Principles of Weapon Control Systems I

Gregg Bock

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

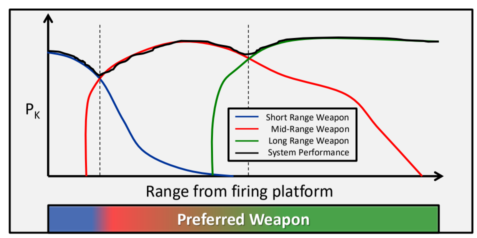
- Uniformly good system performance throughout the battle space
  - Optimum performance at each intercept point may not required
- Continuity
  - Performance "holes" for any weapon are unacceptable
  - Well-behaved performance regions for each weapon
  - Use different weapon capabilities to create a 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



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

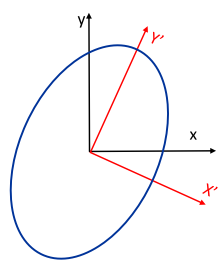
Simplicity Refers to Implementation, Not Assumptions or Capability

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…

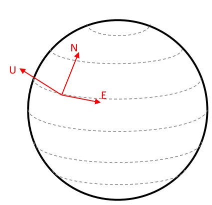
ECEF / LLA
Coordinate Systems

- 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

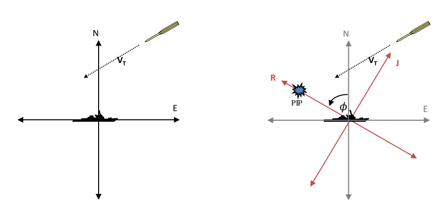
- Usage: The default coordinate system for many weapon systems
- Origin: Local Reference Point (typically fixed to a location on the platform)
- Description:
  - Defined by geographic North and geographic East, both tangent to the surface of the earth
  - The third component of the points up, and completes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

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



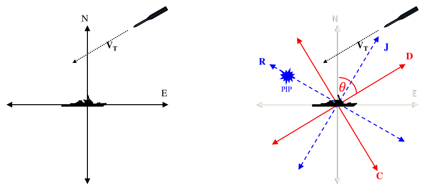
Missile Communications - JRU
Coordinate Systems

- 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

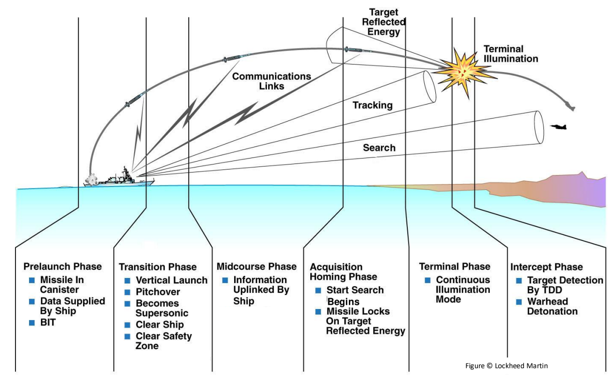


Figure © Lockheed Martin

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

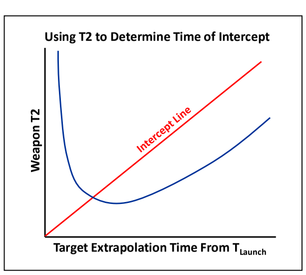
Support Functionality
- ❑ Track Processing (filtering)
- ❑ Resource Management
- ❑ Scheduling
- ❑ Displays

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

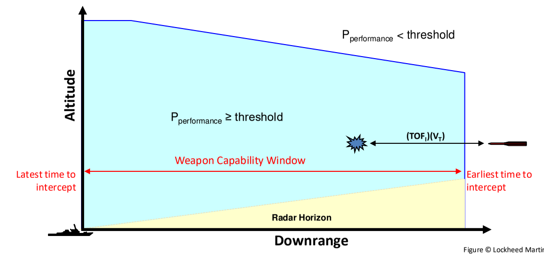
$$ROF = R2 - (V_T)(T2)$$

- ❑ 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 $RINT_T = RINT_M$

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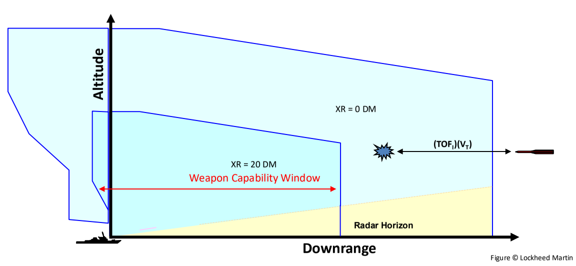
- Weapon capability contours define the boundary where the system has the capability to intercept a target with a specified kinematic characteristic (minimum acceptable P_G or P_K is inferred)
  - A target track quality must assumed
  - A contour is needed for each target speed to account for the changes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

