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ENABLING WARFARE AT THE SPEED OF LIGHT: A COMPARATIVE ANALYSIS OF MULTI-MISSION HIGH ENERGY LASER RADARS

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SYSTEMS ENGINEERING CAPSTONE REPORT

ENABLING WARFARE AT THE SPEED OF LIGHT: A COMPARATIVE ANALYSIS OF MULTI-MISSION HIGH ENERGY LASER RADARS

by

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This capstone report provides a cost effectiveness analysis of various radar systems capable of guiding the Multi-Mission High Energy Laser (MMHEL) from a Stryker platform. The Army's Rapid Capability and Critical Technologies Office (RCCTO) is developing the MMHEL to provide a Mobile Short-Range Air Defense (MSHORAD) capability to maneuver units. The MMHEL requires a radar to cue the fire control system for target engagement. Past efforts to employ high-energy lasers have relied on large, stationary radars for target acquisition. The reliance on such radars limits a unit's ability to maneuver and results in the laser being employed primarily from a defensive posture. To maximize maneuverability and enable the offensive employment of the MMHEL, the U.S. Army needs an on-platform radar that is compact and inexpensive enough to equip multiple Strykers within a Stryker Brigade Combat Team with the capability to engage targets from a mobile platform. The RCCTO is currently tasked with accelerating efforts to fill this need. The intent of this report is to assist the RCCTO in these efforts by generating a list of viable radar alternatives and conducting a cost effectiveness analysis to produce a recommendation of the most optimal solution. The results indicate that RADA's aCHR radar presents the best value in terms of cost and benefit to the warfighter.

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ABSTRACT

This capstone report provides a cost effectiveness analysis of various radar systems capable of guiding the Multi-Mission High Energy Laser (MMHEL) from a Stryker platform. The Army's Rapid Capability and Critical Technologies Office (RCCTO) is developing the MMHEL to provide a Mobile Short-Range Air Defense (MSHORAD) capability to maneuver units. The MMHEL requires a radar to cue the fire control system for target engagement. Past efforts to employ high-energy lasers have relied on large, stationary radars for target acquisition. The reliance on such radars limits a unit's ability to maneuver and results in the laser being employed primarily from a defensive posture. To maximize maneuverability and enable the offensive employment of the MMHEL, the U.S. Army needs an on-platform radar that is compact and inexpensive enough to equip multiple Strykers within a Stryker Brigade Combat Team with the capability to engage targets from a mobile platform. The RCCTO is currently tasked with accelerating efforts to fill this need. The intent of this report is to assist the RCCTO in these efforts by generating a list of viable radar alternatives and conducting a cost effectiveness analysis to produce a recommendation of the most optimal solution. The results indicate that RADA's aCHR radar presents the best value in terms of cost and benefit to the warfighter.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2AD	anti-access, area denial
ADRP	Army Doctrine Reference Publication
AFATDS	Advanced Field Artillery Tactical Data System
ARSTRAT	Army Forces Strategic Command
BCT	Brigade Combat Team
CATS	Combined Arms Training Strategy
COTS	commercial off-the-shelf
C-RAM	Counter Rockets, Artillery, and Mortars
CTP	critical technical parameter
DOD	Department of Defense
DOTMLPF	Doctrine, Organization, Training, Material, Leadership, Personnel, and Facilities
DRM	Design Reference Mission
FCS	fire control system
FOV	field of view
FW	fixed wing
GSR	ground surveillance radar
ISR	intelligence, surveillance, and reconnaissance
KPP	key performance parameter
kW	kilowatt
Mct	mean corrective maintenance time
MEHEL	Mobile Experimental High-Energy Laser
MFIX	Maneuver and Fires Integrated Experiment
MMHEL	Multi-Mission High-Energy Laser
M-SHORAD	Maneuver Short Range Air Defense Weapon System
MTBF	mean time between failure
MTTR	mean time to repair
NSS	National Security Strategy

(O)	objective
OPSIT	operational situations
OTA	other transaction authority
RAM	rocket, artillery, and mortars
RCCTO	Rapid Capability and Critical Technologies Office
RCS	radar cross section
RMA	reliability, maintainability, and availability
RSOI	Reception, Staging, Onward-Movement, and Integration
RW	rotary wing
SBCT	Stryker Brigade Combat Team
SOF	Special Operations Force
SSL	solid state laser
SOP	standard operating procedures
SWaP-C	Size, Weight, Power, and Cooling
(T)	threshold
THEL	Tactical High-Energy Laser
TRADOC	U.S. Army's Training and Doctrine Command
TRL	technology readiness level
UAS	unmanned aircraft systems
USASMDC	U.S. Army Space and Missile Defense Command
VSHORAD	Very Short-Range Air Defense

EXECUTIVE SUMMARY

The U.S. Army has increased efforts to develop directed energy weapons over the past several years. Among these efforts is the Multi-Mission High-Energy Laser (MMHEL), a 50-kW laser designed to provide a Mobile Short-Range Air Defense (MSHORAD) capability to maneuver units. The MMHEL, like all laser weapons, requires a radar to direct the beam to its intended target. Previous efforts to employ lasers have relied on large, stationary radars to serve this function. The reliance on such radars limits a unit's maneuverability and forces the weapon to be used primarily from a defensive posture.

The Army's Rapid Capabilities and Critical Technologies Office (RCCTO) is leading the MMHEL developmental effort. To maximize maneuverability and enable the offensive employment of the MMHEL, the RCCTO intends to mount radars on individual Stryker vehicles to provide an on-platform mechanism for target acquisition. The intent of this report is to assist the RCCTO in its ongoing search for such a radar, and in doing so, address the issue that the U.S. military currently lacks a radar capable of guiding the MMHEL that is compact and inexpensive enough to equip multiple Strykers in a Stryker Brigade Combat Team with the capability to engage targets on the move.

The project team conducted a cost-effectiveness analysis to determine what radar provides the best value in terms of performance and cost. Based on this analysis, the team recommends that the RCCTO procure RADA's aCHR for integration with the MMHEL. Figure 1 depicts the results of the cost-effectiveness analysis. While all the radar alternatives included in this study present unique capabilities, the aCHR provides the highest overall benefit at the lowest cost to the government. Certain radars, such as the ELM-2138M, offer a greater benefit than the aCHR but also have a significantly higher cost.

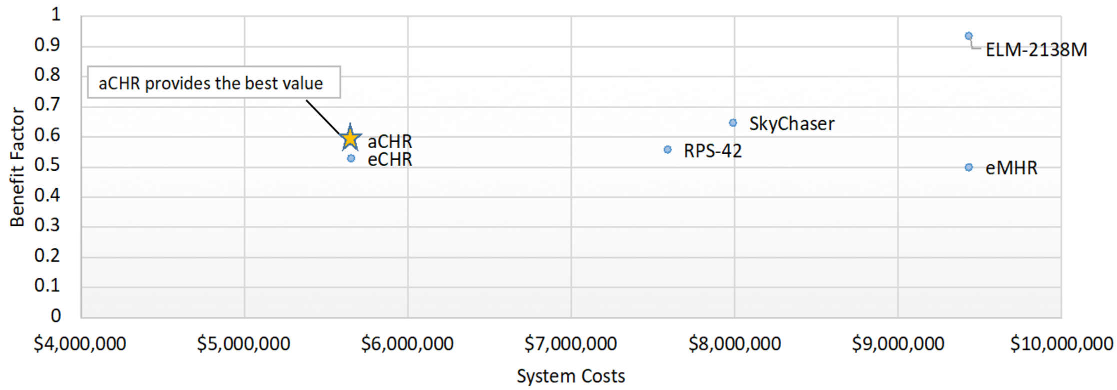

Figure 1. Cost-Effectiveness Chart

The team has two additional recommendations. The first is that the RCCTO conduct further testing to verify the raw data reported by the vendors. The project team acknowledges that the MMHEL Radar cost-effectiveness analysis relies on two fundamental assumptions. First, the study uses raw data from contractor fact sheets. Reporting bias potentially affects the pedigree of this data, as objective third-party testers have not verified the accuracy of the contractor data. Similarly, the project team relied on historical costs of analogous radar systems or contractor quotes to arrive at a cost estimate for most of the MMHEL Radar alternatives. While these cost estimates are certainly informed, they are inevitably imprecise. Consequently, the project team recommends that the RCCTO confirm the veracity of the data used in its own cost-effectiveness analysis.

The final recommendation is that the RCCTO revisit its weighting of the desired system attributes to ensure that they accurately reflect the decision maker's priorities. The sensitivity analysis conducted in support of this study indicates that the manipulation of certain attributes' weights could result in a different radar presenting the best value. If it is later decided, for example, that 360-degree coverage is more important than what is currently reflected in the weighting scheme, or that size is not as important as originally thought, results of the analysis will be significantly different. The RCCTO's revalidation of priorities, acknowledging that priorities can evolve over time, will increase the accuracy of the study's results and better inform the stakeholder's selection decision.

The team largely followed processes outlined in the *Army Cost-Benefit Analysis Guide* (2013) to arrive at these recommendations. This process was informed by additional analysis, which included a functional and requirements analysis as well as an analysis of risks and weighting sensitivity.

This study initially considered 12 different radar alternatives from six separate vendors. The team conducted market research to gain data in particular areas of interest, like radar detection range, which were derived from the RCCTO's prescribed selection criteria. This data was consolidated in Table 1 to enable a quick comparison of all 12 alternatives.

Table 1. MMHEL Radar Vendor Data

		SRC	SRC	Blighter	ELTA NA	ELTA NA	ELTA NA	FLIR	Leonardo	RADA	RADA	RADA	RADA
		SR Hawk	SkyChaser	A400	ELM-2138M	ELM-2026B	ELM-2180	Ranger R20SS	Osprey	eMHR	RPS-42	aCHR	eCHR
Panel Size	Cubic Feet	4.8	4	6	4.52	8.2	3.08	6.04	2.2	8.2	5.8	3.64	5.56
Panel Weight	Pounds	180	200	220	176.37	660	88	152	248	356	202.8	299.8	211.64
Detection Range (km)	Group 1-3 UAV	20	30	10	50	15	6	12	370	25	30	15	15
	RAM				15					8.5		4	4
	RW/FW	20	30	10	80	15	6	12	370	30	30	15	15
FOV	Elevation	55	90	90	90	60	10	45		90	80	90	90
	360˚ Coverage	360	360	360	180	360	360	360	360	360	360	360	360
Power	Watts	100	500	96	500	500	90	245	245	590	320	250	250

Three top-level screening criteria were applied to the 12 alternatives to determine entrance into the cost-effectiveness study. The first criterion was that the radar be capable of performing MSHORAD operations. This is the primary function of the MMHEL, making it a non-negotiable attribute of the radar. The second criterion was that the radar be capable of being mounted on a ground vehicle. This is critical as the radar's intended platform is a Stryker. The final and most exclusive criterion was that the radar be capable of operating while on-the-move. This function is necessary to provide the unique capability of employing the MMHEL while the platform is in motion. These three criteria eliminated six alternatives from consideration, leaving six alternatives from three different vendors as subjects of the cost-effectiveness analysis.

The team conducted a cost analysis on the remaining six alternatives, which are listed in Table 2. Verified cost data was received for the SRC SkyChaser and RADA RPS-

42, while a parametric cost estimating method was applied to determine the costs of the remaining radar alternatives. This method involved using detection range as an independent variable to develop a cost estimating relationship, as detection range was identified as a major cost driver for radar systems. This study uses cost data from the two verified alternatives and a third analogous radar system, the AN/TPQ-50, to generate three separate cost estimates for each of the remaining radar alternatives. These three estimates were then averaged together to produce a single cost estimate for each radar.

Table 2. Radar Cost Estimates

	SRC	ELTA NA	RADA	RADA	RADA	RADA
	SkyChaser	**ELM-2138M**	**eMHR**	**RPS-42**	**aCHR**	**eCHR**
Costs based on AN/TPQ50	$ 4,598,940	$ 7,664,900	$ 3,832,450	$ 4,598,940	$ 2,299,470	$ 2,299,470
Costs based on RPS 42	$ 1,900,000	$ 3,166,667	$ 1,583,333	$ 1,900,000	$ 950,000	$ 950,000
Costs based on Skychaser	$ 2,000,000	$ 3,333,334	$ 1,666,667	$ 2,000,000	$ 1,000,000	$ 1,000,000
Average	$ 2,832,980	$ 4,721,633	$ 2,360,817	$ 2,832,980	$ 1,416,490	$ 1,416,490
Verified Price	**$ 2,000,000**			**$ 1,900,000**		

The cost analysis was followed by an analysis of both the quantitative and qualitative benefits of each alternative. The quantitative benefits, which are outlined in Table 3, illustrate how well each alternative fulfills the RCCTO's requirements. Each alternative's score is the sum of every performance attribute's weighted value, with the highest sum representing the radar with the greatest quantitative benefit to the warfighter. The ELM-2138M scores the highest, mostly due to its superior detection ranges and light weight. However, these detection ranges are somewhat constrained by the radar's limited field of view, which is 180 degrees as opposed to the desired 360 degrees. The radar's light weight is also a product of this limited coverage, as the radar system only consists of two radar panels instead of the four panels that comprise each of the other alternatives. The SkyChaser has the second highest benefit score at 0.64, primarily due to its relatively low size and weight. The four remaining RADA products have comparable benefit scores, offsetting comparative advantages over each other in size or weight with lower scores in other categories, like detection range.

