Test Design for Ship Defense Against a Small Boat Threat
A Case Study

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Executive Summary

A rigorous methodology is required to effectively define the objectives, responses, factors, and test designs required to evaluate the small boat threat (SBT) requirement. Testing warships against the SBT poses many challenges. There are myriad systems and variables at work in these scenarios making the geometry difficult to define. The remote control targets used for testing are limited in number and costly to destroy. The requirements are typically ambiguous regarding test conditions. Mission decomposition is effective in determining the appropriate test geometry and design of experiments (DOE) provides the necessary rigor. This case study details one method used to transform the complex events into a testable strategy. The results of this testing can be integrated into tactical publications to enable tactical risk assessment and support development of response strategies.

Keywords**:** small boat threat, mission decomposition, design of experiments

Problem Outline

The operational scenario is a warship transiting through a narrow waterway when a number of fast, small attack craft converge on the ship from over the horizon, behind island cover, or simply from local boating traffic in the surrounding area. Ship requirements specify a minimum defensive capability against these threats. This requirement is typically stated as a probability of kill (Pk) per boat against a target raid of X small boat threats by Y yards (a minimum from the ship). The shaded area is the percentage of craft killed outside the minimum distance (equal to probability of kill). This indicates, under certain factor combinations, some target boats are expected to pass through the minimum required distance before, or without, being killed. Figure 1 shows a schematic of this requirement.

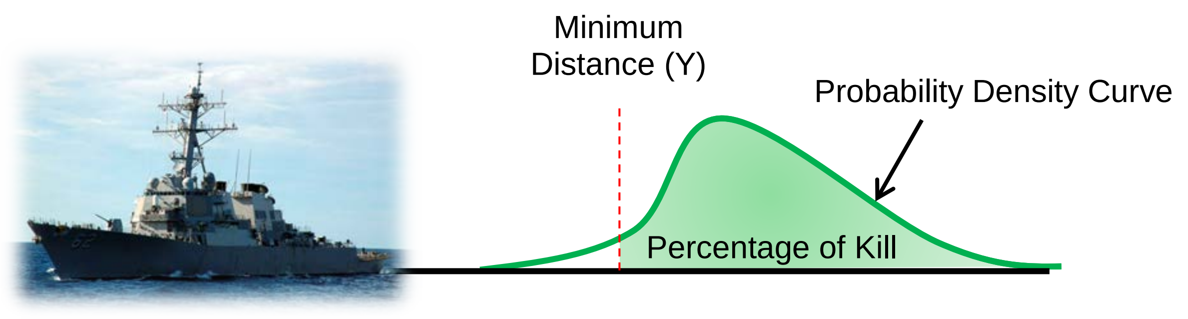


Figure 1: Requirement Schematic

This one dimensional, simply stated requirement dramatically understates the complexity of this problem and it lacks specificity about the test conditions. The weapons designed to support the requirement are guns in the 25-30mm caliber (e.g. MK-38, MK-44: referred to as "crew served"), potentially augmented by the 20mm Phalanx close in weapon system (CIWS). Additionally, there are myriad systems and variables at work in these scenarios and we can expect performance to vary with conditions.

This study will detail a test design methodology to address the requirement through the use of mission decomposition and design of experiments. This process will produce a test design sufficient to address the requirement.

Test objective: Characterize mission performance against small boat targets using selected guns under varying conditions.

Response variable: Measure the small boat target kill distance from the ship under varying conditions.

Factor Generation and Discussion

Factors are those conditions that impact the response. The contributing factors must be evaluated in order to adequately plan and scope the design. In particular, DOE requires the correct application of randomization, replication, and blocking to deliver statistically meaningful data. This factor list includes a description and any difficulties controlling or using the factor.

- Starting Range
    - Range at which the SBT begins the event.
    - This is easy to control.
- SBT Speed
    - Average SBT speed given prevailing conditions.
    - This is easy to control.
- Crossing Angle
    - The angle the SBT crosses the arc of the gun. The crossing direction is not specified so the SBT may come from either side of the gun arc.
    - This is easy to control.
- SBT Maneuvering
    - How the SBT behaves as it closes the ship which serves to increase the difficulty for the gunner to hit the SBT.
    - This is easy to control but difficult to define and results in numerous ambiguous factors. The SBT may close on a direct path, weave back and forth, turn abruptly, or circle. These maneuvers may make it harder for the gunner to engage but maneuvering also serves to lower the closure rate with the ship, effectively giving the gunner more time to act.
- Light Level
    - Comprised of amount of light (lumens) and angle of the sun (e.g. low-sunrise, high-noon, none).
    - This is very hard to control and makes randomization very costly.
- Target Type
    - These are the attributes that impact the ability to detect, track, and sink the SBT. This includes the shape, reflectivity, profile, and material of a given target.

  - This is hard to control because of the limited type of targets available. Not all threats are represented by the test targets. Testing has typically employed only the high speed maneuvering surface target (HSMST).
- Weapon Type/Location
  - Includes weapons in the 25-30mm range like MK-38, MK-44, and CIWS.
  - Selecting which weapon (or combination) to use is easy to control.
- Ship Speed
  - Own ship speed is easy to control.
- Ship Maneuvering
  - Similar to SBT maneuvering, this factor is hard to define and is related to tactics employed by the crew to optimize weapons employment and advantage.
- Detection System
  - Multiple systems are available to detect the SBT including radar (RF), electro-optical (EO), and infrared (IR).
  - Selecting which system (or combination) to use is easy to control.
- Visibility
  - Prevailing visibility is a combination of ambient light and atmospheric conditions (e.g. fog, rain).
  - This is very hard to control and impacts the ability to fully randomize the events.
- Wave Height
  - Negatively impacts the SBT speed and maneuverability as wave height increases. This may also negatively impact the accuracy of the gun as the target motion becomes more erratic in larger waves.
  - This is very hard to control and impacts the ability to fully randomize the events.
- Crew Performance
  - Individual performance is difficult to define and is impacted by experience, conditions (light, heat), alertness, etc.
  - The objective of this testing is to characterize the overall system performance, including any inherent variability imparted by the operators. The randomization of events required as a fundamental part of the design of experiments methodology should effectively nullify individual operator differences.
  - This factor is very hard to control.
- Multi-Layered Defense
  - This is the systematic employment of multiple assets to defeat the SBT. The crew may employ a multi-layered defense beyond the guns including such things as air assets, Marine snipers, and aggressive ship maneuvering. While realistic and effective, including these additional factors merges tactics and techniques with testing and significantly complicates the test space.
  - This factor is easy to control.
- Threat Geometry

  - This describes the dispersion of SBT around the ship and includes both the axis and number of SBT per axis. The number of possible combinations is proportional to the number of axes selected and the total number of SBT specified in the requirement which results in many levels.
  - This is easy to control.

