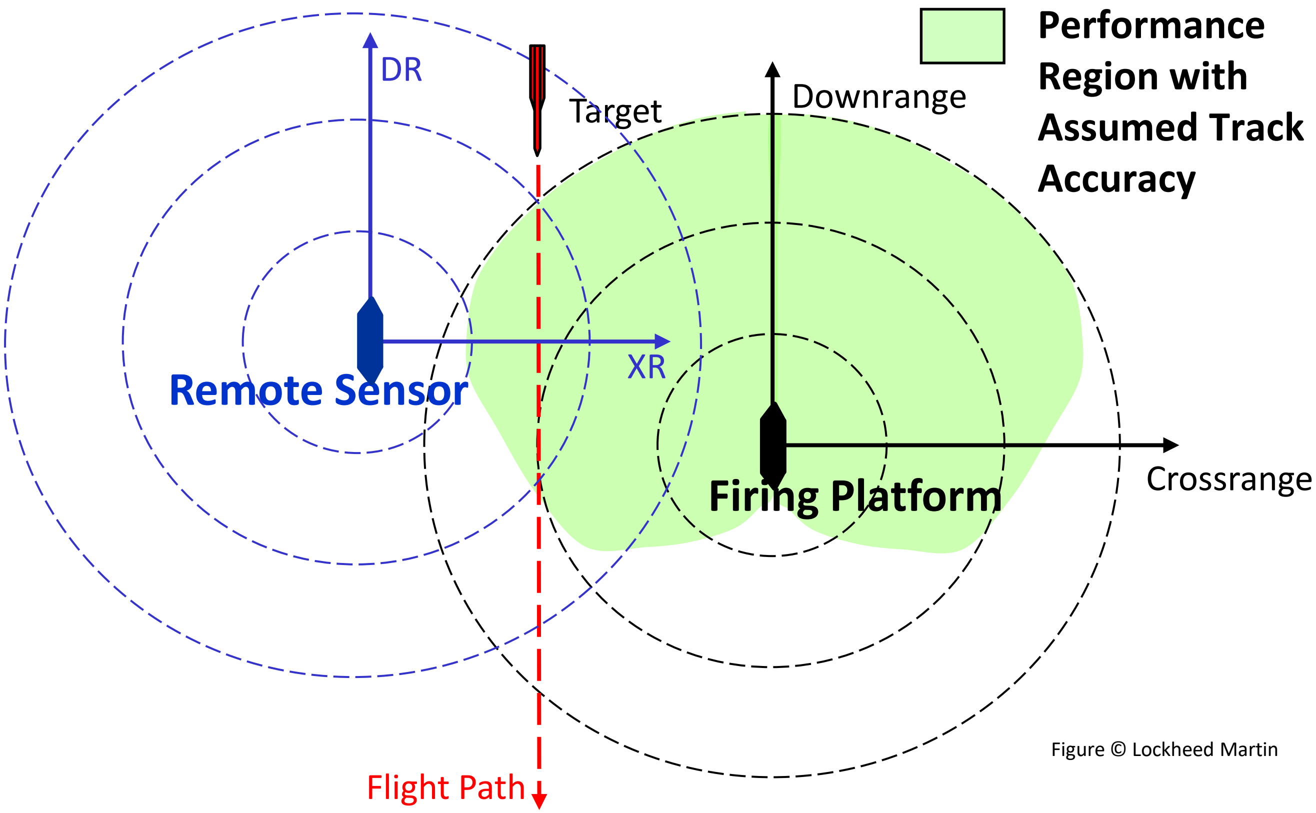
Weapon capability decreases as the target speed increases primarily due to seeker pointing constraints

Weapon Capability (A)Symmetry

- The introduction of a different sensor (typically a sensor from another platform) into the fire control loop requires modification to the weapon capability assumptions due to different track accuracies