Table 3. Radar Benefit Scores

		SkyChaser			ELM-2138M			eMHR			RPS-42			aCHR			eCHR		
	Weight	Raw	Scaled	Wtd	Raw	Scaled	Wtd	Raw	Scaled	Wtd	Raw	Scaled	Wtd	Raw	Scaled	Wtd	Raw	Scaled	Wtd
Size	30%	4.0	0.91	0.27	4.5	0.81	0.24	8.2	0.44	0.13	5.8	0.63	0.19	3.6	1.00	0.30	5.6	0.65	0.20
Weight	20%	200.0	0.88	0.18	176.4	1.00	0.20	356.0	0.50	0.10	202.8	0.87	0.17	299.8	0.59	0.12	211.6	0.83	0.17
UAV Detection Range	15%	30.0	0.60	0.09	50.0	1.00	0.15	25.0	0.50	0.08	30.0	0.60	0.09	15.0	0.30	0.05	15.0	0.30	0.05
RAM Detection Range	15%	0.0	0.00	0.00	15.0	1.00	0.15	8.5	0.57	0.09	0.0	0.00	0.00	4.0	0.27	0.04	4.0	0.27	0.04
RW/FW Detection Rang	15%	30.0	0.38	0.06	80.0	1.00	0.15	30.0	0.38	0.06	30.0	0.38	0.06	15.0	0.19	0.03	15.0	0.19	0.03
FOV - Elevation	2%	90.0	1.00	0.02	90.0	1.00	0.02	90.0	1.00	0.02	80.0	0.89	0.02	90.0	1.00	0.02	90.0	1.00	0.02
FOV - Azimuth	2%	360.0	1.00	0.02	180.0	0.50	0.01	360.0	1.00	0.02	360.0	1.00	0.02	360.0	1.00	0.02	360.0	1.00	0.02
Power	1%	500.0	0.50	0.01	500.0	0.50	0.01	590.0	0.42	0.00	320.0	0.78	0.01	250.0	1.00	0.01	250.0	1.00	0.01
TOTAL	100%			0.64			0.93			0.49			0.55			0.58			0.53

It is important also to consider the qualitative benefits of the radar alternatives. Each of the remaining radar alternatives has particular capabilities that may not be quantifiable, but present valuable decision-making considerations to the RCCTO. Among these benefits is interoperability with other systems. The SkyChaser, for example, is compatible with existing mission command systems such as the AFATDS, which would enable a unit to digitally send target data to other systems within the area of operations. A second benefit, found mostly in the RADA alternatives, is mission flexibility. RADA's eMHR, as outlined in its 2016 data sheet, offers multiple operating modes on one product, including the ability to tune the radar to mission-dependent sensitivity configurations based on likely threat signatures. The aCHR adds the capability of tracking ground targets in addition to aerial threats, which provides options to broaden the scope of the MMHEL's use in the future. The RADA alternatives' panel design also provides flexibility in how it can be mounted on the Stryker. Conversely, the ELM-2138M's design lacks flexibility, as it is specifically designed to be affixed to the top of a vehicle. This increases the vehicle's tactical profile and potentially obstructs the view of the vehicle commander. These benefits must be considered in conjunction with the aforementioned quantitative benefits to gain a holistic understanding of the capability each radar would provide the warfighter.

The project team completed the cost-effectiveness analysis by multiplying the summed benefit factors by the projected per unit price of each radar. The resulting values, which are listed in Table 4, reflect which radar provides the greatest benefit at the best price. These values were also depicted in the Cost-Effectiveness Chart (Figure 1). The values in Table 4 are listed to the third decimal place, not with the intent to communicate a superficial accuracy in the results, but rather to highlight the slight differences in the final scores. The aCHR is ranked the highest, followed closely by the ELM-2138M and eCHR.

Table 4. Cost Effectiveness Ratio

	COST EFFECTIVENESS RATIO				RANK
SkyChaser	0.641	$	8,000,000	0.080	4
ELM-2138M	0.927	$	9,443,267	0.098	2
eMHR	0.493	$	9,443,267	0.052	6
RPS-42	0.554	$	7,600,000	0.073	5
aCHR	0.581	$	5,665,960	0.103	1
eCHR	0.526	$	5,665,960	0.093	3

The relatively small differences in the cost-effectiveness ratios of the top three radars suggest that the weights of the different performance attributes may influence the results more than intended. The team conducted a sensitivity analysis using four weighting variations to determine how manipulating these weights may impact the results. The relative weights and outcomes of the possible variations are depicted in Table 5. The first scenario is reflective of the sponsor's input and serves as a comparative baseline. The results of these weights are what is reflected in Table 4.

In a second scenario, all selection criteria are set to equal weighting. This scenario does not consider one attribute any more important than another, therefore complementing the first scenario's baseline. As a result, the top three radar alternatives remain unchanged; although, the ELM-2138M slips to third because the equal weighting of the attributes mitigates its comparative advantage in detection range. This indicates that the results will not significantly change if decision makers determine that all attributes are equally important.

Table 5. Weighting Sensitivity Analysis

RCCTO WEIGHTING	Weight
Size	30%
Weight	20%
UAV Detection Range	15%
RAM Detection Range	15%
RW/FW Detection Range	15%
FOV - Elevation	2%
FOV - Azimuth	2%
Power	1%
TOTAL	100%

	BENEFIT	RANK
SkyChaser	0.080	4
ELM-2138M	0.098	2
eMHR	0.052	6
RPS-42	0.073	5
aCHR	0.103	1
eCHR	0.093	3

EQUAL WEIGHTING	Weight
Size	13%
Weight	13%
UAV Detection Range	13%
RAM Detection Range	13%
RW/FW Detection Range	13%
FOV - Elevation	13%
FOV - Azimuth	13%
Power	13%
TOTAL	100%

	BENEFIT	RANK
SkyChaser	0.082	5
ELM-2138M	0.090	3
eMHR	0.064	6
RPS-42	0.085	4
aCHR	0.118	1
eCHR	0.116	2

RANGE MOST IMPORTANT	Weight
Size	5%
Weight	5%
UAV Detection Range	25%
RAM Detection Range	25%
RW/FW Detection Range	25%
FOV - Elevation	5%
FOV - Azimuth	5%
Power	5%
TOTAL	100%

	BENEFIT	RANK
SkyChaser	0.057	5
ELM-2138M	0.100	1
eMHR	0.056	6
RPS-42	0.059	4
aCHR	0.074	2
eCHR	0.073	3

RANGE EQUALS COVERAGE	Weight
Size	5%
Weight	5%
UAV Detection Range	14%
RAM Detection Range	14%
RW/FW Detection Range	14%
FOV - Elevation	5%
FOV - Azimuth	42%
Power	1%
TOTAL	100%

	BENEFIT	RANK
SkyChaser	0.088	4
ELM-2138M	0.082	5
eMHR	0.077	6
RPS-42	0.090	3
aCHR	0.117	1
eCHR	0.116	2

The third scenario prioritizes detection range over all other attributes. Detection range is the system attribute most closely linked to technical maturity, and as such could be considered the most important selection criteria. The third scenario allocates a combined 75 percent of the weight to detection range, reflecting the need for superior detection range in an era of near-peer competition. Under this weighting scheme, the ELM-2138M's superiority in raw detection ranges elevate it to first, while the two RADA products trail at a distant second and third. However, similar to the second scenario, the top three alternatives remain the same.

The fourth scenario assigns a weight to Field of View-Azimuth that is equal to the aggregated weight of the detection ranges. Asymmetrical battlefields require responsiveness and rapid target acquisition from employed weapon systems, making it feasible to consider a 360-degree coverage capability as equally important as detection range. As a result, RADA's aCHR, eCHR, and RPS-42 are ranked first to third respectively. As expected, this manipulation in weighting of the Field of View-Azimuth attribute dropped the ELM-2138M to fifth in the ranking. Of the three additional scenarios, this scenario resulted in the most significant changes, which highlights the sensitivity of the comparatively small Field of View-Azimuth weighting of the RCCTO's scale.

The final component of the sensitivity analysis investigates the impact of the cost estimates used in the comparative analysis. Since most costs are based on analogous estimates, this scenario mitigates any bias by assuming all costs are equal. Therefore, the cost sensitivity solely compares benefit scores using the RCCTO-informed attribute weighting. As a result, the ELM-2138M ranks first among the alternatives due to its comparative advantages in detection range, while SRC's SkyChaser ranks second driven by its relatively smaller size and lighter weight. However, RADA's aCHR still ranks in the top three alternatives. The complete results are illustrated in Table 6.

Table 6. Cost Sensitivity Analysis

	BENEFIT	RANK
SkyChaser	0.641	2
ELM-2138M	0.927	1
eMHR	0.493	6
RPS-42	0.554	4
aCHR	0.581	3
eCHR	0.526	5

The sensitivity analysis indicates that the relative difference in benefit score between the top three radar alternatives is highly dependent on the weighting scheme. Therefore, a decision maker presented with these radar alternatives must ensure the weights are truly reflective of the organization's priorities. With this consideration, the aCHR provides the best value and is the most cost-effective solution. The aCHR ranked in the top three of all alternatives in all five sensitivity scenarios, scoring the highest in three of those five scenarios. Still, the aCHR's cost estimate is assumed from analogous estimates and should be re-evaluated against comparative systems when verified cost estimates become available. The ELM-2138M provides the greatest detection range of all the alternatives. However, further analysis should be conducted on the MMHEL's physical dimensions to determine if the ELM-2138M's top-mounted design would interfere with the laser's operation. Additional tests could also determine whether the ELM-2138M can provide

360-degree coverage if mounted counter-directionally on multiple vehicles. If these issues remain unresolved, the ELM-2138M can be eliminated from the comparative analysis, leaving the aCHR as the primary candidate.

This report serves as a critical step forward in the process of equipping multiple Strykers in a Brigade Combat Team with the capability to employ the MMHEL from an offensive posture. While the content of this report will help inform the RCCTO's 2021 technology demonstration, there are significant opportunities for future research. This future research may include a level of modeling and simulation that assists in the evaluation of FY23 MMHEL Radar alternatives as the program advances through its acquisition timeline. Regardless of the particular effort, maintaining a close relationship with the RCCTO and delivering this critical capability to the warfighter is paramount.

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I. INTRODUCTION

A. BACKGROUND

1. High-Energy Laser Science and Technology Research in the U.S. Army

The Defense Science Board (2001) concluded that a national investment in high-energy laser technology was not only necessary but could potentially serve as a paradigm shift in weapon engagement speed and supportability. According to General (R) Larry Welch and Mr. Donald Latham, who co-authored the Defense Science Board study, "the potential for speed of light engagement, unique damage mechanisms, greatly enhanced multi-target engagement, and deep magazines suggest a new level of flexibility and adaptability, attributes that are particularly valuable in the complex national security environment currently existing and unfolding" (Defense Science Board 2001). The investment in laser technology would greatly benefit the military by adding flexibility to the U.S. government arsenal of weapon systems.

The United States Department of Defense (DOD) has spent several decades researching and testing directed energy weapons. High-energy lasers were of particular interest due to the multitude of potential applications across all the military services. From 1996–2005, the U.S. Army worked with the Israeli military and Northrop Grumman to develop the Tactical High-Energy Laser (THEL). The laser advanced through several development iterations and concluded with several technological demonstrations where it successfully defeated 28 Katyusha rockets, 5 artillery projectiles, 3 large caliber rockets, 10 mortars, and 3 other rocket variants (Northrop Grumman n.d.).

The THEL was among the Army's most prominent attempts to develop laser technology for tactical use. The Army considered high-energy lasers for integration into the Future Combat System family of vehicles during its development, but the THEL's size limited it to be employed as a fixed-site weapon system. The fixed-site aspect enabled the THEL's integration within a larger family of enabling systems that allow it to detect and orient-on incoming targets by relying primarily on an organic, but separate, radar structure. The THEL configuration is an effective way to achieve a high degree of laser power and radar coverage simultaneously because of the range and coverage that a large radar can provide. However, the set-up denies a unit its desired freedom of maneuver because of the constraints of a fixed-site system.

The THEL program did not consider the Army's post-Global War on Terror transition to a multi-domain force; a force that requires a higher level of maneuverability, operational access, and protection. The program certainly did not account for the resurgence of state actors, such as China and Russia, and their growing capability to employ measures that deny U.S. forces freedom of maneuver. The potential ramifications of these measures, from the strategic level down to the tactical level, make it desirable to incorporate high-energy lasers into mobile platforms capable of penetrating adversarial defenses and engaging targets on the move. While incorporating a high-energy laser into a combat vehicle platform may not present a significant engineering challenge, incorporating the target acquisition system as part of that same platform requires further development. Figure 1 illustrates the THEL concept, which displays how the system relies on a separate radar for detecting the target. While the THEL itself is far too large for a combat vehicle platform, current laser and radar technology is improving the size to capability ratio. This technological improvement could help fuel efforts to equip the Army with an on-platform high-energy laser and radar system.