Constraints

The constraints are significant and will impact the test design. These need to be carefully considered before proceeding with the development of a test design.

- Randomization is costly for these events
  - DOE requires the randomization of events to control noise from unwanted and/or unknown sources of variability. Correct execution requires randomizing day and night events which is inefficient given range costs. Blocking (all day events together and all night events together) is efficient execution but removes the ability to provide a statistical comparison between day and night responses.
  - Impact: Day and night results are of interest but the test design would result in lengthy (costly) range time with significant wasted time waiting for light conditions to change. Similarly, trying to set lighting and sun angles, while of interest, further exacerbates the complexity of the design in order to have a statistically meaningful analysis.
  - Mitigation: Day and night events can be executed in blocks (all day events and then all night events) and a non-statistical qualitative assessment can be performed. Risk exists that the data may be confounded to the point that no clear day/night differences can be explained or analyzed.
- Range time/target costs are high
  - The HSMST (and other remote control targets) are expensive to destroy. Therefore, the design must minimize consumption of these assets while obtaining the required data.
  - Impact: The specified raid size also impacts the overall cost. If every event uses the required SBT raid size in the water then each event multiplies the raid size by the number of events.
  - Mitigation: The design must focus on characterizing performance against individual boats with a strategy to assess the overall requirement.
- Threat geometry is excessive
  - Critical to addressing the requirements is adequately describing the geometry of the attack including how many axes are threatened and how the threats are dispersed.
  - Addressing the geometry depends on how the “system” is viewed. Detection and tracking can occur using various sensors simultaneously and in all directions but the component directly responsible for stopping the SBT is the individual gun. If the geometry remains centered on the entire ship geometry then the number of combinations rises quickly. Figure 3 shows three possible geometries for a notional 6 boat raid. In total, a 4 axis, 6 boat raid results in more than 60 geometries.

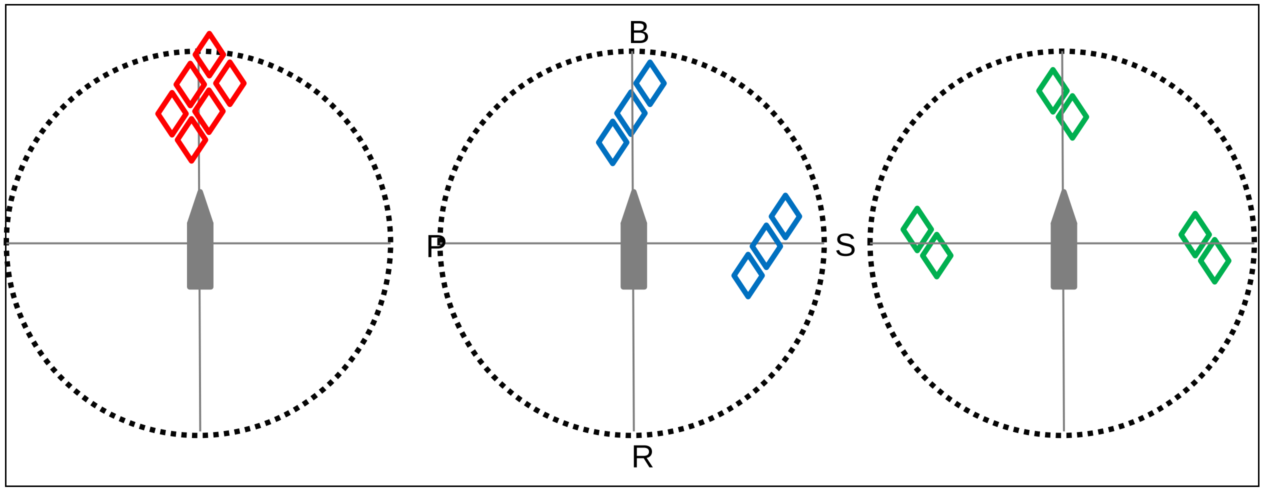


Figure 2: Possible Scenario Geometry

  - Impact: While easy to control, defining the geometry at this level will dramatically increase the design size if all legitimate geometries are considered.
  - Mitigation: The design scope will focus on the individual engagement between a gun and a target.
- Night/low visibility shooting on the range may be prohibited
  - Range safety rules may preclude shooting events at night and in low visibility.
  - Impact: This will eliminate the ability to assess performance at night.
  - Mitigation: A strategy to characterize both day and night detection ranges may permit some insight into engagement differences. While no shooting data would be available, tracking information will inform whether the SBT gains any benefits during night operations.
- Realistic gunner feedback is limited with remotely piloted targets
  - Actual threat boats operate with a controlling human who is subject to harm. Without a live operator to disable, a remotely piloted target may remain viable longer. Short of sinking the target craft (a catastrophic kill), this lack of live operator realism changes the feedback the gunner receives about when to stop shooting and transition to the next target.
  - Impact: Assessing a mission kill (SBT not sunk) cannot be accomplished until the target leaves the range. This may preclude some sequential testing if data from one event is needed to inform the next.
  - Mitigation: Failing performance results should be assessed using the multiple position responses collected. This may assist in determining if the lack of live operator feedback impacted the outcome to the point of reducing it below threshold.
- Limited target set will limit extrapolation/inference
  - The target craft may not represent all possible threat craft attributes like size, speed, and radar reflectivity.
  - Impact: Test results cannot be extrapolated beyond the target types used.

  - Mitigation: Real world threat differences can be compared against test results to assess the likelihood that performance would fall below threshold given the applicable threat changes.

These mitigation strategies will be used to define an effective and affordable test design that will address the test objective and provide the required response data.

Sequential Test Strategy

Sequential testing allows each set of tests to inform the next and provides time to conduct some needed analysis in between. This analysis may improve data collection procedures or identify and remove insignificant factors from subsequent testing. The recommended strategy contains two parts aimed at conducting lower cost testing when more targets are required and reduced testing when targets are actually consumed.