Weapon Capability
Downrange-Crossrange View



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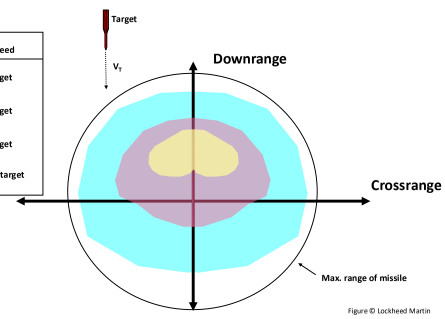
- The size of the capability contour will decrease as the crossing component of the intercept point increases

Weapon Capability
Top Down View

Color	Target Speed
(yellow)	Mach 3 target
(pink)	Mach 2 target
(cyan)	Mach 1 target
(white)	Stationary target



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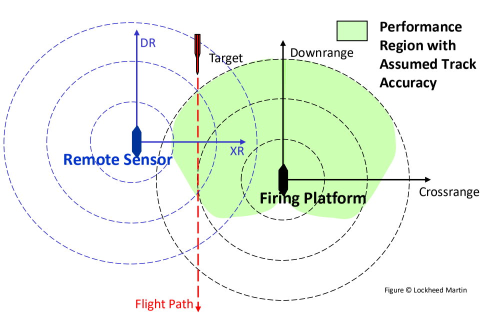
Weapon capability decreases as the target speed increases primarily due to seeker pointing constraints

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



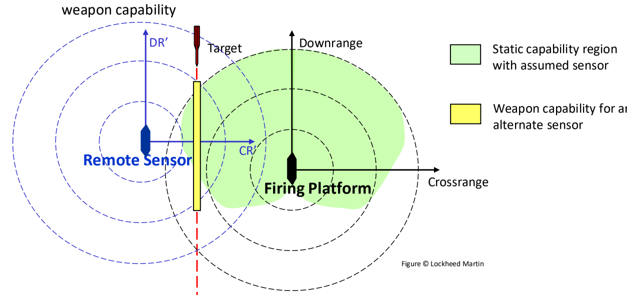
Weapon capability is only symmetric if the sensor data is symmetrical about the downrange axis

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

Figure © Lockheed Martin

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-29 Sea Sparrow Launcher

Image from reference 2

Mk-41 Launcher

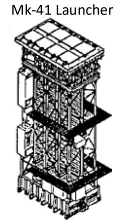


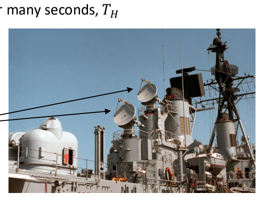
Image from reference 2

- 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

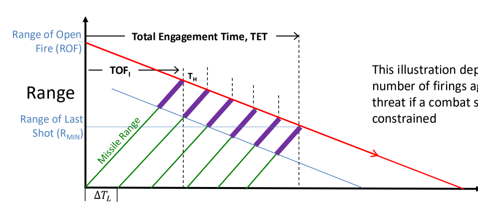
The most common illuminator type consists of a dish transmitter (AN/SPG-51 is shown)



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



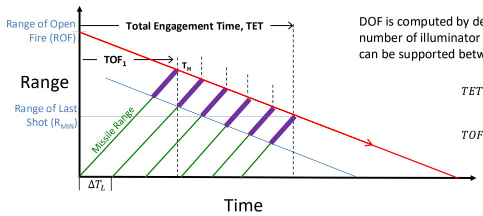
This illustration depicts then maximum number of firings against a radially inbound threat if a combat system was illuminator constrained

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

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

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

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

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

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

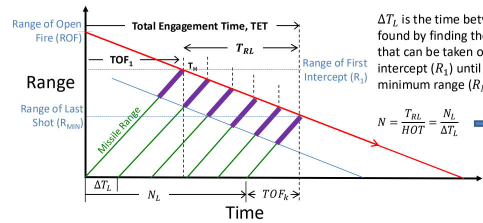
TOF_1 is the entire duration of the first shot, one must add an additional depth of fire as $TET - TOF_1$ doesn't include the first engagement

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

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

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})

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

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

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

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

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

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

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

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

Optimization Philosophies

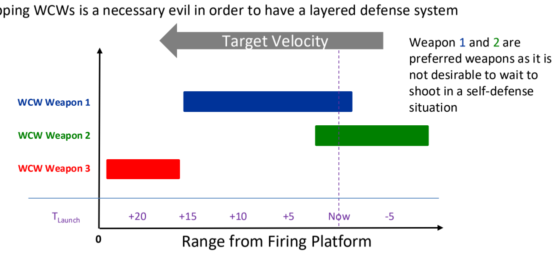
Scheduling

- 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



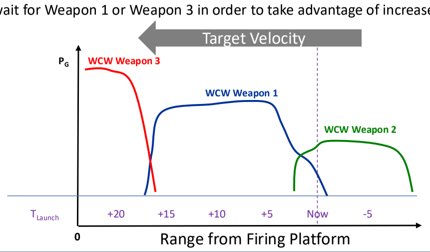
Weapon 1 and 2 are preferred weapons as it is not desirable to wait to shoot in a self-defense situation

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