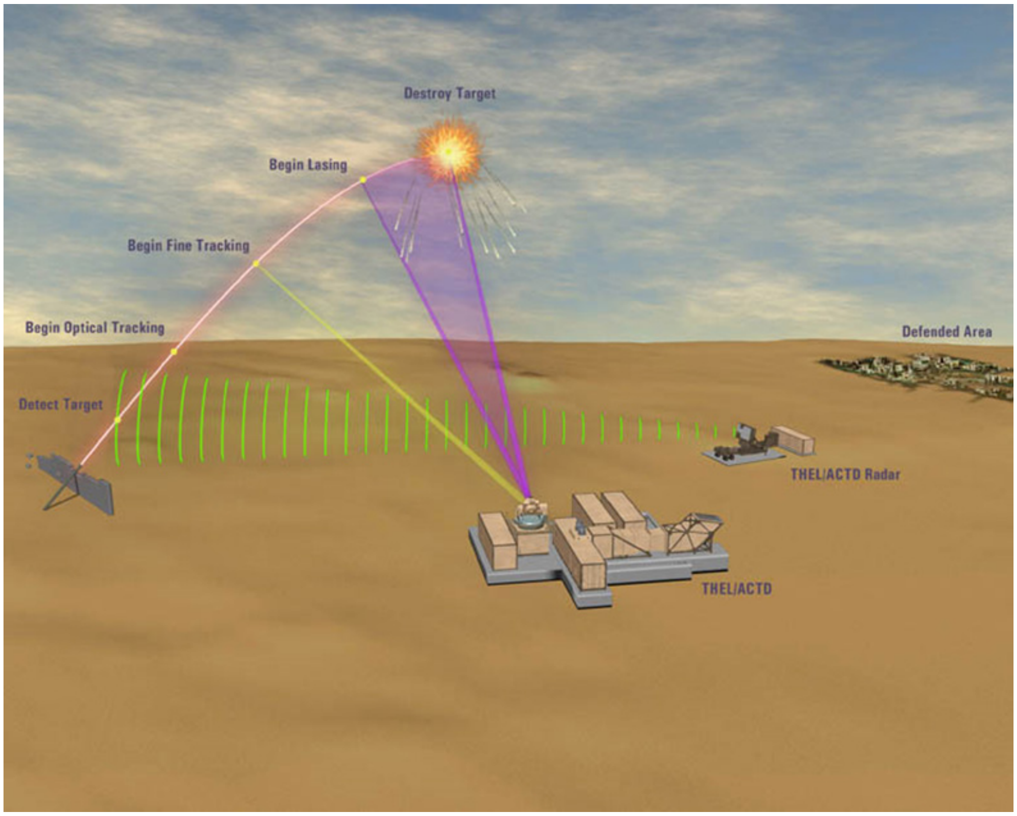

Figure 1. Northrop Grumman's THEL Concept. Source: Northrop Grumman (n.d.).

2. The Target Acquisition Problem

It has been 18 years since publication of the Defense Science Board findings. The Board found that high-energy laser technologies presented the DOD with an investment opportunity for low-cost air defense capabilities. Other technological improvements have created a defense market for smaller and more precise high-energy lasers. Technology associated with high-energy lasers is currently mature enough to conduct technology demonstrations for real-world application. However, there are issues associated with target acquisition systems at the tactical level; issues that are highlighted even greater in a multi-domain environment, in which surface combatants are not the only threats present. The multi-domain environment contains a variety of threats other than service combatants, which includes rockets, artillery, mortars, rotary and fixed wing aircraft, and unmanned aerial vehicles. To effectively combat these threats, the U.S. Army requires a target acquisition system that is capable of integrating with high-energy lasers on existing combat platforms.

Historically, high-energy laser systems require additional system support to detect targets prior to engagement. More specifically, high-energy lasers require radars to acquire targets and to orient the laser. Radar-enabled target detection is not a significant issue in fixed-site positions, as demonstrated by the THEL program, but it becomes a major issue when the system is required to be employed while on the move. Fixed-site radars are large and capable of long-range detection in a 360-degree area, but they lack the capacity to move at the same pace as a maneuver unit. The most maneuverable fixed-site radars take time to set-up, break down, and move with a trailer, making them highly vulnerable to threats within a multi-domain environment. Attempting to achieve the same range and coverage of fixed-site radars with a vehicle mounted radar is nearly impossible with the existing market technologies. For this reason, high-energy laser capabilities are directly tied to whatever target detection options exist. According to Professor David Jenn of the Naval Postgraduate School's Electrical and Computer Engineering Department, longer detection ranges require larger antenna size relative to wavelength (Jenn 2008). In order to detect targets at longer distances, a larger antenna with a lower frequency is the ideal fit. This is problematic for a combat vehicle platform because of the resulting increased signature, among other things. However, several defense contractors, including foreign-based contractors, dedicated significant research and development dollars in search for a potential radar solution.

3. Current Efforts

The current landscape of advanced foreign capabilities motivated the Army to investigate U.S. technologies that would provide greater force protection to troops facing near peer adversaries across a large variety of terrains. More specifically, low cost small unmanned aircraft, among other threat systems, are now easily obtained by adversaries, driving the need to pursue inexpensive countermeasures. The U.S. Army Space and Missile Defense Command/Army Forces Strategic Command (USASMDC/ARSTRAT) commenced an effort in 2016 that would demonstrate laser technologies to improve force protection. The USASMDC/ARSTRAT integrated a 5-kilowatt (kW) laser onto a Stryker platform vehicle called the Mobile Experimental High-Energy Laser (MEHEL). Contractors demonstrated the MEHEL at the Joint Improvised-Threat Defeat Organization's Counter-Unmanned Aerial System Hard-Kill Challenge in March 2017. The system successfully defeated small rotary and fixed-wing unmanned aircraft systems (UAS). Subsequently, Soldiers received training on the system at the Maneuver and Fires Integrated Experiment (MFIX) in 2017 and successfully engaged a UAS (USASMDC/ ARSTRAT-MEHEL 2019). MFIX is a two-week event designed to demonstrate and validate advanced weapon capabilities. The exercise considers changes in doctrine that could provide U.S. warfighters with a competitive advantage against adversarial threats (Guthrie 2018). Soldiers also tested the MEHEL at MFIX in 2018 and the Joint Warfighter Assessment in 2018. The Army upgraded the MEHEL to a 10-kW laser in 2019 for testing at the annual MFIX (USASMDC/ARSTRAT-MEHEL 2019).

The Army's Rapid Capability and Critical Technologies Office (RCCTO) accelerates such capability development to meet the Army's modernization needs. The RCCTO assumed responsibility for developing the MEHEL, which it ultimately plans to develop into the Multi-Mission High-Energy Laser (MMHEL) to deliver Maneuver Short Range Air Defense Weapon System (M-SHORAD) capabilities. The MMHEL is a 50-kW solid state laser (SSL) designed to protect maneuvering forces from rocket, artillery, and mortars (RAM), UAS threats, and fixed-wing and rotary-wing manned aircraft. The system's optical sensor also provides enhanced long-range intelligence, surveillance, and reconnaissance (ISR). The MMHEL will lower the cost per engagement and reduces a unit's logistical burdens by neutralizing threats with no ordnance resupply requirements (USASMDC/ARSTRAT-MMHEL 2019).

The RCCTO awarded a $200M contract to Kord Industries based in Huntsville, AL to develop the MMHEL. Kord Industries subcontracted with Northrup Grumman and Raytheon to build competitive prototypes to meet the Army's requirements (Kord Technologies 2019). The competition will culminate with a procurement of three additional prototypes from the vendor that best achieves the MMHEL radar requirements for transportability, technology readiness, operational environment, and Size, Weight, Power, and Cooling (SWaP-C). The RCCTO scheduled the first prototype demonstration for April 2021, with hardware procurement set to begin in July 2020. The RCCTO contracted with the vendors with a cost-sharing strategy using other transaction authority (OTA). This contract type allows the vendors to demonstrate the 50-kW laser with whatever type of radar that enables them to do so, regardless of whether it meets the full list of requirements or not. This is because the intent of the demonstration is to prove the 50kW laser is capable of fulfilling the M-SHORAD mission, with less emphasis being placed on the type and capabilities of the radar itself. The RCCTO anticipates that the required radar subcomponent will not be commercially available for fielding in 2023. However, the MMHEL could potentially be fielded with a commercial off the shelf (COTS) radar while the Army pursues development of a more optimal radar that meets all the key performance parameters (KPPs).

The radar sensor that provides target cues to the Battle Management Command and Control subsystem is a critical component of the MMHEL. Laser-based weapons generally require a separate radar sensor to illuminate a target and track its movement for beam control. The beam control system must be able to focus the laser on a precise target and stay focused on the target "like a blowtorch" as the target moves (Freedberg 2019). The MEHEL demonstrations utilized a basic Ku band radar mounted to the front of the Stryker solely for proof of concept (USASMDC/ARSTRAT-MEHEL 2019). The Ku band radar limited the field of view (FOV) to 90 degrees, minimizing its effectiveness in a combat environment. While larger radars that are organic to a typical Brigade Combat Team (BCT), like the AN/TPQ-53, can provide a 360-degree FOV, they are too large to mount on a vehicle platform and would limit the maneuverability required at the tactical level.

According to the High Energy Laser Executive Review Panel Beam Control Working Group, "beam control refers to all functions required to transport a high-energy laser beam from the laser device to the target" (cite DSB). The working group found 20 terms that encompass beam control. Ten functions and 10 components that are mostly present in all high-energy laser systems. Since beam control is a critical aspect of high-energy laser systems, current development efforts in the military industrial base have focused efforts on creating beam control mechanisms for ground-based systems; however, the target acquisition function remains one of the least developed aspects of beam control. The slower progress may be a result of interoperability with existing radar infrastructure in Army formations, or perhaps because the technology maturation process is lacking for target acquisition systems. Regardless the cause, the slower progress in this function of beam control made it a prime candidate for research. This capstone report focuses on one of the beam control functions: target acquisition.

B. PROBLEM DESCRIPTION

1. Problem Statement

The aforementioned 2017 demonstration of the MEHEL was among the Army's first efforts to field an on-platform radar to support the beam control system and more effectively direct high-energy laser weapons. Prior to that demonstration, the employment of high-energy lasers relied on the unit's organic radars to provide beam control, target acquisition, and other enabling capabilities. A Stryker Brigade Combat Team (SBCT) has six organic radars: two AN/TPQ-53 radars, which are currently replacing the older AN/TPQ-36 and AN/TPQ-37 variants, and four AN/TPQ-50 Lightweight Counter Mortar Radars. There are two primary issues with using these radars to employ high-energy lasers. First, the AN/TPQ-53 must be stationary to be employed, limiting the range in which the Stryker can effectively activate the laser. The second issue is that the limited number of radars places a constraint on when and where they are employed, often times being positioned in areas that hinder the laser from being employed as intended. Primarily serving as a protection asset, for example, these radars are more likely to be positioned near key mission command nodes rather than forward of the main body with an assault element. The overall impact of these issues is that both force the high-energy laser to be used as a defensive weapon rather than an offensive weapon; a weapon capable of being fired while advancing toward an objective. To use this weapon offensively, as well as improve its accuracy and lethality, a radar must be placed on the platform itself. This necessary condition highlights the problem: *the U.S. military lacks a radar capable of guiding the Multi-Mission High Energy Laser that is compact and inexpensive enough to equip select Strykers in an SBCT with the capability to engage targets on the move.*

2. Scope

The scope of this project is defined by three key factors. First, the cost-benefit analysis will be limited to radars that are compatible with the Stryker vehicle. A fixed platform type will prevent external variables, like vehicle power generation or weight, from unduly influencing the results. The second factor that refines the project's scope is that all analysis will exclusively focus on radars capable of guiding the MMHEL. The term "directed energy weapons" refers to a broad family of weapons, which includes lasers, microwaves, and other forms of highly focused energy. This project will focus specifically on the MMHEL, which is a particular type of laser that the U.S. Army is currently developing to provide Mobile Short-Range Air Defense (MSHORAD) capabilities. Finally, alternatives considered in our analysis will be limited to technology that currently exists or that will be available prior to the end of fiscal year 2020. This boundary is driven by the technology readiness level (TRL) 7 demonstration the RCCTO is conducting on initial prototypes in April 2021. Input received from key stakeholders influenced the project's scope and directed the team's efforts.

3. Key Assumptions

There are two primary assumptions that guide this study. First, this study assumes that the Stryker will continue to serve as the platform of choice for the MMHEL and its associated radar. Therefore, all concerns for the radar's power generation, mount configuration, and systems integration center on Stryker-specific considerations. This nests with the RCCTO's efforts, as the current technology maturation efforts focus on integrating the MMHEL on the Stryker. While the intent is undoubtedly to implement the MMHEL or a similar system across multiple platforms in the future, this study necessarily scopes the integration hurdles to the near-term time horizon. Finally, this critical assumption also enables a true comparison of various radar alternatives by holding the variable of a ground-based weapons platform constant.

Similarly, this study assumes that while the MMHEL currently focuses on an MSHORAD mission set, the long-term focus will broaden to include surface threats. Consequently, this study will primarily consider MSHORAD-specific radar attributes, while incentivizing any radar alternatives' ability to feasibly expand its capability for the search, identification, and tracking of near-peer surface and ground threats.

C. PROJECT OBJECTIVES

This capstone project has three primary objectives. First, the project seeks to inform the U.S. Army's ongoing search for a compact, vehicle-mounted radar that enables the use of a 50-kW laser weapon system. This is not just a material effort, but must integrate the additional aspects of the Doctrine, Organization, Training, Material, Leadership, Personnel, and Facilities (DOTMLPF) framework to deliver a holistic competitive advantage. Beginning with a description of the current gap in capability, this study links user needs, as defined by current strategic joint doctrine, with the desired system attributes.

While the Army has successfully demonstrated the capability of a radar system in support of a 5-kW laser weapon system mounted on a Stryker, the capability required to prosecute a near-peer UAV threat demands a vehicle-mounted radar array in support of a 50-kW laser weapon system. Therefore, the second project objective, in concert with the RCCTO, aims to evaluate the various radar alternatives currently assessed to be technologically mature by the beginning of FY21. Presented as a cost effectiveness analysis, this evaluation is informed by measurable and weighted system attributes developed, in part, from the capability gap assessment conducted in support of the first project objective.

Finally, this project assists in addressing the larger issue of the U.S. military's lack of a mobile, ground-based mechanism for defeating a near-peer air threat in an anti-access, area denial (A2AD) environment. Therefore, this study looks at the operational context in which this weapons system will be employed. Since the RCCTO is still in the nascent stages of hardware procurement, this study constructs several mission profiles that may be used for further modeling and simulation studies of the various MMHEL radar alternatives.