- Part 1: Detection/Tracking Only (non-shooting)
  - Characterize detection ranges across a variety of conditions.
  - This testing will highlight any issues with detection that would preclude engagement. Without this information we cannot assess the potential for failed detections which preclude engagements.
  - Can be accomplished both day and night.
  - No shooting involved so targets are not consumed (lower cost).
- Part 2: Engagement
  - Determine significance between the gun types.
  - If no statistical difference exists between weapon types then this factor can be removed from subsequent events (making the matrix smaller).
  - Potentially alter starting range based on detection ranges observed in Part 1.

This strategy does not specify which portions belong in developmental test (DT) or operational test (OT) because the range and procedures used are the same. It is recommended that DT executes part 1. Part 2 can be executed by any combination of DT and OT.

Detailed Design Development

Responses

Kill range is an obvious response taken directly from the requirement. However, elapsed time to detect, the distance travelled before detection, and engagement distances and duration are likely to vary with each event. Using mission decomposition will facilitate the determination of responses. Figure 2 shows a schematic of the SBT timeline for a single target.

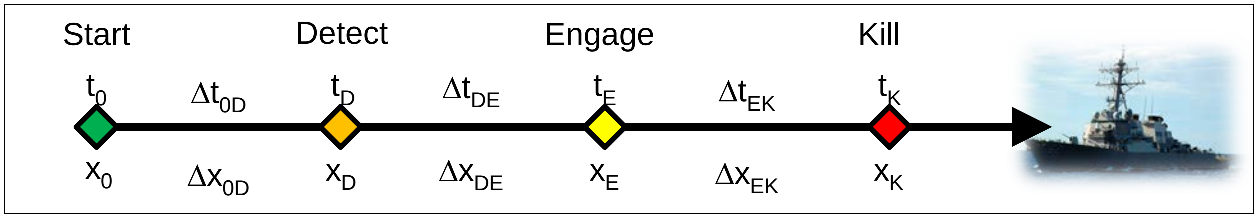


Figure 3: Mission Segment Timeline Schematic

Following commencement, some time and distance is covered by the SBT until detected by the ship. After detection, some additional time and distance may be covered until the gun engages the target. Upon engagement, the SBT continues to travel some distance until its progress is stopped. This decomposition provides granularity to the requirement and clarifies which response variables should be recorded. The three discreet segments (start to detect, detect to engage, and engage to kill) will also provide the ability to analyze which portions contribute to any marginal or failing performance. The enumerated set of responses is

- Elapsed time until detection Δt_{0D} (sec)
- Distance travelled until detection Δx_{0D} (yards)
- Detection range x_D (yards)
- Elapsed time until engagement Δt_{DE} (sec)
- Distance travelled until engagement Δx_{DE} (yards)
- Engagement range x_E (yards)
- Elapsed time of engagement Δt_{EK} (sec)
- Distance travelled during engagement Δx_{EK} (yards)
- Kill range x_K (yards)
- Number of rounds per engagement (shots/kill).

This transformation from a single outcome into distinct segments will support the development of designs to characterize segment performance and allows more in depth analysis.

Geometry Refined

Mission decomposition also clarifies the geometry. Each engagement, regardless of the number of actual targets, is a one-on-one event. Given multiple targets, the gunner engages only one until it is stopped or moves away. At that point he moves to the next threat, and so on. Even given a worst case scenario of multiple targets approaching in a line abreast, he can only engage one target at a time. Figure 4 details this geometry using the same timeline as in Figure 2. The distance travelled by the other three threats during the first engagement simply changes the location of where the remaining engagements begin. For any target, 1-4, each engagement follows the same process. Variation in time to detect, time to engage, and distance travelled during engagement will be a function of test conditions. Varying test factors will produce conditions that mimic engagements resulting from varying raid sizes. Centering the geometry on a single gun scenario enables development of factors that can be clearly defined and controlled.

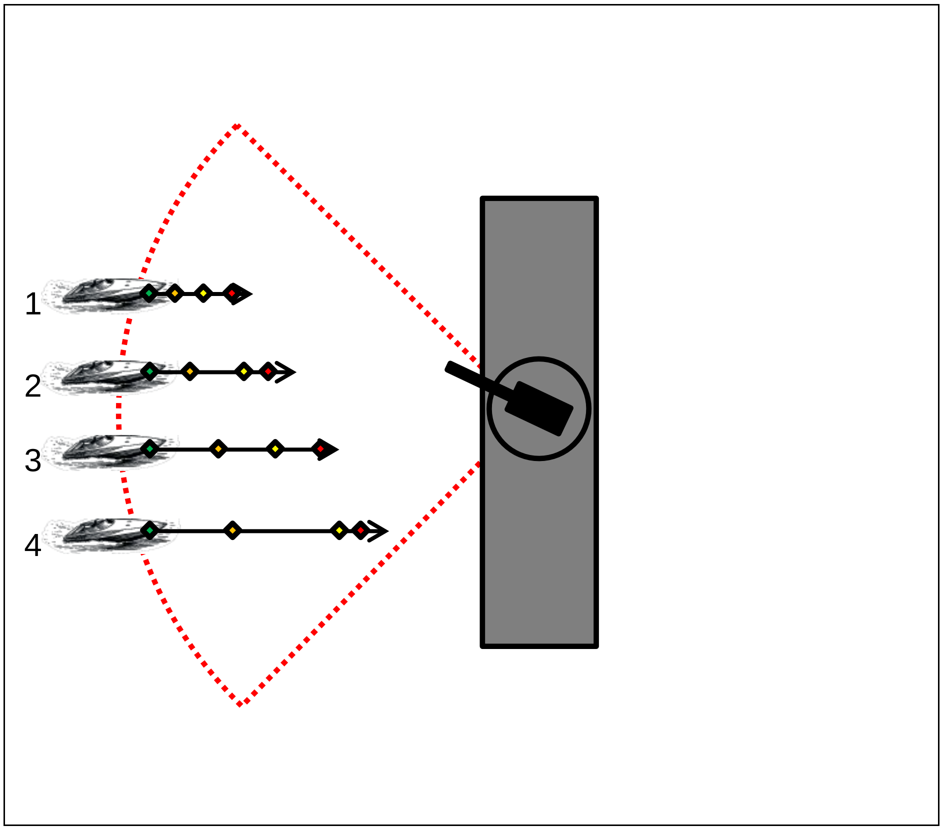


Figure 4: Multiple Target Scenario Schematic

Therefore, Part 2 planning will focus on a single target from detection through engagement.