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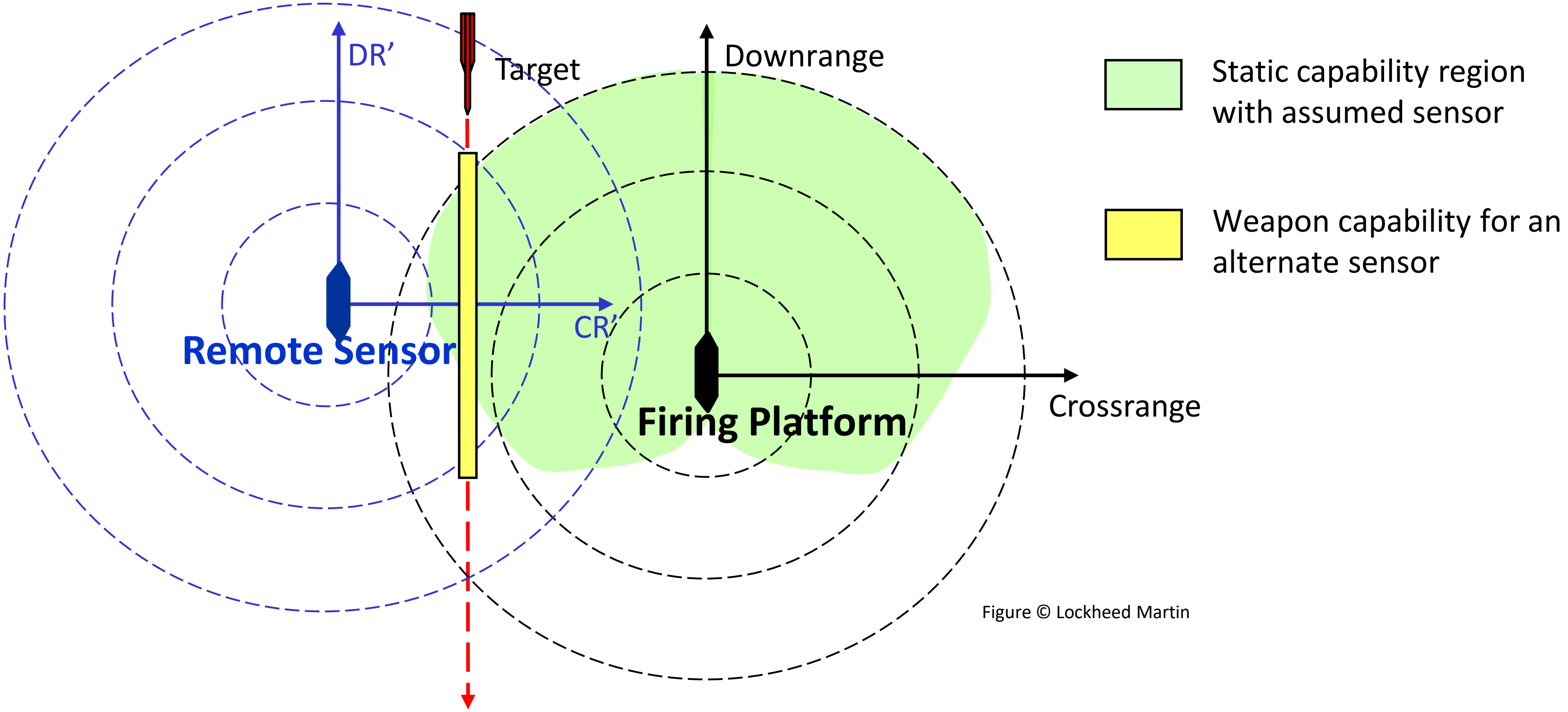
Weapon capability is only symmetric if the sensor data is symmetrical about the downrange axis

Capability contours can be a poor representation of performance when using remote sensors

Weapon Capability Along the Target's Path

- The only way to consider "unplanned" track accuracies in the weapon capability function is to abandon contours and evaluate intercept points one at a time using an ***error budget***
  - Computationally intensive
  - Requires a complete understanding of the weapon and how track accuracy can affect weapon capability



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Weapon Capability Function

Summary

- Capability contours are computed a priori assuming
  - Track accuracy
  - Resource support
  - Known target trajectory
- When contours are not appropriate, ***error budgets*** must be combined with knowledge of the weapon trajectory, target kinematics, seeker operations (if any), and track accuracy
  - Robust approach
  - Computationally cumbersome
  - Fewer assumptions are “baked in”
  - This concept will be explored further during our lecture on error budgets