D. STAKEHOLDER ANALYSIS

This project has several stakeholders. The primary stakeholder is the RCCTO, with whose efforts this project is intended to align. As such, this stakeholder analysis was developed from the RCCTO's perspective in an effort to better focus efforts at nesting the project's objectives with those of the RCCTO. The early recruitment of key stakeholders allows the RCCTO to leverage a wide spectrum of knowledge which will inform the development of a solution to the identified problem.

The capstone team conducted an initial brainstorming session to determine relevant stakeholders who are currently involved, or who may become involved, in the RCCTO's technology maturation effort of the MMHEL. The output of this analysis is captured in the stakeholder register that has categorized stakeholders by using an Influence/Impact Grid (Figure 2). The grid is an analytical tool that provides a method of "grouping the stakeholders based on their active involvement, or influence, in the project and their ability to effect changes to the project's planning or execution" (PMI 2013, 396). The four categories within the Influence/Impact Grid are defined as:

- Manage Closely: Viewed as stakeholders who are most important and vital to the RCCTO's success. These stakeholders should be continuously informed and prioritized highly.

- Keep Satisfied: Viewed as stakeholders to keep informed with noteworthy progress and issues. These stakeholders are very interested in day-to-day updates that may affect their roles and responsibilities.

- Keep Informed: Viewed as stakeholders to keep well-informed while ensuring they remain satisfied with the progress and direction of the RCCTO's effort.

- Monitor: Viewed as stakeholders who only require periodic updates. Awareness of RCCTO progress can be received monthly.

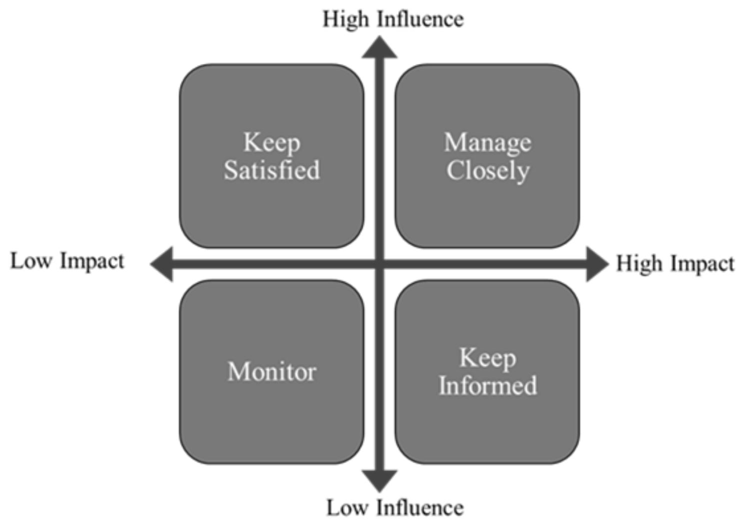

Figure 2. Influence/Impact Grid. Adapted from Project Management Institute (2013).

The Stakeholder Register outlined in Table 1 is expected to evolve and will be reviewed regularly to capture all necessary changes. The expected updates will occur when new stakeholders are added or when current stakeholders are no longer required to assist in the RCCTO effort. The accurate identification of relevant stakeholders is vital for the RCCTO to better determine how to leverage additional support as the effort progresses. The advantage of this process is that "it provides a clear, actionable plan to interact with project stakeholders to support the project's interests" (PMI 2013, 399).

Table 1. Stakeholder Register

Expected Stakeholders	Needs / Interests	Influence Level	Impact Level	Involvement/Classification
Rapid Capabilities and Critical Technologies Office (RCCTO)	• Leverage innovation from industry • Receive Warfighter feedback • Deliver solution on an accelerated timeline	High	High	Current; Internal; Supporter
Army Futures Command	• Provide expertise and guidance to help integrate solution into SBCT • Oversee development and fielding of solution to the Warfighter	Low	High	Periodic; External; Supporter
Maneuver Center of Excellence (MCoE)	• Update maneuver doctrine, training, and education to incorporate new solution	Low	Low	Periodic; External; Neutral
Combat Capabilities Development Command (CCDC) Ground Vehicle Systems Center	• Integration of solution onto manned ground system • Utilize existing ground system capabilities as platform for the solution • Provide future development alternatives to fill long term capability gap	High	Low	Periodic; External; Supporter
PM-Stryker Brigade Combat Team (SBCT)	• Involvement with all RCCTO decisions associated with Stryker Family of Vehicles (FoV)	High	Low	Current; External; Supporter
Congress (HASC/SASC)	• Continuous oversight of RCCTO progress on solution • Review funding request and authorize appropriate funding	Low	High	Periodic; External; Neutral
Assistant Secretary of the Army (Acquisition, Logistics, and Technology) ASA(ALT)	• Continuous progress reporting to inform USD(AT&L) • Facilitate cross branch communication with Navy and Air Force Acquisition Executives	Low	High	Periodic; External; Supporter
Army Foreign Comparative Testing (FCT) Program	• Connect foreign technologies as options for solution • Strengthen ties with foreign vendors for partnership	Low	Low	Periodic; External; Neutral
Industry Partners	• RFPs for prototype contracts • Completed designs to test	High	Low	Current; External; Supporter
Director, Operational Test and Evaluation	• Provide independent and objective assessments throughout all testing • Determine that solution is operational effective, operationally suitable, and survivable	Low	High	Future; External; Neutral
Army Test and Evaluation Command	• Assist with development of RCCTO operational test planning	Low	High	Future; External; Supporter

II. DESIGN REFERENCE MISSION

A. CHAPTER INTRODUCTION

The Design Reference Mission (DRM) provides an operational context for the MMHEL Radar as a supporting component to small unit force protection in an anti-access, area denial (A2AD) environment. The DRM frames the employment of the MMHEL in a Stryker Brigade as a tool to combat UAS, RAM, and fixed or rotary wing aircraft. The operational narrative theorizes enough details to enable further scenario-based wargaming in a variety of similar combat environments. The DRM considers the MMHEL Radar's role as a force multiplier that enhances the SBCT's overall environmental awareness by slewing target data to adjacent friendly radar systems for improved fire control responsiveness. This reference mission postulates the use of the MMHEL system as an offensive weapon that offers a lower cost per engagement against aerial threats. The DRM highlights the MMHEL's ability to conduct follow-on missions without the need for logistical support or added resupply requirements. This offers the RCCTO a basis for developing mission success requirements in the execution of the MMHEL Radar operations. This reference mission also defines measures for the system's success in the realm of target acquisition; more specifically, how well the MMHEL Radar tracks, detects, and classifies targets. It also defines measures for how well the MMHEL Radar interoperates with the MMHEL itself and the Stryker vehicle.

The following is the analysis question motivating the development of this DRM: How could an on-platform radar be employed to increase the mission success of a Stryker-mounted Multi-Mission High Energy Laser, while reducing the latency in the target engagement sequence, as compared with an architecture that does not utilize a compact, cost-effective, and interoperable radar system?

B. SYSTEM TRACEABILITY

Prior to examining the DRM in further detail, it is first important to establish how the MMHEL Radar system nests within current strategy. Figure 3 depicts the system's Traceability Diagram, illustrating how this system provides a critical capability at the tactical level, which can ultimately be traced up to requirements outlined in the National Security Strategy (NSS). The 2018 NSS outlines four "pillars" of the nation's strategy, the third of which being to "Preserve Peace Through Strength" (White House 2017, 25). This is further divided into three lines of effort, one of which is to regain the nation's competitive advantage. The NSS states that the U.S. has displayed a high degree of "strategic complacency" over the last few decades, which has allowed a great power competition to return with large state actors like Russia and China (White House 2017, 27). This is in part due to the country's involvement in the Afghanistan and Iraq conflicts over the last two decades, which has caused the majority of research and development efforts to be committed to more defensive-oriented weapon systems and those best suited for the counterinsurgency operating environment. This has allowed countries like Russia and China to invest heavily in the development of their own offensive weapons, as America's focus in the Middle East provides little reason to invest defensively. One way to reverse this trend at the strategic level and to restore this "competitive edge" is for the U.S. to develop offensive weapons aggressively using innovative technology, like directed energy, to force countries like Russia and China to divert resources to the development of more defensive-oriented weapon systems and slow progress on offensive systems that serve as a proximate threat to national security.

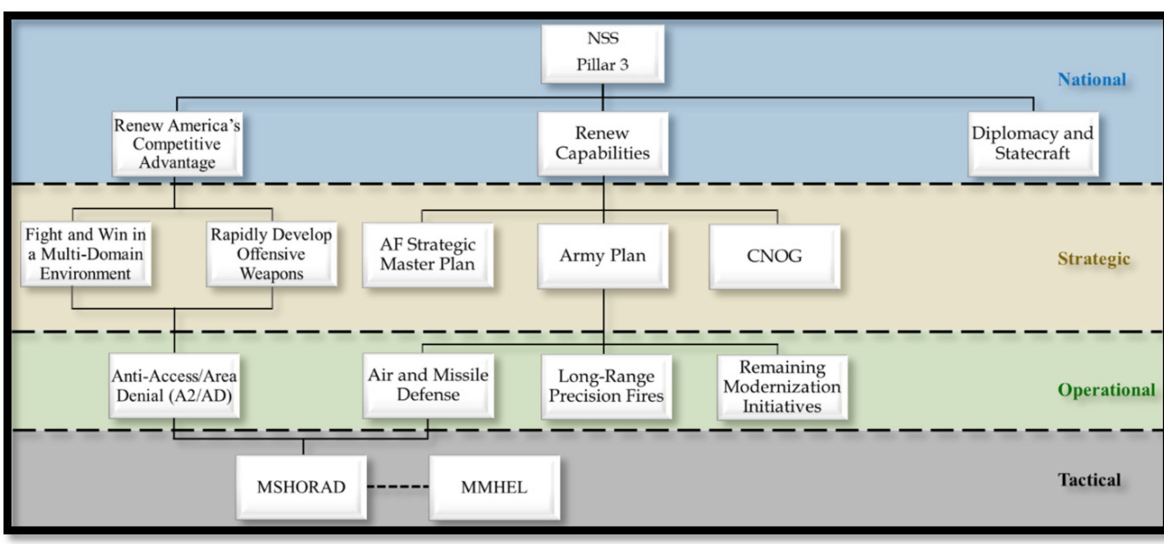

Figure 3. MMHEL Radar Traceability Diagram

A second line of effort under the Strategy's third pillar is to renew capabilities, which includes military capabilities. To address this effort, as well as address the rest of the guidance outlined in the NSS, each military service develops its own planning guidance. The Army outlines its plan to renew military capabilities in the second line of effort of the Army Plan, which lists the service's six modernization priorities: Air and Missile Defense, Long Range Precision Fires, Next Generation Combat Vehicles, Future Vertical Lift, Army Network, and Soldier Lethality (Esper and Milley 2018, 7). The MMHEL and its supporting radar is a type of directed energy weapon that provides a unique MSHORAD capability because of its low cost per engagement, among other things, which directly supports one of the six Army modernization priorities. This system also supports operations in an A2AD environment, which will be explained in more detail in the following DRM.

C. MISSION BACKGROUND

The return of great power competition has elevated foreign threat capabilities to a level that forces the U.S. to prepare for a multi-domain conflict. The U.S. Army's Training and Doctrine Command (TRADOC) Pamphlet 525-3-1, The U.S. Army in Multi-Domain Operations 2028, describe an operational environment comprised of Russian and Chinese A2AD systems employed in times of competition or times of armed conflict (TRADOC 2018). This description, shown in Figure 4, illustrates that the A2AD environment will likely be saturated with adversarial indirect fire capabilities, which includes rockets, artillery, and mortars, unmanned aerial systems, rotary and fixed wing aircraft, and long-range precision munitions. Chinese and Russian layers of stand-off vary slightly from a competition environment to an armed conflict environment. The primary difference exists primarily in the desired policy objective. Competition A2AD seeks to separate alliances and win without fighting, whereas A2AD in armed conflict seeks to win quickly in an overwhelming manner.

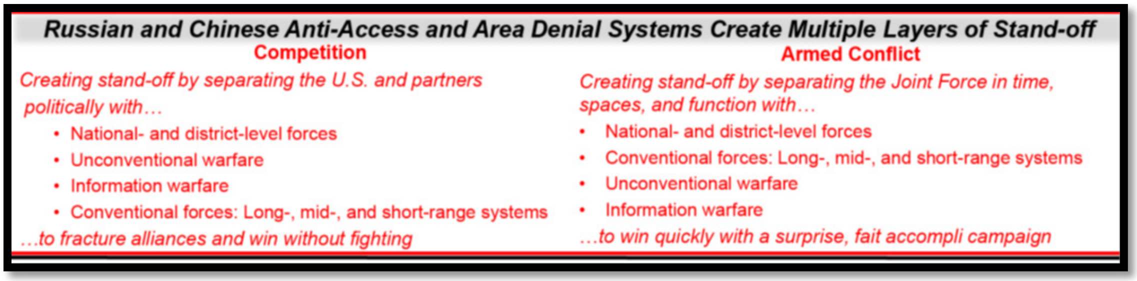

Figure 4. U.S. Army A2AD Description. Source: TRADOC (2018).

The MMHEL capability enables the U.S. Army to defeat threats in an A2AD environment, either while penetrating enemy A2AD layers or while preventing enemy encroachment into allied stand-off areas. The ability for maneuver forces to create operational access by forcible entry relies on the destruction of enemy anti-air and anti-naval weapon systems by means of offensive fires. One way to reduce the threat to friendly air and naval forces is to employ these fires from ground-based systems. However, in doing so, these ground-based, often immobile, long range fires are highly susceptible to enemy targeting. The MMHEL provides ground force commanders a critical MSHORAD capability to protect these vulnerable systems from indirect and aerial fires, enabling their employment. Facilitating the employment of ground-based, long range precision fires, combined with the minimal logistical requirements of a laser-based weapon, makes the MMHEL the optimal system to employ in an A2AD environment.