The single target engagement geometry may appear to inadequately represent the complete operational environment. However, it does represent a complete engagement scenario from the gun's frame of reference. This effectively reduces any raid size to a single-target event and makes a very complex set of conditions testable. If additional "freeplay" events are deemed necessary in operational testing they can be conducted as capstone events with the specified raid size. If this is done, sufficient details regarding geometry, factors, and conditions should be recorded for any uncontrolled events to ensure the proper analysis can be conducted.

Design Factors and Levels

Table 1 details all the factors to be used in the design.

Table 1: Factors and Levels

Factor Name	Factor Range	Ease of Control	Notes
Starting range (TRACKING) (kyards)*	5, 10	Easy	VARY
Starting range (SHOOTING) (kyards)*	2.5, 5	Easy	VARY: levels may be modified based on Part 1 analysis

Target speed (kts)*	10, 30	Easy	VARY
Light level	Day/Night	Hard	Repeat test blocks for day and night
Target crossing angle	0, 60	Easy	VARY: above 60 degrees, target closure rate drops significantly
Weapon type/location employed	Crew served, CIWS	Easy	VARY IN PART 2: Vary weapon type. Randomize/record which location is employed if more than one mount exists on the ship.
Ship speed (kts)	Fixed @ 10	Easy	HOLD: simulate restricted maneuvering conditions
Ship maneuvering	Fixed on course	Easy	HOLD: simulate restricted maneuvering conditions
Detection system employed*	EO/IR/RF	Easy	VARY: for Part 1 tracking events. RECORD: for Part 2/3 shooting events.
Environmental conditions (wave ht, visibility, wind, rain, etc)		Very hard	RECORD

*Numbers/examples are used for illustrative purposes. Actual values may be classified and/or dependent upon requirements.

Figure 5 shows a complete schematic of the controlled factors and levels that will make up the design.

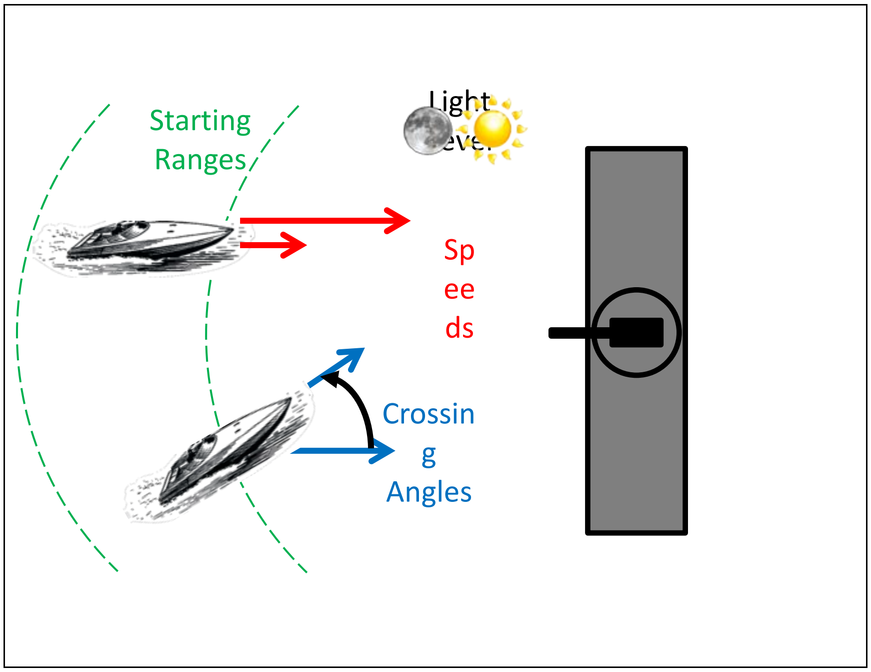


Figure 5: Factor Schematic

Design Parameters and Assumptions

The goal for test power is 80% and the signal to noise ratio (SNR) was assumed to be 1. This was used as a conservative value due to limited data. This ratio can be updated if further information becomes available through other test or training events. Increasing SNR serves to increase test power and vice versa. These designs use a confidence of 80%, typical in DOD testing. The model specified to assess power is main effects and two factor interactions.

Part 1 (Detection/Tracking only)

Part 1 Objective: Characterize elapsed time and distance to detect and assign the target for engagement under varying conditions.

This part varies all factors and measures all responses in the segments up until the engagement begins. The reduced list of responses is:

- Elapsed time until detection Δt_{0D} (sec)
- Distance travelled until detection Δx_{0D} (yards)
- Detection range x_D (yards)
- Elapsed time until engagement Δt_{DE} (sec)
- Distance travelled until engagement Δx_{DE} (yards)
- Engagement range x_E (yards).

To provide flexibility two design options are presented for Part 1. The resource and analytical differences are described for each.

1. Control/specify the sensor employed on each run.
    - This design comprises 32 runs in 4 factors and is located in the appendix.
    - This design specifies which sensor will be used on each event. This may not be normal operating procedure but it will facilitate discernment between sensor capabilities for the SBT.
    - This design is a complete set for day events. It must be completely repeated to assess night performance.
2. Do not control/specify sensor use.
    - This design comprises 20 runs in 3 factors and is located in the appendix.
    - This design removes the sensor factor from the matrix. The inherent risk in that the various sensors produce distinctly different detection results which will not be discernible in the data set. If the sensors are routinely employed all at the same time and the differences are considered negligible or of little interest then this design should be used.
    - This design is a complete set for day events. It must be completely repeated to assess night performance.

Part 2 (Limited Shooting/Gun Type Screening)

Part 2 Objective: Characterize kill range from detection through engagement under varying conditions.

Part 2 measures all responses:

- Elapsed time until detection Δt_{0D} (sec)
- Distance travelled until detection Δx_{0D} (yards)
- Detection range x_D (yards)
- Elapsed time until engagement Δt_{DE} (sec)
- Distance travelled until engagement Δx_{DE} (yards)
- Engagement range x_E (yards)
- Elapsed time of engagement Δt_{EK} (sec)
- Distance travelled during engagement Δx_{EK} (yards)
- Kill range x_K (yards)
- Number of rounds per engagement.
- Number of hits/engagement.

The starting range levels may be modified based on effective gun ranges and data compiled in Part 1. To provide flexibility in resource constraints two design options are presented for Part 2.