Scheduling

- Assigns a launch time for all engagements in the queue
  - Ensures proper resources are allocated for each engagement
  - Shift engagements in time when resource conflicts prohibit launching the weapon
  - It's kind of like a game of Tetris
- Scheduling looks to maximize **firepower** and **depth of fire**
- Firepower
  - Number of projectiles simultaneously in the air
  - Resource Limitations
    - Launcher
    - Illuminator
    - Communications link

    Systems requiring such resources are often referred to as resource dependent systems
  - Spatial / Temporal Limitations
    - Intercept range

Depth of Fire (DOF)

Scheduling

- The number of shots that can be supported in the engagement space against a single target is called the depth of fire (DOF)
- Resource dependent weapon systems have lower DOF values than resource independent weapon systems
  - DOF is critical to scheduling algorithms when weapons are resource dependent
    - Semi-active missiles that require illuminator support
    - Launching systems that require significant time between firings
    - Missile systems that have a limited number of communication systems
  - DOF is not critical to scheduling algorithms when weapons are resource independent
    - Typical of gun systems capable of shooting hundreds or thousands of rounds/min
- DOF limitations aid the scheduler in prioritizing launch times

Launcher

Scheduling

- Modern missile launchers have a minimum time between missile launches, $\Delta T_{L_{MIN}}$
  - $\Delta T_{L_{MIN}}$ is on the order of seconds, and can affect performance in a raid
- The minimum time established considers many different factors, including
  - Power draw (consumption)
  - Safety
  - Proximity of launch cells in consecutive launches

Mk-41 Launcher

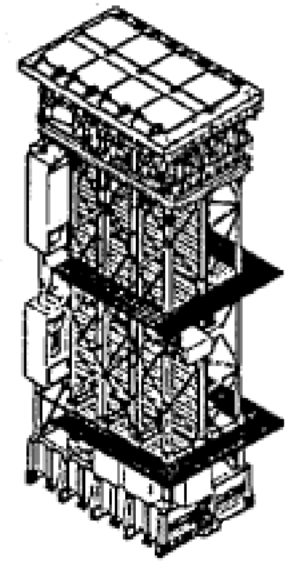


Image from reference 2

Mk-29 Sea Sparrow Launcher

Image from reference 2

- Gun systems have a minimum time between firings, ΔT_F
  - This time is often far smaller than ΔT_L

Illuminator

Scheduling

- Illuminators are used to provide energy which is reflected off the target and to the incoming missile
- The illuminator must support a missile inflight for many seconds, T_H
  - Missile seeker search for the target
  - Missile guidance during terminal homing

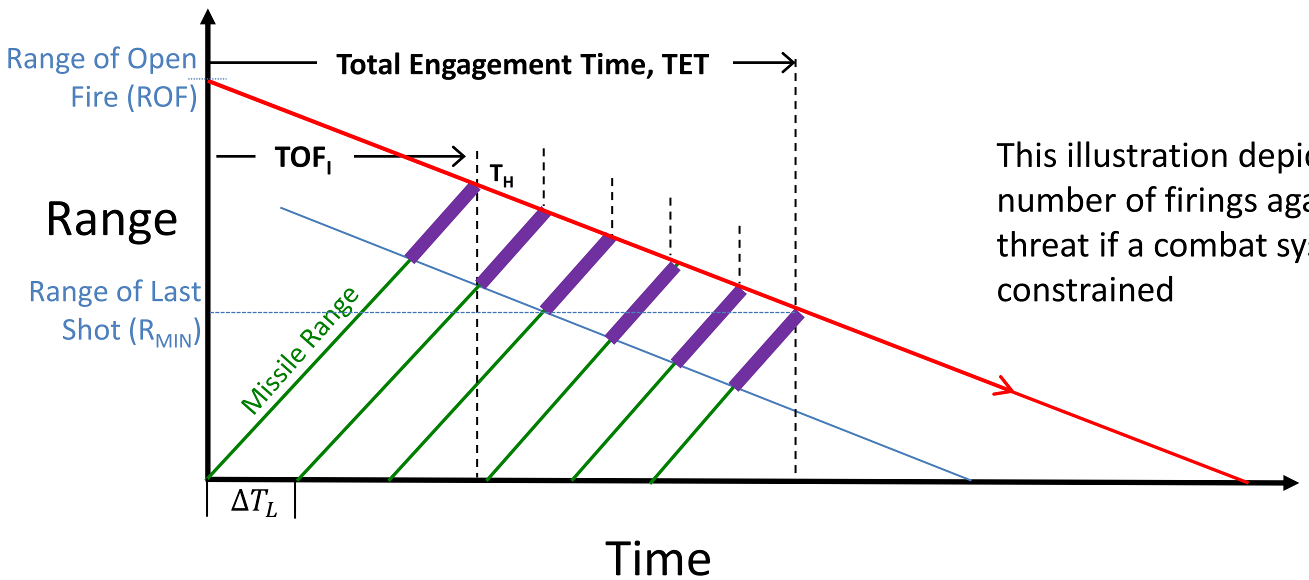
The most common illuminator type consists of a dish transmitter (AN/SPG-51 is shown)