D. PROJECTED OPERATING ENVIRONMENT

1. Operational Context

The 2018 NSS is clear about China's antagonistic role in Southeast Asia. According to the NSS, China is using a multifaceted approach that includes the use of economic, political, and military means to influence other states to favor its political and security concerns (White House 2017, 46). China's current trade strategies and infrastructure investments are evidence of their desire to influence Southeast Asia (White House 2017, 46). China is developing its A2AD strategy to deny the freedom of maneuver and operational access of potential adversaries. Operational access is a key enabler to the pursuit of U.S. national interests in the Indo-Pacific region.

China's strategy seeks to limit U.S. influence in the region while simultaneously increasing their own. According to OSD (2019), China has recently tested its strategy with some success by establishing a military presence on the Spratly Islands in 2018. Furthermore, OSD notes that China positioned ground-based, anti-ship missiles in the Spratly Islands despite Chinese President Xi Jinping's pledge to not militarize the islands (OSD 2019, ii). The Spratly Islands are in the center of the South China Sea shipping lanes through which much of Asia's trade currently passes. Additionally, the Spratly Islands potentially hold lucrative gas and oil reserves (Bonds et al. 2017, 25). As a result, it may be inferred that many nations within the region consider the Spratly Islands to be key terrain. Permanent occupation of the Spratly Islands would allow the Chinese to gain a distinct advantage within the region by extending their operational reach and providing an additional defensive barrier to deter any attacks on the mainland. This also would enable China to influence maritime operations and the movement of shipping commerce within its "nine-dash line," an area of the South China Sea that China claims as their rightful authority to control.

The United States can respond with a variety of military options in the event China extends its A2AD environment by weaponizing the South China Sea. Air and naval assets have the range and lethality required to defeat any threats deployed in the South China Sea. However, as mentioned in the previous section, the air defense and anti-naval weapon systems typically employed in an A2AD environment significantly increase risk to friendly air and naval assets. Instead, the Department of Defense may first choose to employ ground forces to defeat the air defense and anti-naval weapon systems and to enable follow-on air and naval strikes. This course of action establishes a joint, multi-domain posture within the region to deter a potential Chinese encroachment onto disputed island territories.

The Stryker Brigade Combat Team (SBCT) provides a highly mobile maneuver force that, when augmented with air defense capabilities, would be well-suited to fill the identified MSHORAD capability gap with the employment of the MMHEL. The MMHEL also provides the option to transition rapidly to offensive operations with the ability to engage enemy targets on the move. The system's high-level operational concept is depicted in Figure 5, which displays how the system would operate in such an environment. The deployment of MMHEL-equipped SBCTs within the region would provide the U.S. with mobile air defense assets capable of protecting the employment of ground-based long-range precision fires and ultimately enabling the commitment of air and naval assets.

2. Scenario Overview

A Chinese Infantry Brigade has established a mission command node at the Spratly Islands to facilitate China's plan to invade the Northwestern coastline of Luzon Island in the vicinity of Laoag City. A Chinese infantry battalion has been tasked to gain an initial foothold for follow-on enemy forces to occupy and emplace air defense and long-range missile systems on the island. The infantry battalion is escorting and providing security for an air and missile defense company to initiate the emplacement of these systems to support China's A2AD strategy. The Chinese infantry battalion is also tasked to reconnoiter 40 kilometers to the north of Laoag City and report suitable locations for additional air and missile defense systems. United States intelligence reports the possibility of a Chinese Special Operations Force (SOF) element positioned off the northern coast of Luzon to provide additional ISR support for the infantry battalion if needed.

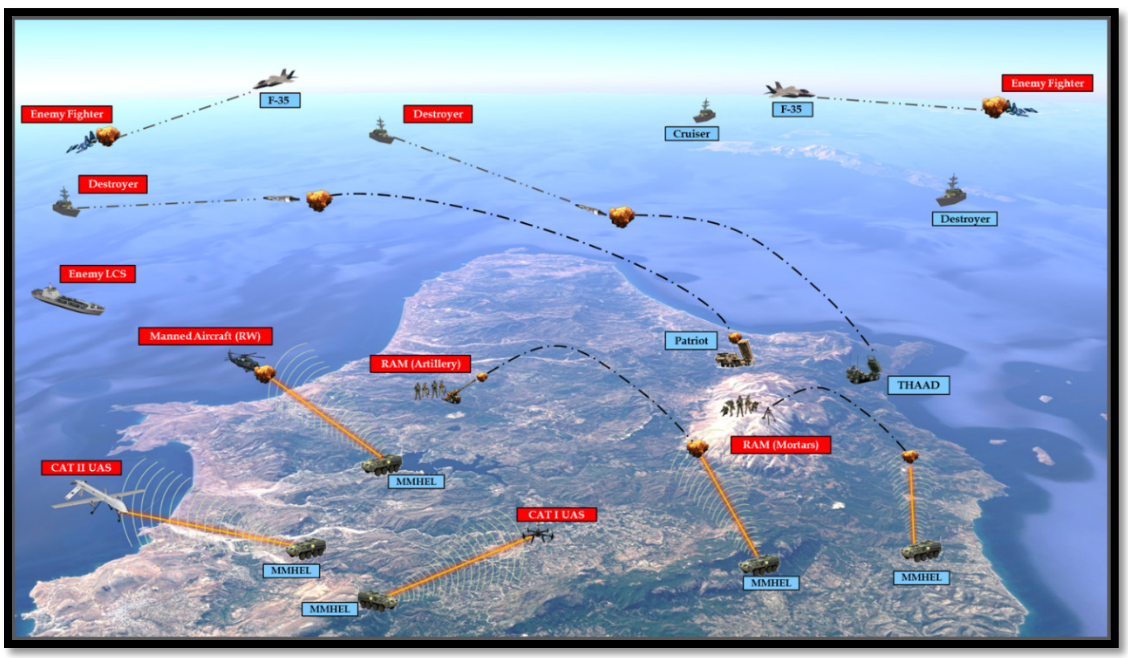

Figure 5. MMHEL Radar OV-1

The U.S. Army has deployed one SBCT to Luzon utilizing the seaport of Batangas and international airports at Manilla and Angeles to rapidly facilitate Reception, Staging, Onward-Movement, and Integration (RSOI) and continued logistical support (see Figure 6). The SBCT is tasked with clearing the island of enemy forces to enable the deployment of ground-based long-range precision fires. The SBCT tasks one company to conduct a movement to contact to identify and to maintain contact with enemy forces on the island.

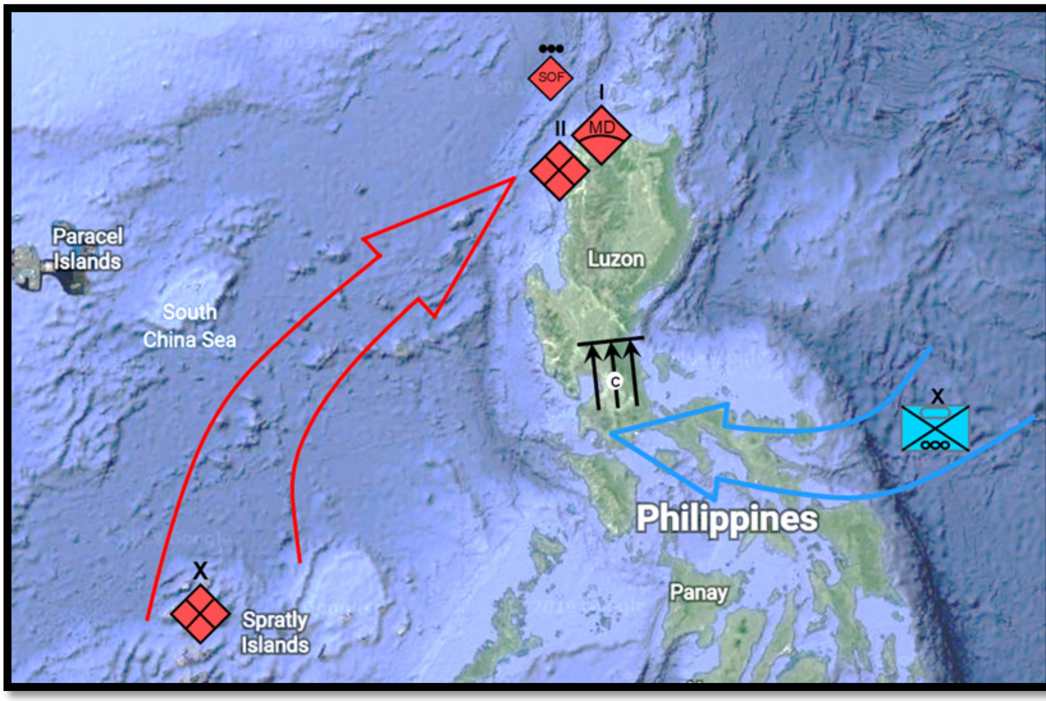

Figure 6. Concept of Operations

3. Environmental Conditions

The MMHEL systems provide the SBCT with a distinct ground force advantage over its enemy, but there are operational factors that could adversely impact the weapon system. The Army's intelligence estimate is defined in Army Doctrine Reference Publication (ADRP) 2–0 as "a logical and orderly examination of intelligence factors affecting the accomplishment of a mission" (ADRP 2–0 2012, 5–9). Included in these intelligence factors are various weather elements. The intelligence estimate prepared for an SBCT will analyze weather effects "based on the military aspects of weather which include visibility, wind, precipitation, cloud cover, temperature, and humidity" (ADRP 2–0 2012, 5–3). Additionally, it is important to consider how other aspects of weather may affect the MMHEL's performance in the projected environment and during sea transit. Minor assumptions were made on the system's durability because it remains in the early stages of development and lacks environmental testing to date; however, MMHEL systems are expected to withstand or be capable of operating in the following conditions:

- day or night operations
- altitudes from sea level to 10,000 feet
- temperatures between 0 degrees Celsius and 45 degrees Celsius
- sustained winds up to 220 kilometers per hour (>119 knots)
- heavy precipitation
- heavy fog
- sea spray
- sand and dust

4. Threat Details

The MMHEL Radar must detect a variety of aerial threats. This variety requires the radar to be capable of acquiring targets with significant differences in radar cross section (RCS), speed, range, and ceiling. The threats include tier one, two, and three unmanned aerial systems, rotary and fixed wing aircraft, and a number of rocket, artillery, and mortar weapons. Understanding the capabilities of each of these threats is critical to inform the development and further refinement of the radar's requirements.

The following tables provide examples of each type of threat, accompanied with data on each respective threat's capabilities.

Table 2. Unmanned Aerial Vehicles. Adapted from Jane's by IHS Markit (2019).



UAV	ASN 217 Tier 1	ASN 209 W50 Tier 2	Cloud Shadow Tier 3
Max Speed	119km/h	180km/h	620km/h
Range	20km	100km	88km
Max Ceiling	4,000m	4,600m	14,000m

Table 3. Rotary Wing Aircraft. Adapted from Jane's by IHS Markit (2019).


Rotary Wing	Z-9A Attack Helicopter	Z-8A Multi-role Helicopter
Max Speed	315km/h	315km/h
Range	859km*	851km*
Max Ceiling	4,750m	6,000m

Table 4. Fixed Wing Aircraft. Adapted from Military Factory (2019a)(2019b).

Fixed Wing	Xian Y-20 Strategic Airlifter	J-20 Multi-role Fighter
Max Speed	920km/h	2,100km/h
Range	4,500km	3,400km
Max Ceiling	13,000m	18,000m

Table 5. Artillery and Rockets. Adapted from Jane's by IHS Markit (2019).

Artillery and Rockets	NORINCO AH4 155mm Howitzer
Min Range	UNK
Max Range	30km
Muzzle Velocity	Approx. 800m/s

Table 6. Mortar System Types. Adapted from Jane's by IHS Markit (2019).



Mortars	Type WW90 60mm Mortar	NORINCO 81mm Mortar	T86 120mm Mortar
Min Range	130m	800m	400m
Max Range	5,500m	4,270m	7,500m
Muzzle Velocity	<272m/s	272m/s	<308m/s

E. MISSION AND MEASURES

1. Mission Success Requirements

Four high-level system requirements must be met in order for the mission to be considered successful. These high-level requirements correspond directly with the four critical functions of the system, which are to detect, classify, and track targets, as well as interoperate with the MMHEL.

- The MMHEL Radar shall detect threats at a distance that allows sufficient time to employ countermeasures that effectively combat the threat.
- The MMHEL Radar shall classify targets in a way that clearly distinguishes friendly from enemy targets.
- The MMHEL Radar shall track threats to increase the accuracy of the MMHEL.
- The MMHEL Radar shall send targeting data to the MMHEL to facilitate its engagement of the threat.