1. Control/specify the gun type employed on each run.
    - This design comprises 22 runs in 4 factors and is located in the appendix.
    - Each run utilizes 1 target.
    - This design specifies which gun type will be used on each event. This may not be normal operating procedure but it will facilitate discernment between gun type capabilities for the SBT.
    - This design is a complete set for day events. It must be completely repeated to assess night performance.
2. Do not control/specify sensor use.
    - This design comprises 20 runs in 3 factors and is located in the appendix.
    - Each run utilizes 1 target.
    - This design removes the gun type factor from the matrix. If only one gun type is used then this design is applicable without any confounding risk. If two guns are actually used then the risk is that the gun types actually produce distinctly different kill ranges which will not be discernible in this data set. If 2 gun types are routinely engaged on the same target or the differences are considered negligible or of little interest then this design should be used.
    - This design is a complete set for day events. It must be completely repeated to assess night performance.

Execution Information

Randomization is important to control unwanted sources of variation (i.e. trends and human factors). Any changes to the run order should be discussed with the test designer before execution.

The crew should not be cued about any raid parameters although it is realistic to assume this scenario would unfold in a choke point or restricted maneuvering situation. Therefore, the ship can be at a heightened state of alert and aware of possible threats.

Any changes to the test plan, run order, or other parameters that occur during the natural course of testing should be noted for potential use during the analysis.

If the SBT crosses the arc before being engaged the craft can be turned to the opposite direction at the same angle to maintain the geometry.

There may be differences in performance depending on the gun location on the ship. To account for this, the gun location on each test should be randomized so that each gun is exercised on several occasions during testing. The geometry for each engagement is relative to the gun frame of reference facing outboard from the ship so this is not impacted.

Analysis Methods

The analysis will be comprised of 4 portions.

- Analysis of variance (ANOVA) and determination of significant factors.
- Analysis of anomalies (missed detections or other failures).
- Day/night performance comparison (non-statistical).
- Evaluation of the requirement.

Analysis of Variance (ANOVA)

ANOVA is a collection of statistical models used to analyze the differences between group means and their associated procedures (Wikipedia). It is used to determine factor significance for a given response and supports generation of a mathematical model (equation) that can be used to predict performance throughout the test space. This model can also be used to assess the requirement via Monte Carlo simulation should the raw results appear marginal or too sparse to provide direct evaluation.

Analysis of Anomalies

Test events that do not complete or are not counted can still be analyzed to determine the contributing factors. For instance, detection failures can be assessed to see what factors contributed to this result. Conducting the Part 1 detection events first provides crucial information about the kill chain. Failure to detect may be catastrophic for the ship and knowing where the system has difficulties informs the tactical employment of the systems.

Day/Night Comparison

All data will be assessed using ANOVA but the overall day and night performance differences cannot be compared statistically due to the lack of randomization in the data. However, the variability, underlying distributions, and other attributes can be compared with the intent to provide useful performance information to the user.

Evaluation of the Requirement

This can be accomplished by comparing the overall data distribution (as in Figure 1) to the requirement and evaluating factorial test point performance. The aggregate data includes performance across all factor combinations and is the best way to compare the results to the requirement although it cannot provide information about factor combinations that result in marginal or failing performance. Examining performance at the factorial points allows the analyst to understand how conditions impacted the response. Even if the overall performance passes the requirement it is useful to know what factor conditions drive failing or marginal results. This information can be used to bolster weaknesses in the system or improve tactical employment.

Example Analysis

This example contains portions of the full analysis using the aforementioned methods in order to clarify the steps and outputs. Data was simulated from fabricated factor values to produce the "Time to Detect" data set in Appendix B. Table 2 shows that at least one of the effects is significant because the p-value is below the 20% alpha value (80% confidence) level: shown as **<.0001*** beneath **Prob > F**.

Table 2: ANOVA Table

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	14	947503.41	67678.8	656.8573
Error	17	1751.58	103.0	**Prob > F**
C. Total	31	949254.99		<.0001*

Table 3 shows the effect of the factors on the response. Significant factors are indicated by a p-value less than 0.20. This table indicates that all four main effects are significant and two of the interactions are significant (**Speed*Sensor** and **Angle*Start Range**).

Table 3: Effect Significance

Effect Tests

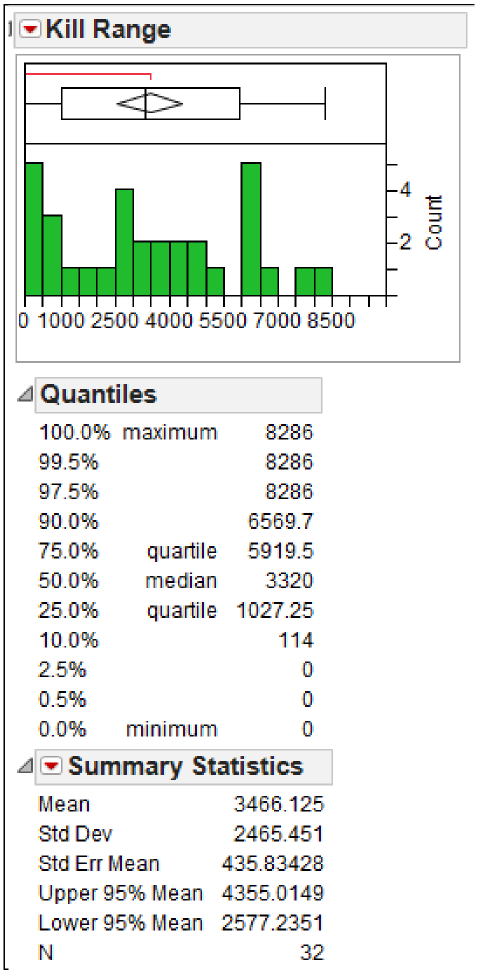
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Speed(10,30)	1	1	2023.86	19.6426	0.0004*
Angle(0,60)	1	1	389608.62	3781.350	<.0001*
Start Range(5000,10000)	1	1	57451.34	557.5945	<.0001*
Sensor	2	2	470038.36	2280.981	<.0001*
Speed*Angle	1	1	1.59	0.0154	0.9025
Speed*Start Range	1	1	2.97	0.0288	0.8672

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Speed*Sensor	2	2	610.01	2.9602	0.0789
Angle*Start Range	1	1	55828.37	541.8427	<.0001*
Angle*Sensor	2	2	53.59	0.2600	0.7740
Start Range*Sensor	2	2	100.86	0.4894	0.6213

We can use the significant effects to build an empirical model (see Appendix B) which can be employed to interpolate response between the factor settings, conduct simulations if further testing cannot be accomplished, and evaluate areas of interest.