Picture taken by Don S. Montgomery, USN (Released) / Public Domain

- Illuminator support is often the greatest resource limitation
  - How many illuminators do you need???

Depth of Fire Illustration

Scheduling



This illustration depicts then maximum number of firings against a radially inbound threat if a combat system was illuminator constrained

- Duration of illuminator support for each engagement T_H
- Delay between missile launches ΔT_L

$$DOF = \frac{\frac{ROF}{1+V_T/V_M} - R_{Min}}{(V_T)\,(T_H)} + 1 \qquad \Delta T_L = T_H\left(1 + \frac{V_T}{V_M}\right)$$

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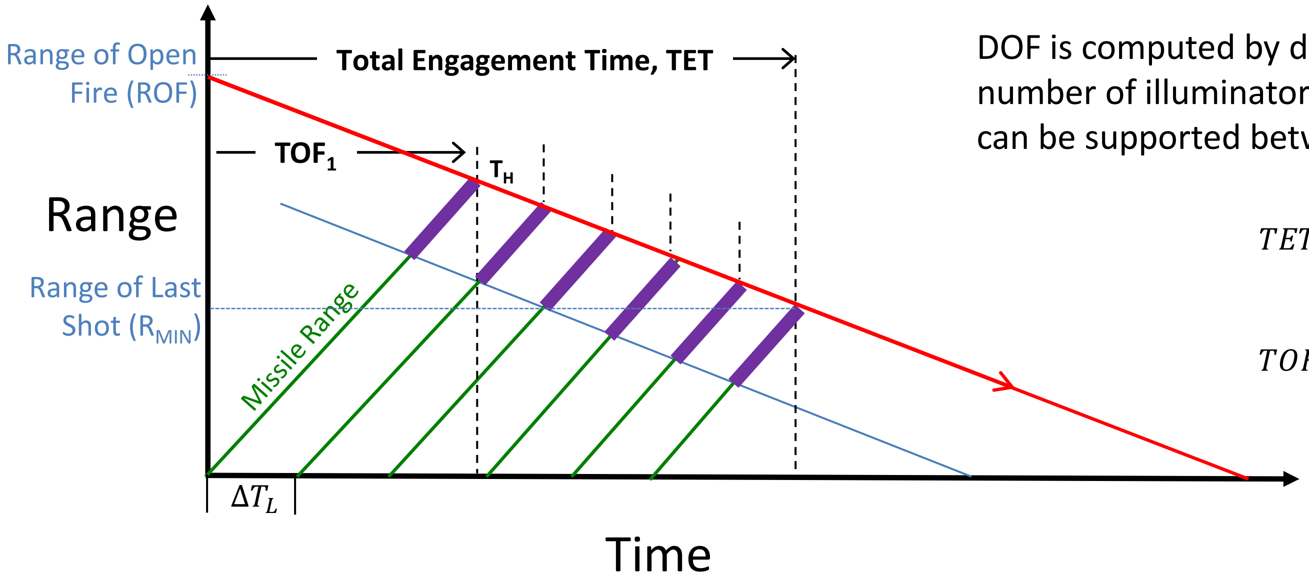
Derivation of Depth of Fire