2. Mission Definition

It is necessary to define a main reference mission as part of the DRM to provide a framework in which measures can be collected to assess the mission success requirements (Giammarco, Hunts, and Whitcomb 2015). This reference mission is named "Conduct Mobile Short-Range Air Defense Operations in a Resource-Constrained Environment." This mission was developed to answer the following capability need statement: The U.S. military needs a cost-effective, on-platform radar capable of guiding the MMHEL that is compact enough to place on the Stryker to enable offensively-postured Mobile Short-Range Air Defense (MSHORAD) operations in a resource-constrained environment. This reference mission consists of several operational situations (OPSITs), which are notional scenarios that capture a collection of variables to help define the mission's environmental conditions. The following section defines two primary OPSITs, both of which introduce unique variables that highlight the radar's critical attributes.

a. OPSIT 1 – Stryker Unit Receives Mortar Fire during Movement to Contact

In response to China's forcible occupation of the island of Luzon, U.S. leaders deploy a land force composed, in part, of MMHEL-equipped Strykers to destroy enemy forces and restore the island's sovereignty. Among the first to land on the southeastern part of the island is a Stryker company, consisting of three platoons that each contain two MMHEL-equipped Strykers and two standard Strykers. The company conducts a movement to contact, traveling overwatch in a company wedge formation at approximately 30 mph from southeast to northwest. The radars on every MMHEL-equipped Stryker are in operational mode, actively emitting signals to detect potential threats in support of their MSHORAD mission. The company's mission is to gain and maintain contact with the enemy to enable a follow-on assault force to destroy the enemy. Positioned in the northwest region of the island are several 60mm mortar positions that are providing indirect fire support to enemy forces. An enemy forward observer gains observation of the U.S. Stryker company advancing toward his position at approximately 1530. A high cloud ceiling provides clear visibility to both U.S. and enemy forces. The observer alerts the forward-most mortar pit that the lead U.S. element is within 3000 meters of their location. The mortar crew fires a 60 mm mortar round at the approaching Stryker Company.

b. OPSIT 2 – Mobile Area Defense against UAV Swarm

Following the initial attack on China's invasion force on Luzon, coalition forces assume a defensive posture in the northwestern section of the island amidst consolidation and reorganization activities. The presence of Chinese naval threats in the vicinity of Luzon prevent the regular resupply of CL V ammunition. China has also stationed several SOF-manned surface vessels disguised as fishing boats approximately 40 km north of Luzon in preparation for reconnoitering a route to counterattack coalition forces. An MMHEL-equipped Stryker task force conducts a mobile area defense in the vicinity of Pagudpud, employing roving patrols of platoon-sized elements. Starting at 0230 on D+3, one such patrol is traveling overwatch in a column formation from west to east along Route AH26 at a march rate of 15 mph. The sky is overcast, with gentle winds of 5 mph from the southwest bringing warm, tropical air that leaves overnight temperatures hovering around 80 degrees Fahrenheit, while humidity remains constant at 85%. Visibility is limited to two miles due to the low cloud ceiling, inhibiting naked eye observation of air traffic overhead. This particular patrol has been briefed on the possibility of Chinese SOF operating in the vicinity of Pagudpud, and remain vigilant for signs of an enemy counterattack. Accordingly, the MMHEL Radars are set to active search mode and scan the airspace north of Luzon. At 0250, the Chinese SOF launch a UAV swarm of ten quadcopters from their fishing vessels, moving toward Pagudpud at an airspeed of 125 mph. At 0310, the lead MMHEL-equipped Stryker's radar system detects a target of interest approximately 30 km north of Pagudpud on a magnetic azimuth of 175 degrees.

3. Mission Execution

a. OPSIT 1 – Stryker Unit Receives Mortar Fire during Movement to Contact

1. The lead MMHEL-equipped Stryker detects an incoming projectile at a 45-degree azimuth and 60-degree elevation. The projectile is approximately 2500 meters from the company's position.

2. The MMHEL radar's user interface alerts the operator of a potential threat. The operator, in turn, alerts his chain of command. The Stryker unit maintains its speed of 30 mph.

3. The radar transmits initial targeting data to the MMHEL fire control system (FCS), causing the laser to orient in the direction of the incoming projectile.

4. The radar classifies the target as a rocket, artillery, mortar (RAM) threat at 2000 meters.

5. The radar tracks the projectile's azimuth, elevation, and speed while providing updated tracking data to the MMHEL fire control system (FCS). The forward movement of the Strykers, combined with the speed of the projectile, result in a rapidly decreasing distance between the unit and threat that requires the radar to send frequent data transmissions to the FCS.

6. The remaining MMHEL radars that are not engaged with this current threat scan the surrounding airspace to determine presence of any friendly aerial assets in the area. The radars confirm there are no friendly units in the immediate airspace.

7. The commander determines the airspace is clear and grants the MMHEL operator approval to engage the target. The MMHEL operator engages and defeats the mortar round.

8. The Stryker unit continues its movement to contact without the need to alter its direction of travel, movement formation, or rate of march.

b. OPSIT 2 – Mobile Area Defense against UAV Swarm

1. The MMHEL Radar makes initial detection of an inbound UAV swarm through active air search at a range of 30 km.

2. Radar sends initial detection data to MMHEL's FCS and friendly mission command systems. Simultaneously, the radar's user interface alerts the operator to an initial target detection.

3. The MMHEL radar initiates target classification protocol and classifies the target of interest as one hostile Group 2 UAV at a range of 60 km.

4. The Chinese UAV swarm continues on azimuth toward Pagudpud. The radar rejects target clutter and recalculates the target classification at a range of 20 km, identifying the target of interest as a target group of ten individual Group 1 UAVs.

5. The MMHEL Radar sends updated target data to MMHEL FCS and friendly mission command systems.

6. The radar tracks the azimuth, elevation, and air speed of all ten UAVs and continues to send the target data to the MMHEL FCS and friendly mission command systems.

7. The MMHEL operator receives authorization to engage and defeats all ten Chinese UAVs.

4. Measures

The following tasks highlight the primary functions expected of the MMHEL Radar. Each task is loosely linked to tasks found in the U.S. Army's Combined Arms Training Strategy (CATS) and to the Army's MSHORAD initiative. While current tasks in CATS are directly linked to legacy platforms, the below tasks are similar to those focused on target acquisition, fire control system interoperability, and clearance of airspace. Specific measures have been assigned to each task to provide a metric for how well the MMHEL Radar performs these critical functions.

a. Conduct Target Acquisition

M1	Percent	Of aircraft detected within threshold range
M2	Seconds	Of mean time to correctly classify target of interest
M3	Meters	Of mean variance between true versus observed target location

b. Interoperate with MMHEL's Fire Control System

M4	Seconds	Of mean time to transfer target data to MMHEL FCS
M5	Seconds	Of mean cycle time for transfer data to MMHEL FCS
M6	Percent	Of failed data transfers

c. Clear Airspace

M7	Percent	Of lost tracks once acquired
M8	Seconds	Of mean time to transfer target data to AFATDS
M9	Seconds	Of mean cycle time for transfer data to AFATDS

III. METHODOLOGY

A. CHAPTER INTRODUCTION

The overall intent of this chapter is to provide transparency to the methodology employed by the project team in its execution of a preliminary cost effectiveness analysis. This chapter is comprised of three parts—the systems engineering approach, the functional and requirements analysis, and the cost effectiveness analysis—each of which contains its own objective that nests with the chapter's overall intent.

The first objective is to inform readers of the systems engineering approach taken by the project team to develop this report. The description of this approach highlights actions taken prior to the cost effectiveness analysis to frame the problem effectively and to better inform the process. The second objective is to illustrate the traceability of system functions to system requirements. This objective is achieved through a functional analysis and the identification of key system requirements. The final objective is to detail the processes included in the development and execution of the cost effectiveness analysis. To meet this objective, both the cost and benefit analysis are included in this chapter. While this may be more analysis than is normally included in a chapter on methodology, its inclusion is important to provide a fully transparent perspective of how the cost effectiveness analysis was conducted. Chapter IV includes the results of this analysis, as well as more detailed analysis into risk and weighting sensitivity.

B. SYSTEMS ENGINEERING APPROACH

1. Overview of Approach

This report was developed using a tailored systems engineering "vee" model, which resulted in the development of a functional hierarchy, design reference mission (DRM), and a preliminary cost-effectiveness analysis for various MMHEL Radar alternatives. Figure 7 is a graphical representation of the process that captures each step and the resulting deliverables. The project team's research effort was focused on the left side of the "vee," stopping short of modeling, simulation, and further developmental testing. However, the preliminary cost-effectiveness analysis produced by this tailored systems engineering approach provides the necessary modeling and simulation inputs for further research.

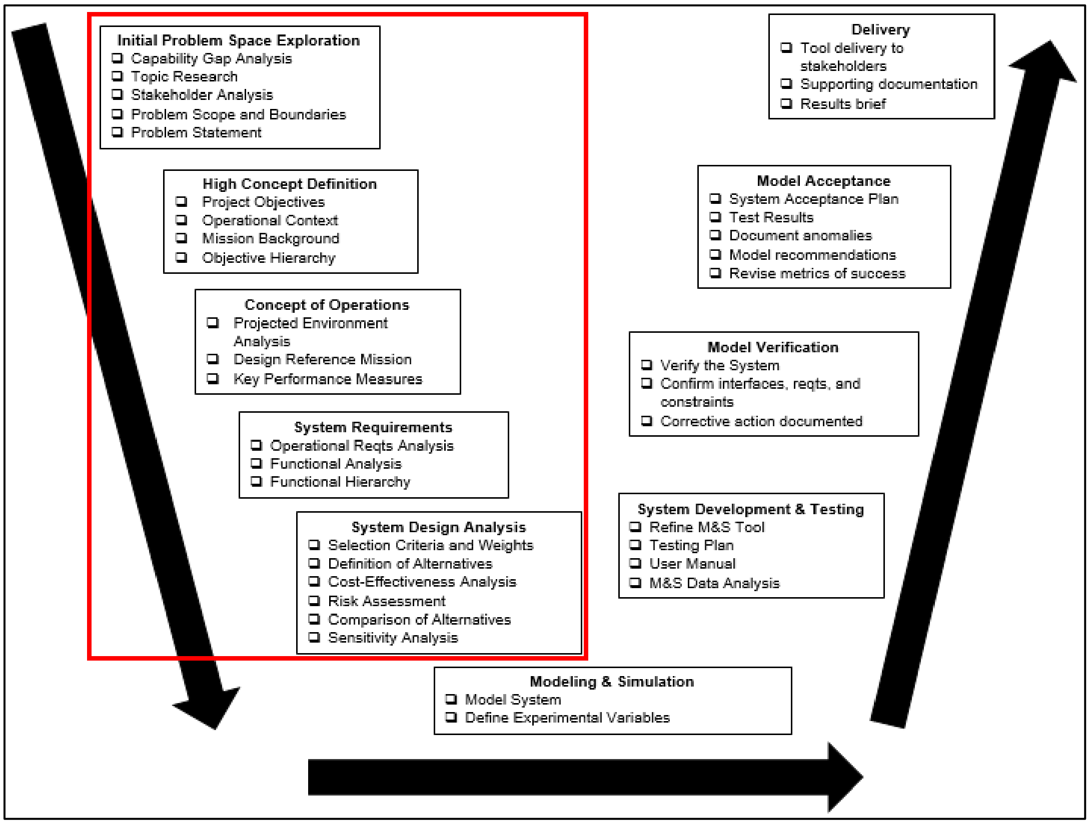

Figure 7. Tailored Systems Engineering "Vee" Approach. Adapted from Miller (2019).

2. Description of Approach

The project team began its approach by first exploring the initial problem space, as outlined on the upper left-hand corner of the tailored systems engineering "vee." This exploration incorporates technical research, capability gap analysis, and stakeholder input to define the problem's scope and boundaries. A succinct yet comprehensive problem statement is the main output of this project phase, as it focuses the research effort toward providing possible solutions to the critical problem.

The approach continues to the High Concept Definition phase, which defines the project's objectives based on the problem statement. The traceability diagram guides the high concept definition by illustrating how the MMHEL Radar nests into the strategic context. The mission background further outlines how the MMHEL supports a counter-A2AD strategy, while the operational context serves as a backdrop for the design reference mission.

The project team then developed relevant mission scenarios as part of an overall design reference mission, illustrating how a Stryker-mounted MMHEL Radar may be employed in an operational environment. The design reference mission conveys the projected environmental factors, mission success requirements, and key performance measures against which an MMHEL Radar can be evaluated.

Efforts advance down the left side of the "vee" as the project moves from conceptual elements toward a practical view of the specific system requirements needed to satisfy the operational requirements. Encapsulated in the functional hierarchy, the report outlines specific functions and critical technical parameters that a radar must possess to meet its requirements. This analysis also considers the longer-term supportability issues that, if satisfactorily addressed, would contribute to a deliberate life-cycle design that accommodates the realities of resource management and logistics (Blanchard and Fabrycky 2011, 497). Consequently, the functional analysis serves to inform the selection criteria for the MMHEL Radar's attributes and associated weights.

In the final phase of the process, system design analysis combines a cost analysis, benefit analysis, and selection criteria with associated weights to produce the project's main deliverable—a preliminary cost-effectiveness analysis that compares the radar alternatives. A risk assessment and sensitivity analysis accompany the preliminary cost-effectiveness analysis to present a holistic body of evidence from which the project team makes a recommendation to the RCCTO about which radars to procure for further development and testing.

C. FUNCTIONAL ANALYSIS

Functional analysis is necessary to clearly identify the functions a radar must be able to perform to be effective. This step of the systems engineering process assists in refining early requirements analysis, trade-off analysis, and the evaluation of system effectiveness and cost (Blanchard and Fabrycky 2011, 33). The MMHEL Radar functional hierarchy provides a foundational understanding of the system's sub-functions and attributes that are required for it to be operationally effective. This foundational understanding serves as the technical underpinning for the cost-effectiveness analysis of the various radar solutions. Additionally, a preliminary trade-off analysis provides early system performance considerations for the RCCTO during its evaluation of alternative solutions.

1. Functional Hierarchy

The functional hierarchy shows the connection between the top-level system requirements and the functions, sub-functions, and lowest level attributes that make up the system configuration and enable the system to meet its requirements. Moreover, the system's "hierarchical structure illustrates the critical top-down traceability" from critical function to lowest-level system attribute (Blanchard and Fabrycky 2011, 139). The radar must demonstrate the ability to achieve four critical functions—detect, classify, and track targets, as well as interoperate with both the MMHEL and the Stryker's command and control system (Figure 8). These functions were initially identified as part of the "mission success requirements" of the DRM earlier in this report and will be further explored in the following sections.