If the data set contains any failures (craft never detected or detected too late to stop before the minimum distance) then this detection data can be analyzed to assess what factor combinations produced the late detection.

Assessing the requirement can be done by looking at the aggregate distribution. Figure 6 shows the data as a factorless histogram of the response. While this does not shed light on the contributing factors it does help replicate the data in a manner consistent with how the requirement is described. The distribution informs the percentage of SBT stopped outside the minimum distance.



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Kill Range

Quantiles
100.0%  maximum      8286
99.5%                8286
97.5%                8286
90.0%              6569.7
75.0%     quartile  5919.5
50.0%     median      3320
25.0%     quartile 1027.25
10.0%                 114
2.5%                    0
0.5%                    0
0.0%     minimum        0

Summary Statistics
Mean              3466.125
Std Dev           2465.451
Std Err Mean     435.83428
Upper 95% Mean   4355.0149
Lower 95% Mean   2577.2351
N                       32
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Figure 6: Kill Range Histogram

Conclusion

This complex test space is effectively addressed by decomposing the mission, critically evaluating the factors, and applying the rigor of design of experiments. Constraints are a significant obstacle in this test space which must be accounted for in order to create an executable plan. The development of a sequential test strategy allows the most efficient use of time and resources and supports smaller designs capable of addressing the original requirement satisfactorily. The designs produce sufficient data enabling evaluation using a number of effective methods.

Recommendations

Including Existing Knowledge into the Design Process

Information that better informs the design space will improve the SNR estimate and may further clarify the factors and levels. Collecting performance data during routine fleet training gunnery exercise will serve this purpose. A data collection card has been developed for use on the LHA-6 program for this express purpose and is available upon request.

Enterprise Solutions

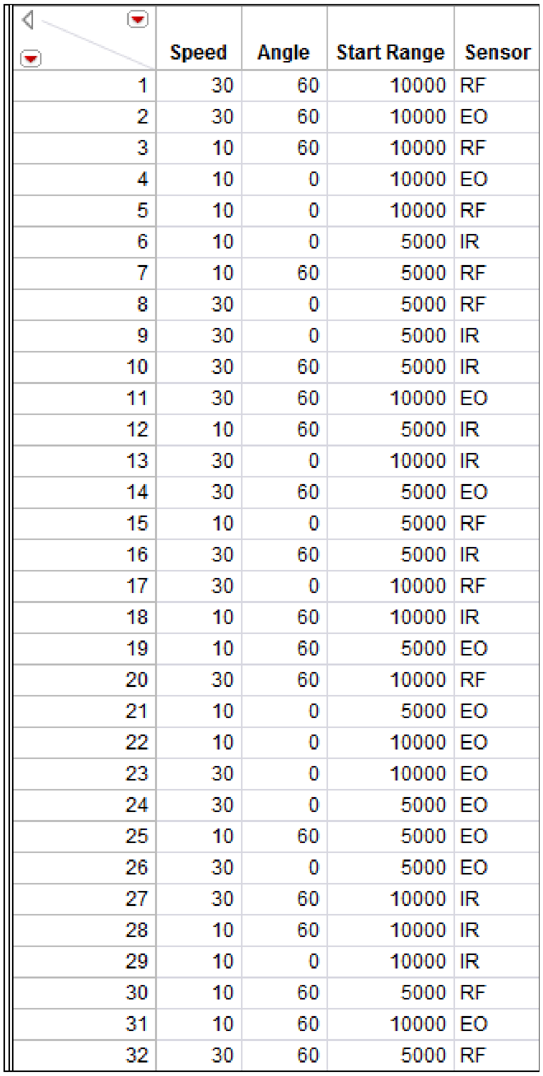
This design reflects what could be called the "first test" for a system like this. Follow-on testing would not need to repeat the entire design. Instead, well documented processes to augment these data with later testing can be incorporated to grow the data set without replicating all previous events. This can serve to validate previous results or make comparisons to previous results. While beyond the scope of this paper, this type of design could be applied as an enterprise solution to address the requirement across the fleet. The long term effect is to grow the data set in a meaningful way while keeping resource costs to a minimum.

Tactical Inference

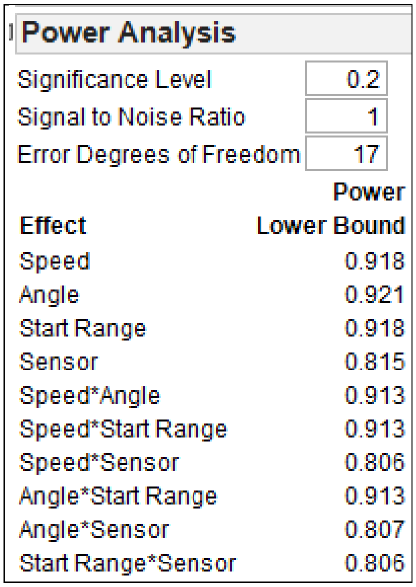
The scope of this testing will serve to adequately characterize the gun system(s) against the SBT. This data can be integrated into tactical publications to inform the crew of strengths, limitations, and risk areas and support development of larger systems-of-systems responses.

Appendix A: Test Designs

Part 1 Design Matrix (Sensor Specific)



	Speed	Angle	Start Range	Sensor
1	30	60	10000	RF
2	30	60	10000	EO
3	10	60	10000	RF
4	10	0	10000	EO
5	10	0	10000	RF
6	10	0	5000	IR
7	10	60	5000	RF
8	30	0	5000	RF
9	30	0	5000	IR
10	30	60	5000	IR
11	30	60	10000	EO
12	10	60	5000	IR
13	30	0	10000	IR
14	30	60	5000	EO
15	10	0	5000	RF
16	30	60	5000	IR
17	30	0	10000	RF
18	10	60	10000	IR
19	10	60	5000	EO
20	30	60	10000	RF
21	10	0	5000	EO
22	10	0	10000	EO
23	30	0	10000	EO
24	30	0	5000	EO
25	10	60	5000	EO
26	30	0	5000	EO
27	30	60	10000	IR
28	10	60	10000	IR
29	10	0	10000	IR
30	10	60	5000	RF
31	10	60	10000	EO
32	30	60	5000	RF