Scheduling



DOF is computed by determining the number of illuminator time periods (T_H) can be supported between TOF_I and TET

$$TET = \frac{ROF - R_{MIN}}{V_T}$$

$$TOF_1 = \frac{ROF}{V_M + V_T}$$

$$DOF = \frac{TET - TOF_1}{T_H} + 1$$

⟺ TOF_1 is the entire duration of the first shot, one must add an additional depth of fire as $TET - TOF_1$ doesn't include the first engagement

Combine like terms (ROF) and then factor out the V_T

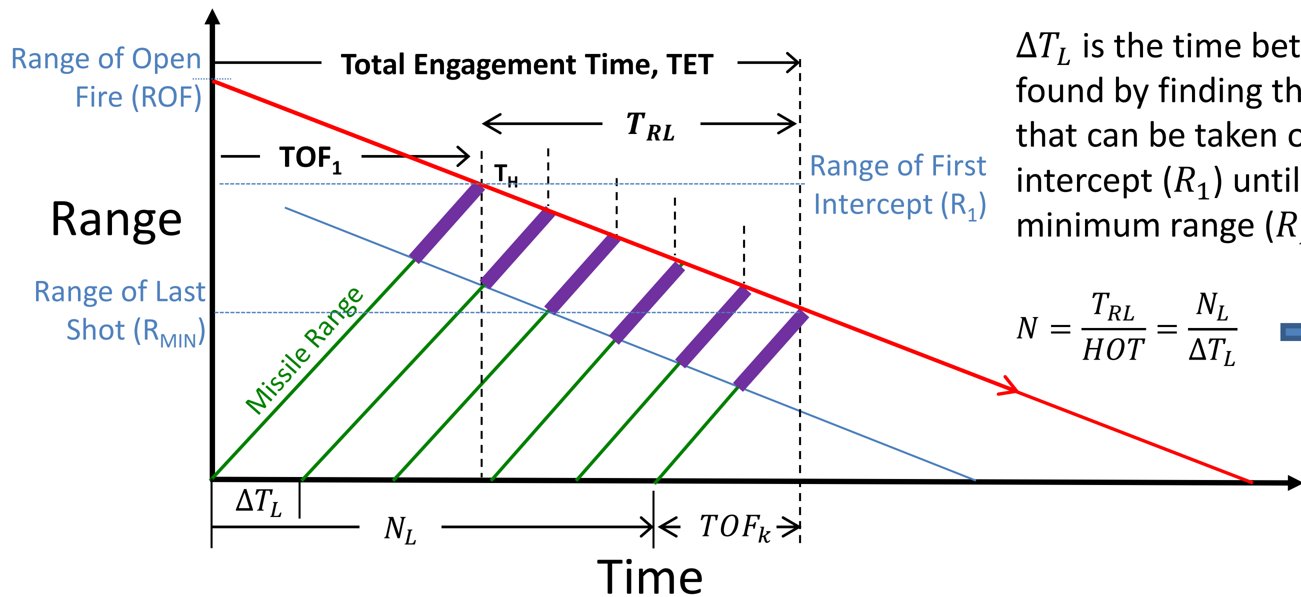
$$DOF = \frac{\frac{ROF - R_{MIN}}{V_T} - \frac{ROF}{V_M + V_T}}{T_H} + 1$$

$$DOF = \frac{ROF\left(\frac{1}{V_T} - \frac{1}{V_M + V_T}\right) - \frac{R_{MIN}}{V_T}}{T_H} + 1$$

$$\boxed{DOF = \frac{\frac{ROF}{1 + V_T/V_M} - R_{Min}}{(V_T)\,(T_H)} + 1}$$

Derivation of ΔT_L

Scheduling



ΔT_L is the time between launches. It can be found by finding the number of firings (N) that can be taken over the range of the first intercept (R_1) until the target reaches minimum range (R_{MIN})

$$N = \frac{T_{RL}}{HOT} = \frac{N_L}{\Delta T_L} \Rightarrow \Delta T_L = \frac{N_L}{T_{RL}} HOT$$

$$TOF_1 = \frac{R_1}{V_M}$$

$$TOF_k = \frac{R_{MIN}}{V_M}$$

$$T_{RL} + TOF_1 = N_L + TOF_k$$

$$\Longrightarrow\ N_L = T_{RL} + TOF_1 - TOF_k$$

$$TOF_1 - TOF_k = \frac{R_1 - R_{MIN}}{V_M} = \frac{V_T}{V_M} T_{RL}$$

$$N_L = T_{RL} + \frac{R_1}{V_M} - \frac{R_{MIN}}{V_M} = T_{RL}\left(1 + \frac{V_T}{V_M}\right)$$

$$\Rightarrow \boxed{\Delta T_L = \frac{N_L}{T_{RL}} HOT = \left(1 + \frac{V_T}{V_M}\right) HOT}$$