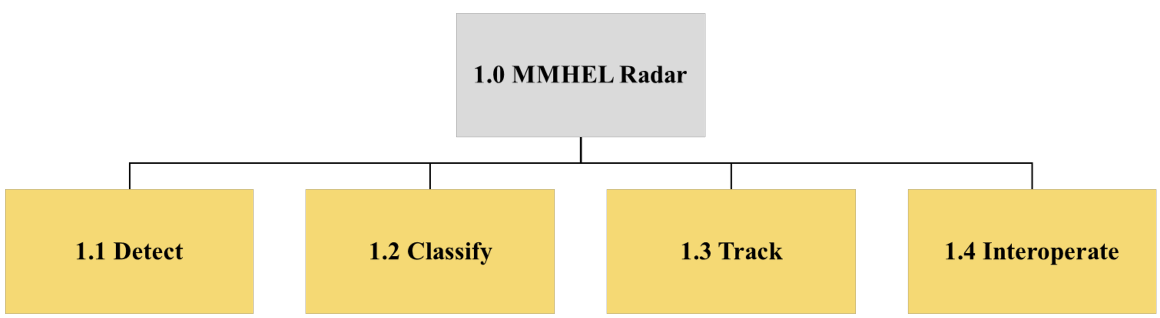

Figure 8. MMHEL Radar Primary Functions

The first critical function of the radar is to detect enemy threat targets. Following this function, the radar begins to collect basic target information such as the target's speed and direction of travel. The radar detects targets by cycling radiation through its search sector and processing any reflections to confirm a target's existence in its sector. The radar accomplishes this by "sending out a pulse of high-frequency electromagnetic waves within its search sector…until it encounters an object that reflects off of it" (Cloer 2017). While the concentration of emitted radiance depends on the beam width that the radar is capable of projecting, the radar determines target probability by computing reflected radiance and rejecting clutter through the fusion of unknown pixels. Simultaneously, the radar fuses "the results of the spatial and radiometric features which presents a target as an image" (Page et al. 2009, 3). The image is then "segmented…by using pixel radiance and pixel image position as features in order to partition the image" (Page et al. 2009, 6). Consequently, the radar reduces false alarm detection rates by evaluating target characteristic data along with developing the initial raw data that it will use to calculate a target's position and heading. The "Detect" function is depicted in Figure 9.

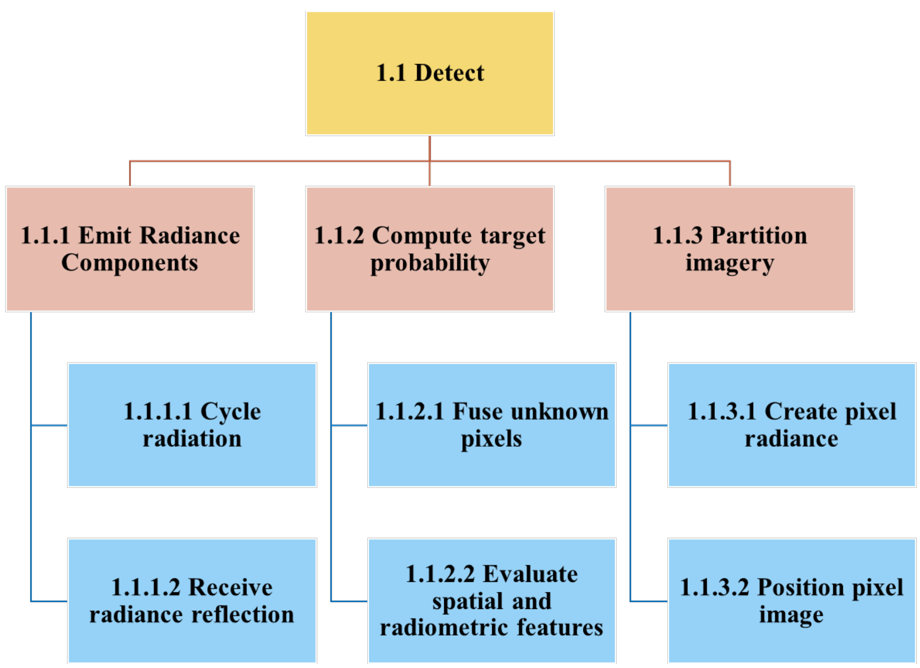

Figure 9. "Detect" Function

The second primary function of a radar is to classify targets. This is done by using look-up tables where the system compares the received target signature data against previously recorded data with similar features. Specifically, once an image is partitioned, "pre-computed" look-up tables are necessary to "enable real-time classification of the integrated reflected and emitted radiance components from the target surface" (Page et al. 2009, 5). Target classification continues by using look-up tables produced over a variety of "look-angles and target altitudes from historical mission profile scenarios" (5). The radar completes this critical function by predicting the target threat after parsing all look-up tables and analyzing the compiled data, as depicted in Figure 10.

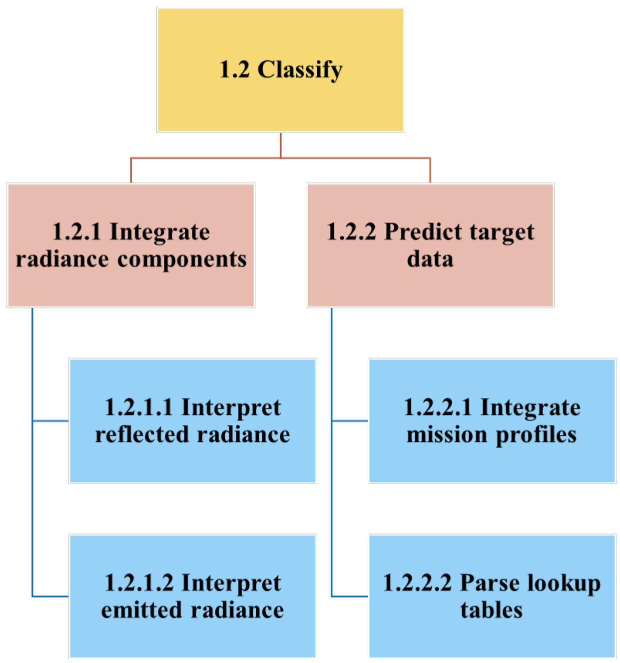

Figure 10. "Classify" Function

The third critical function in a radar's target acquisition process is to track targets. The radar performs this function by refining its target track data with the continued reception of target reflections from the imaging geometry. The radar then correlates the size and brightness of the track with the strength and confidence of the signal received. Additionally, the radar receives distance, altitude, heading, and speed data from a spatial detection algorithm, which supplies the radar with "suppressed background clutter" while clearly identifying the target profiles (Page et al. 2009, 10). "Tracking" remains continuous through stored heading and speed data until the threat is defeated or the situation dictates a target handoff. This function and its respective sub-functions are illustrated in Figure 11.

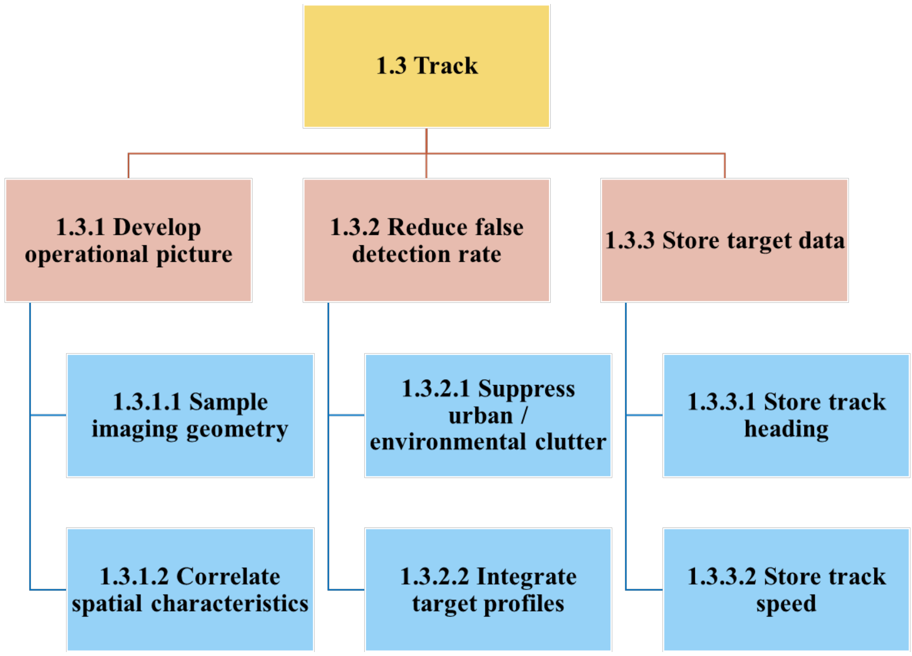

Figure 11. "Track" Function

The final primary function of the radar is that it must interoperate with the four external systems identified in Figure 12. Unlike the first three functions, this function is unique to the MMHEL Radar. First, it must be able to achieve target handoff with peer MMHEL Radars. This means that the radar sends and receives stored tracking data from other MMHEL-equipped Stryker platforms. The radar's ability to achieve this sub-function involves interoperating with the second external system, the MMHEL operator. Human factors engineering is important when considering the radar's usability, which allows for crewmembers to effectively and efficiently operate the system. The radar must also communicate with the MMHEL's fire control system, which enables the beam director to focus its energy on the target accurately. Lastly, the radar must be able to integrate with three applicable systems within the Stryker vehicle, or the host platform as labeled in Figure 12. The platform's internal command and control systems must be compatible with the radar to store and relay target data between computers and other network components. Therefore, the radar's operational effectiveness relies heavily on the platform's ability to provide support for the radar's SWaP-C requirements. Specifically, the external thermal management system and external battery pack must connect to the radar and accompanying components that make up the MMHEL.

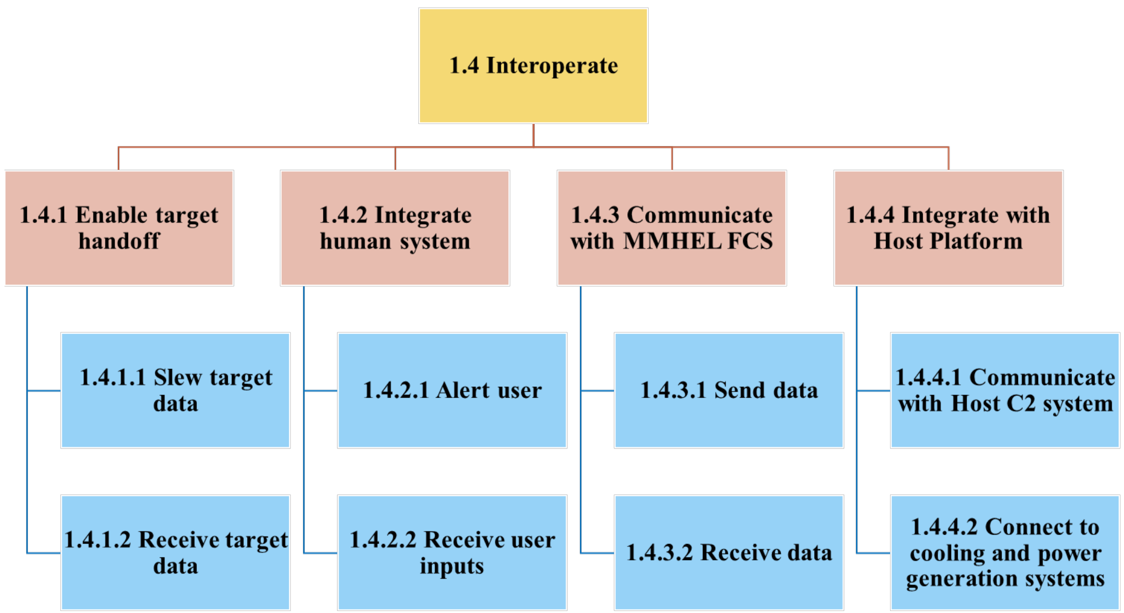

Figure 12. "Interoperate" Function

2. System Trade-off Analysis

The functional hierarchy allows for the identification of potential trade-off considerations that stakeholders may explore during the comparison of alternatives. According to Blanchard and Fabrycky, a good trade-off analysis considers "only those attributes that are essential to meet the requirements—not too many or too few…as measured in terms of the user needs" (Blanchard and Fabrycky 2011, 114). Consequently, the capstone team derived the following functional trade-off considerations by considering only the attributes perceived to have the most significant impact on the radar's performance and its operational effectiveness.

- Target resolution for range: A radar's resolution is dependent on the pulse length, with a wider pulse longer-range radar providing less resolution, and a narrow pulse shorter-range radar providing a "finer resolution" (Akerson 2018). This trade-off is important to consider because a radar's ability to differentiate between clutter and an actual threat directly influences the MMHEL's lethality and survivability. The applicable sub-functions are 1.1.2 Compute Target Probability (Figure 9) and 1.3.1 Develop Operational Picture (Figure 11).

- Field of view for initial engagement sequence: Limitations to a radar's field of view, which consist of azimuth and elevation, will result in a delayed engagement sequence, whereas an expansive field of view will significantly reduce the probability that an enemy threat could evade detection, classification, and tracking. The two most significant sub-functions that apply within this trade-off consideration are 1.1.1 Emit Radiance Components (Figure 9) and 1.4.3 Communicate with MMHEL FCS (Figure 12).