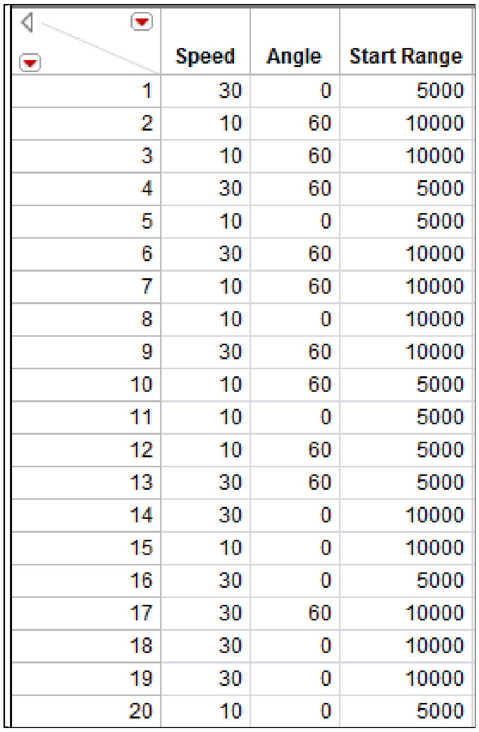


Power Analysis

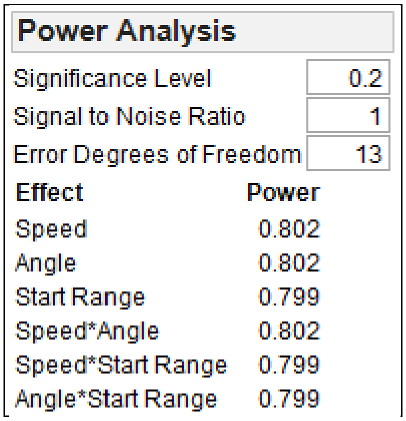
Significance Level 0.2
Signal to Noise Ratio 1
Error Degrees of Freedom 17

Effect	Power Lower Bound
Speed	0.918
Angle	0.921
Start Range	0.918
Sensor	0.815
Speed*Angle	0.913
Speed*Start Range	0.913
Speed*Sensor	0.806
Angle*Start Range	0.913
Angle*Sensor	0.807
Start Range*Sensor	0.806

Part 1 Design Matrix (Not Sensor Specific)



	Speed	Angle	Start Range
1	30	0	5000
2	10	60	10000
3	10	60	10000
4	30	60	5000
5	10	0	5000
6	30	60	10000
7	10	60	10000
8	10	0	10000
9	30	60	10000
10	10	60	5000
11	10	0	5000
12	10	60	5000
13	30	60	5000
14	30	0	10000
15	10	0	10000
16	30	0	5000
17	30	60	10000
18	30	0	10000
19	30	0	10000
20	10	0	5000

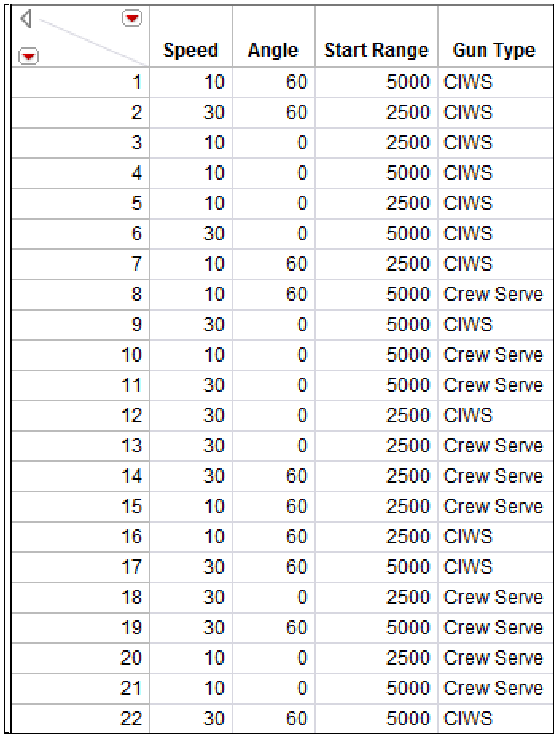


Power Analysis

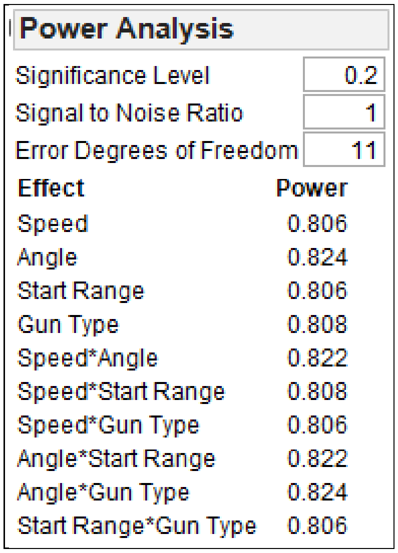
Significance Level	0.2
Signal to Noise Ratio	1
Error Degrees of Freedom	13

Effect	Power
Speed	0.802
Angle	0.802
Start Range	0.799
Speed*Angle	0.802
Speed*Start Range	0.799
Angle*Start Range	0.799

Part 2 Design Matrix (Gun Specific)



	Speed	Angle	Start Range	Gun Type
1	10	60	5000	CIWS
2	30	60	2500	CIWS
3	10	0	2500	CIWS
4	10	0	5000	CIWS
5	10	0	2500	CIWS
6	30	0	5000	CIWS
7	10	60	2500	CIWS
8	10	60	5000	Crew Serve
9	30	0	5000	CIWS
10	10	0	5000	Crew Serve
11	30	0	5000	Crew Serve
12	30	0	2500	CIWS
13	30	0	2500	Crew Serve
14	30	60	2500	Crew Serve
15	10	60	2500	Crew Serve
16	10	60	2500	CIWS
17	30	60	5000	CIWS
18	30	0	2500	Crew Serve
19	30	60	5000	Crew Serve
20	10	0	2500	Crew Serve
21	10	0	5000	Crew Serve
22	30	60	5000	CIWS