Optimization Philosophies

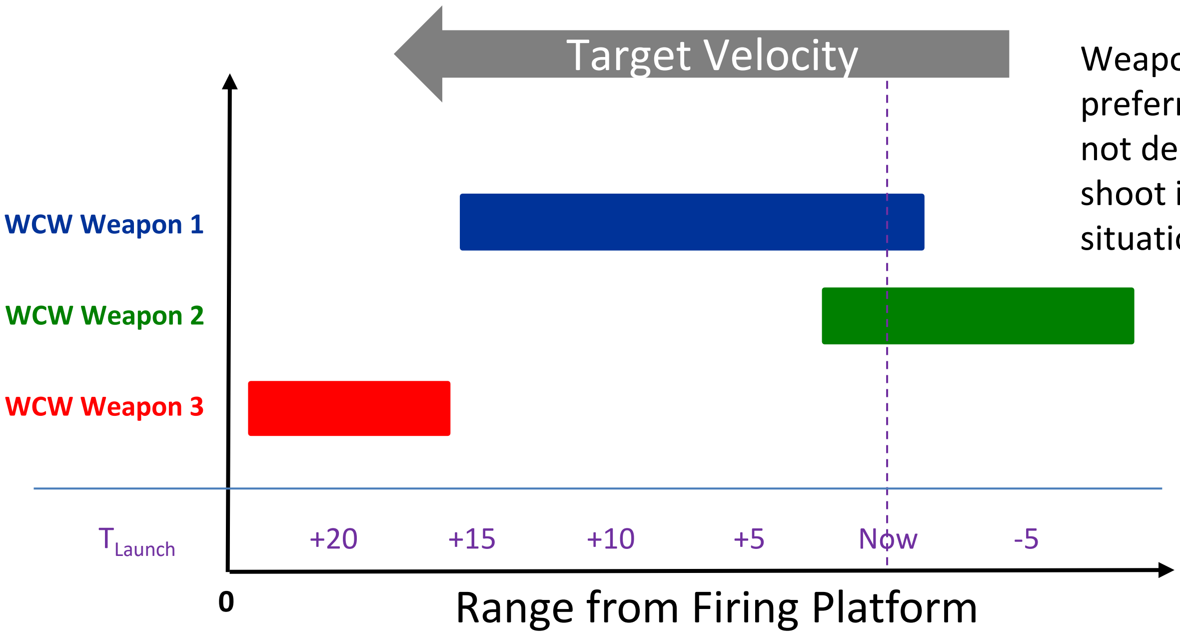
Scheduling

- Designed to optimize engagements based upon one of two philosophies
  - “Quick Draw”
    - Requires a minimum threshold of performance to considering shooting
    - Shoot early and often to maximize shot opportunities
      - More than one projectile per threat is a realistic possibility
      - Keeps the threat “at arms length”
  - “Sharpshooter”
    - Use statistics and assumed performance metrics to determine when to fire
      - Requires detailed information regarding performance metrics
      - Requires proper target ID to schedule the engagement
    - Trade depth of fire to improve performance of each engagement
      - Doesn’t waste projectiles
      - Maximizing performance on every shot

Quick Draw

Scheduling Philosophy

- For systems with multiple weapon types, it is possible that more than one weapon has a significant weapon capability window (WCW)
- Overlapping WCWs is a necessary evil in order to have a layered defense system



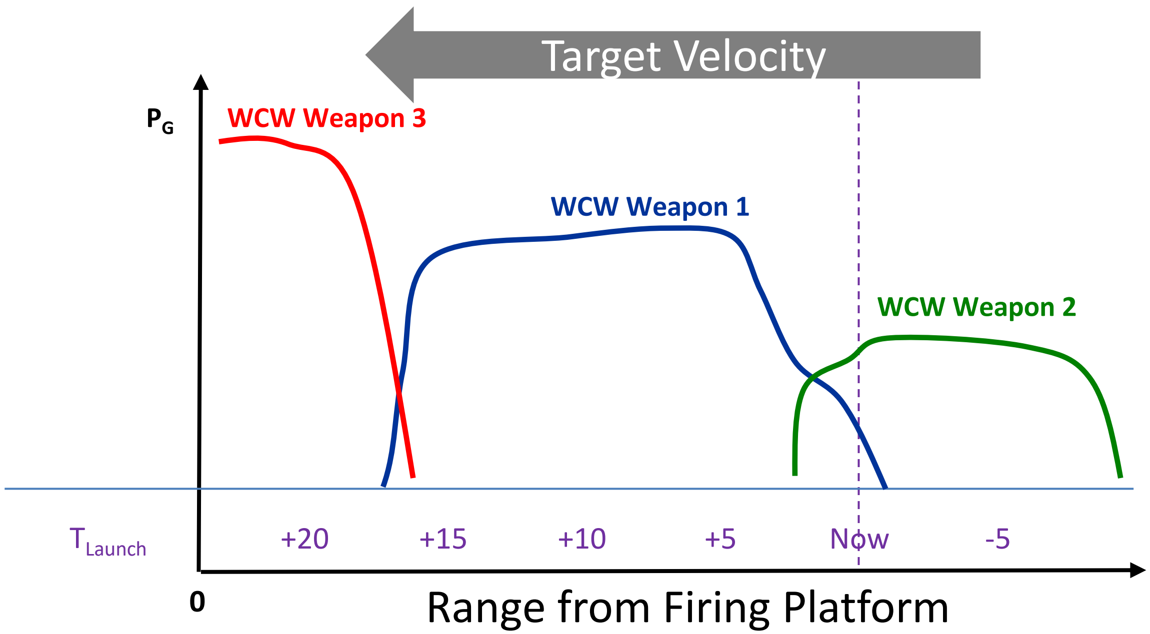
Weapon 1 and 2 are preferred weapons as it is not desirable to wait to shoot in a self-defense situation

Quick Draw Systems Shoot as Early as Possible to Maximize Engagement Opportunities

Sharpshooter

Scheduling Philosophy

- Some systems trade off depth of fire in an attempt to maximize weapon performance
  - This requires detailed weapon performance data on specific target types
- Do you wait for Weapon 1 or Weapon 3 in order to take advantage of increased P_G?



Sharpshooter Systems Will Trade Depth of Fire for Higher Performance Per Engagement

Weapon Selection Logic

- Weapon selection logic is unique to each weapon system
- Rules of thumb
  - Inventory is king
  - Use the most expendable weapon that can get the job done
- Engagement specific considerations
  - Indication of a particular threat?
    - Threat speed and altitude
    - High maneuver capability
    - Potential for electronic attack
  - Environmental considerations
    - Multipath / clutter
    - Land/sea
  - Operator input dictates a specific weapon be used

WCS with More than One Weapon Have a Hierarchy of Weapon Preferences Based Upon Engagement Specifics

Weapon Initialization

- Just prior to launch, the weapon initialization process occurs
- This process consists of any/all of the following
  - Projectile loading (guns, rail launched weapons)
  - Battery start-up (intelligent weapons)
  - Initialization data
- The contents of the initialization data is weapon specific
  - Direction to aim and time to fire
  - Intelligent weapon (missile, rocket, etc) may also include
    - GPS information
    - Initial location and speed
    - Target information (states, cue, other)
    - Supervisory information
      - Frequency list (communication channel, RF sensor/transmitter frequencies)
      - Mission specific information (low altitude, slow target, etc.)

References

1. *Corse, Joe. Midcourse Guidance Course*. 1998.
2. NAVEDTRA 14110, *Gunner's Mate 1 & C*. November 1996.
3. NAVEDTRA 14099, *Fire Controlman, Volume 2 – Fire Control Radar Fundamentals*. October 2000