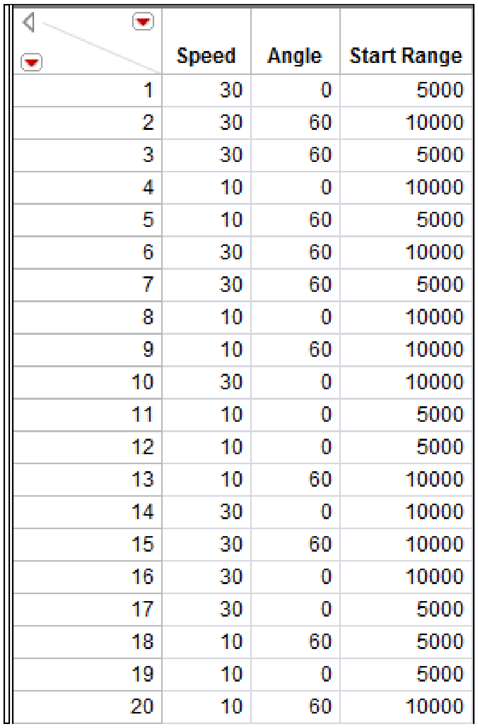


Power Analysis

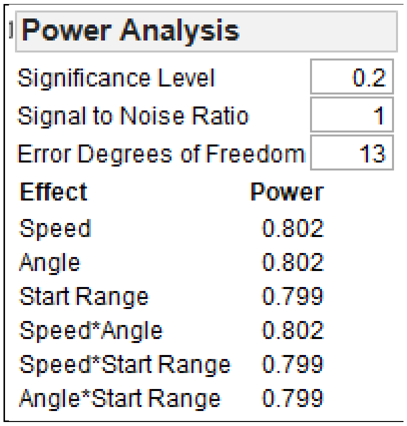
Significance Level	0.2
Signal to Noise Ratio	1
Error Degrees of Freedom	11

Effect	Power
Speed	0.806
Angle	0.824
Start Range	0.806
Gun Type	0.808
Speed*Angle	0.822
Speed*Start Range	0.808
Speed*Gun Type	0.806
Angle*Start Range	0.822
Angle*Gun Type	0.824
Start Range*Gun Type	0.806

Part 2 Design Matrix (Not Gun Specific)



	Speed	Angle	Start Range
1	30	0	5000
2	30	60	10000
3	30	60	5000
4	10	0	10000
5	10	60	5000
6	30	60	10000
7	30	60	5000
8	10	0	10000
9	10	60	10000
10	30	0	10000
11	10	0	5000
12	10	0	5000
13	10	60	10000
14	30	0	10000
15	30	60	10000
16	30	0	10000
17	30	0	5000
18	10	60	5000
19	10	0	5000
20	10	60	10000



Power Analysis

Significance Level	0.2
Signal to Noise Ratio	1
Error Degrees of Freedom	13

Effect	Power
Speed	0.802
Angle	0.802
Start Range	0.799
Speed*Angle	0.802
Speed*Start Range	0.799
Angle*Start Range	0.799

Appendix B: Sample Analysis

Sample Data Set

Speed (kts)	Angle	Start Range (Yds)	Sensor	Time to Detect (sec)	Kill Range (Yds)
30	60	5000	RF	186	2740
10	60	5000	RF	191	3694
10	60	5000	RF	179	3575
30	0	5000	RF	62	3113
10	0	5000	RF	50	4205
30	60	10000	RF	353	5986
30	60	10000	RF	392	5652
10	60	10000	RF	365	8063
30	0	10000	RF	52	6749
10	0	10000	RF	35	8114
30	60	5000	EO	493	500
10	60	5000	EO	484	758
10	60	5000	EO	478	548
30	0	5000	EO	343	500
30	0	5000	EO	356	500
10	0	5000	EO	332	500
30	60	10000	EO	669	2899
30	60	10000	EO	673	2916
10	60	10000	EO	650	4748
30	0	10000	EO	345	2894
10	0	10000	EO	348	5202
10	0	10000	EO	354	4933
30	60	5000	IR	357	966
30	60	5000	IR	347	666
10	60	5000	IR	323	1754
30	0	5000	IR	213	705
10	0	5000	IR	182	2009
30	60	10000	IR	516	4212
10	60	10000	IR	486	5968
10	60	10000	IR	497	6198
30	0	10000	IR	215	4538
10	0	10000	IR	183	6208

Prediction Expression

$$311.175$$

$$+\ 8.20315656565656 * \left(\frac{\left(\text{Speed} - 20\right)}{10}\right)$$

$$+\ 113.093686868687 * \left(\frac{\left(\text{Angle} - 30\right)}{30}\right)$$

$$+\ 43.7059343434344 * \left(\frac{\left(\text{Start Range} - 7500\right)}{2500}\right)$$

$$+\ \text{Match}\left(\text{Sensor}\right)\left(\begin{array}{lll}\text{"RF"} & \Rightarrow & -147.55946969697\\ \text{"EO"} & \Rightarrow & 149.141666666667\\ \text{"IR"} & \Rightarrow & -1.582196969697\\ \text{else} & \Rightarrow & .\end{array}\right)$$

$$+\left(\frac{\left(\text{Speed} - 20\right)}{10}\right) * \left(\left(\frac{\left(\text{Angle} - 30\right)}{30}\right) * 0.23295454545454\right)$$

$$+\left(\frac{\left(\text{Speed} - 20\right)}{10}\right) * \left(\left(\frac{\left(\text{Start Range} - 7500\right)}{2500}\right) * -0.3181818181818\right)$$

$$+\left(\frac{\left(\text{Speed} - 20\right)}{10}\right) * \text{Match}\left(\text{Sensor}\right)\left(\begin{array}{lll}\text{"RF"} & \Rightarrow & -3.1171717171717\\ \text{"EO"} & \Rightarrow & -3.395202020202\\ \text{"IR"} & \Rightarrow & 6.51237373737374\\ \text{else} & \Rightarrow & .\end{array}\right)$$

$$+\left(\frac{\left(\text{Angle} - 30\right)}{30}\right) * \left(\left(\frac{\left(\text{Start Range} - 7500\right)}{2500}\right) * 43.6261363636364\right)$$

$$+\left(\frac{\left(\text{Angle} - 30\right)}{30}\right) * \text{Match}\left(\text{Sensor}\right)\left(\begin{array}{lll}\text{"RF"} & \Rightarrow & 0.89684343434344\\ \text{"EO"} & \Rightarrow & 1.02904040404039\\ \text{"IR"} & \Rightarrow & -1.9258838383838\\ \text{else} & \Rightarrow & .\end{array}\right)$$

$$+\left(\frac{\left(\text{Start Range} - 7500\right)}{2500}\right) * \text{Match}\left(\text{Sensor}\right)\left(\begin{array}{lll}\text{"RF"} & \Rightarrow & -0.5449494949495\\ \text{"EO"} & \Rightarrow & 2.41641414141414\\ \text{"IR"} & \Rightarrow & -1.8714646464647\\ \text{else} & \Rightarrow & .\end{array}\right)$$