- Signal-to-noise ratio (SNR) for the probability of detection: Radar performance depends on the SNR, "which is defined as the ratio of reflected target energy to average thermal noise power" (Jeffrey 2009, 3). A greater SNR will result in maximizing the probability of detection, whereas a lower SNR will limit a probability of detection while maximizing the probability of false alarms. The relevant sub-functions for this trade-off consideration are 1.2.1 Integrate Radiance Components (Figure 10) and 1.3.2 Reduce False Detection Rate (Figure 11).

D. SYSTEM REQUIREMENTS

1. System Requirements Introduction

This section identifies top-level operational needs, specified system requirements, and system critical technical parameters. The operational needs were largely derived from this report's design reference mission, an analysis of requirements provided by the

RCCTO, and current Joint Operational Access Standard Operating Procedures (SOPs). The RCCTO developed the majority of the MMHEL Radar requirements and the critical technical parameters outlined in this section as part of a technology maturation and risk reduction effort. The remainder of the requirements were developed based on the critical functions identified in the previous section. This section concludes by introducing certain system supportability factors that should be considered when choosing a radar alternative.

2. Operational Needs

The system must meet five top-level operational needs.

- The system must be cost-effective for the purposes of outfitting multiple platforms in a Stryker Brigade Combat Team.
- The system must be compatible with the Stryker vehicle platform. The system must be compact enough to fit on the Stryker body or be mounted on top to provide mobile capabilities.
- The system must be capable of detecting RAM, UAVs, rotary wing, and fixed wing aircraft. This includes UAVs from classes I, II, and III. The detection distance requirements vary by target type.
- The system must enhance the ground force's common operating picture through early warning and discrimination of threat from friendly air platforms.
- The system must be transportable by a C-17 aircraft and meet NATO Envelope "M" rail line transportability requirements.

3. Requirements Definition and Traceability

Table 7 outlines the MMHEL Radar's specified and derived requirements, links those requirements to a pertinent top-level function, and provides a description and further context that support the requirement. For example, Requirement #1 states the various threat ranges that the MMHEL Radar must be able to detect. This requirement is linked to the top-level function of "detect," and is necessary to support the MMHEL Radar's target acquisition sequence. Requirements are organized in Table 7 by the function they are linked to, with requirements highlighted in gray annotating those specified by the RCCTO. This traceability matrix reinforces the importance of each requirement and illustrates which system attributes are important for the follow-on comparative analysis.

Table 7. Requirements Definitions and Traceability

#	Requirement	Function(s)	Requirement Description
1	The system shall be able to detect RAM (60 mm, 80 mm, and 120 mm mortars; 122 mm rockets; 122 mm and 152 mm artillery) at a range of 7 km (T) to 10 km (O).	1.1 Detect	The radar detection capabilities for rockets, artillery, and mortars enable the MMHEL to orient on incoming RAM by providing adequate time through a 7 km minimum detection range.
2	The system shall be able to detect Group 1–3 UAVs at a range of 10 km (T) to 30 km (O).	1.1 Detect	The 10 km threshold range is outside the maximum engagement distance for most armed UAVs.
3	The system shall be able to detect manned aircraft at a range of 50 km (T) to 60 km (O).	1.1 Detect	The larger RCS of manned aircraft allow the system to detect it at a further distance. This requirement excludes manned aircraft with known RCS reduction capabilities.
4	The system shall be able to classify and discriminate between various targets with a success rate of 90% (T) to 95% (O).	1.2 Classify	The MMHEL radar distinguishes between the various target types to inform the beam control mechanism.
5	The system shall be able to distinguish between friend and foe with a success rate of 90% (T) to 95% (O).	1.2 Classify	Distinguishing between friend and foe increases the effectiveness of the system by supporting the common operating picture of the ground force.
6	The system shall possess clutter rejection capability.	1.2 Classify	Clutter rejection enables the radar to distinguish between

#	Requirement	Function(s)	Requirement Description
			various targets based on the expected threat set.
7	The system shall possess an angular accuracy of no more than 500 microradians (T) to less than 300 microradians (O).	1.3 Track	The angular accuracy requirements enable the radar to inform the beam control mechanism and increase the predictive accuracy of future target location.
8	The system shall be able to track two or more targets simultaneously.	1.3 Track	A quasi-monostatic or equivalent system capable of transmitting and receiving data simultaneously.
9	The MMHEL radar shall possess a 360-degree FOV.	1.4 Interoperate	Any hardware configuration on the Stryker platform, regardless of form, must yield a 360-degree azimuth FOV.
10	The system shall possess an FOV elevation of 0 to 90 degrees (T), -15 to 90 degrees (O).	1.4 Interoperate	Any hardware configuration on the Stryker platform, regardless of form, must yield a minimum of 0 to 90-degree elevation FOV.
11	The system shall transfer data at a rate that enables a high energy laser to achieve an engagement sequence of no more than five seconds.	1.4 Interoperate	The high-energy laser requires the radar data to be transferred at a speed that produces a focused laser beam engagement of desired targets in no more than five seconds. This increases the likelihood that the threat is engaged before it engages friendly forces
12	The system shall have a mean time to repair of 18 minutes or less.	1.4 Interoperate	Potential A2AD operating environment will be logistically constrained, making a low mean time to repair critical to maintaining a high state of operational readiness
13	The system shall have a reliability measure of .90 (T) and .95 (O)	1.4 Interoperate	The system reliability is critical to successful integration within the SBCT.

4. Critical Technical Parameters

Critical technical parameters (CTPs) are key system characteristics that are normally used during system development (AcqNotes 2018). The MMHEL Radar's CTPs enable the system to achieve the desired operational capabilities, and are focused on design features that must be realized through the development process. The following CTPs mostly include the size, weight, power, and cooling (SWaP-C) characteristics, which are common metrics used to evaluate a variety of defense systems.

- Size. The system shall not exceed 12.5 cubic feet in volume. This is critical due to the limited space available on the Stryker to mount additional equipment.

- Weight. The system shall weigh no more than 750 pounds (T) to 500 pounds (O). A radar exceeding this weight would significantly impact the Stryker's mobility.

- Power. The system shall consume no more than 10 kW of power. This metric is not as great a concern as the previous two, as the MMHEL itself consumes the majority of any additional power required. However, it is still important to consider power shifting issues.

- Cooling. The system shall possess a passive cooling system. This is preferred over active cooling to minimize ambient noise and other negative effects. The system shall also be capable of maintaining an operating temperature between 50–82 degrees F (T) and 68–71 degrees F (O).

5. System Supportability Considerations

There are several supportability factors that must be considered when selecting the optimal radar to support the MMHEL. Considerations for system supportability should be driven largely by the system's projected operating environment. The MMHEL's use of directed energy instead of conventional ammunition results in a significantly lower cost per engagement, making it an ideal system to employ in a logistically-constrained environment. This environment, illustrated in this report's DRM, introduces unique system supportability factors that must be considered when choosing a radar alternative. One such factor is maintenance. Eliminating the need for ammunition resupply certainly does not alleviate the need for things like repair parts, lubricants, and other materials that may be unique to the MMHEL Radar. Similarly, supportability metrics like mean time between failure (MTBF), mean time to repair (MTTR), and mean corrective maintenance time (Mct) must account for the distance this system will be operating from maintenance support above the operator-level. For the same reason, reliability is a critical supportability consideration. While this particular metric is formalized as a requirement, additional consideration should be given to radars that possess a level of reliability beyond what the requirement dictates. Availability serves as the final critical supportability consideration. Availability is defined as the "probability that a repairable system will be functional at a given time, under a given set of environmental conditions" (Van Bossuyt 2019). Again, this consideration presents a particularly high level of significance for this system because of its projected operating environment. These supportability metrics should be heavily considered during the selection process.

E. COST EFFECTIVENESS ANALYSIS

The intent of the preliminary cost effectiveness analysis outlined in this section is to inform the RCCTO's larger analysis of alternatives when selecting the optimal radar to support the MMHEL. While this analysis largely follows the process outlined in the *Army Cost-Benefit Analysis Guide*, a cost effectiveness analysis was chosen instead because it was deemed more useful to initially quantify the benefits and compare them to cost rather than express benefits in terms of dollars. This section will describe the methodology used to conduct the cost effectiveness analysis and analyze the cost and benefit of each alternative to set conditions for further analysis of risk and weighting sensitivity in the next chapter.

1. Definition of Alternatives

This analysis included 12 separate alternatives from six different vendors. Below is a brief description of each alternative by vendor. A comprehensive list of the critical data and metrics for each alternative, including the metrics highlighted in this section, is consolidated in Table 8 located in the following section.

a. SRC Inc.

The Syracuse-based defense contractor, SRC, submitted two separate alternatives to the RCCTO for consideration.

- **SR Hawk (V)2E (SRC Inc. 2017).** The SR Hawk (Figure 13) is a long-range ground surveillance radar (GSR) that is capable of providing the desired 360-degree field of view. Its compact panel design enables it to be vehicle-mounted and the 100 watts of power it requires is the third lowest of the alternatives. It was designed to detect personnel, land vehicles, and marine vessels. While the radar can also detect low-flying aircraft, its maximum elevation of 55-degrees may limit its ability to perform MSHORAD operations effectively.

Figure 13. SR Hawk V(2)E. Source: SRC Inc. (2017).

- **SkyChaser (SRC Inc. 2017).** The SkyChaser (Figure 14) is a multi-mission radar (MMR) that is capable of tracking targets from a moving platform. Like the SR Hawk, the SkyChaser is a compact panel capable of being mounted on a vehicle and providing a 360-degree field of view. Unlike the SR Hawk, however, the SkyChaser is designed to provide short-range air defense, is capable of detecting targets at a 90-degree elevation, and is compatible with several existing military interfaces, such as the Advanced Field Artillery Tactical Data System (AFATDS).

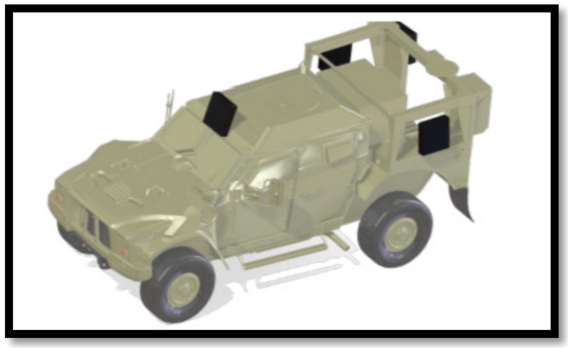

Figure 14. Four SkyChaser Panels on an MATV. Source: SRC Inc. (2017).

b. ELTA North America

ELTA North America has three alternatives.

- **ELM-2026B (ELTA NA 2015).** The ELM-2026B (Figure 15) is a Very Short-Range Air Defense (VSHORAD) radar designed to detect low-flying aircraft and UAVs. Its panel design is 5.83 cubic feet, making it the largest of all panel alternatives. This is a key consideration given the limited space available on the Stryker to install additional equipment. The radar’s 15 km detection range surpasses the RCCTO’s threshold requirements for UAVs; however, it falls well short of the threshold requirement of 50 km for aircraft.

Figure 15. ELM-2026B Single Panel.
Source: ELTA NA (2015).

- **ELM-2138M Green Rock (ELTA NA 2019a)**. The ELM-2138M (Figure 16) is a tactical Counter Rockets, Artillery, and Mortars (C-RAM) radar capable of detecting and tracking enemy indirect fire as well as UAVs and other low-flying aircraft. This radar is the heaviest of the panel alternatives, weighing 176 pounds. Its design also requires the radar to be placed on top of the vehicle, rather than be attached to the sides like other designs. While this would increase the Stryker's profile, it also enables the radar to surpass the RCCTO's objective requirements for detection ranges of UAVs, RAM, and manned aircraft. The ELM-2138M can only provide 180 degrees of coverage, making it the only alternative that fails to provide the full 360 degrees of coverage.

Figure 16. ELM-2138M Green Rock. Source: ELTA NA (2019a).

- **ELM-2180 Watchguard (ELTA NA 2019b).** The ELM-2180 (Figure 17) is a man-portable GSR designed to detect dismounted personnel and ground vehicles. This radar is solely configured to provide stationary, ground surveillance and is incapable of being vehicle-mounted.

Figure 17. ELM-2180 Watchguard. Source: ELTA NA (2019b).

c. RADA Electronic Industries

RADA Electronic Industries, an Israeli defense company, has four viable alternatives to consider.

- **Enhanced Multi-Mission Hemispheric Radar (eMHR) (RADA 2016).** The eMHR (Figure 18) is a tactical air surveillance radar capable of detecting every threat necessary to support the MSHORAD mission. Similar to the other designs, one radar panel provides 90 degrees of coverage, meaning four total panels would be required to provide the desired 360 degrees of coverage. The eMHR consumes the most power of the alternatives at 590 watts.

Figure 18. eMHR Mounted on HMMWV. Source: RADA (2016).

- **RPS-42 (RADA 2019b).** The RPS-42 (Figure 19) is a tactical air surveillance radar designed to conduct VSHORAD operations. It weighs slightly less than the eMHR radar, though it is nearly identical in design. While it is capable of detecting a variety of UAVs and manned aircraft, it is not designed to detect RAM. It is also limited to 80 degrees of elevation instead of the 90 degrees offered by the other three RADA alternatives.

Figure 19. RPS-42 Single Panel. Source: RADA (2019b).

- **Advanced Compact Hemispheric Radar (aCHR) (RADA 2019a).** The aCHR (Figure 20) is an MMR capable of detecting and tracking a variety of UAVs, RAM, and manned aircraft. It has the added benefit of being able to detect dismounted personnel and ground vehicles, something other air surveillance radars cannot do. The aCHR is designed to be attached to the side or on top of military vehicles, giving it an on-the-move capability.

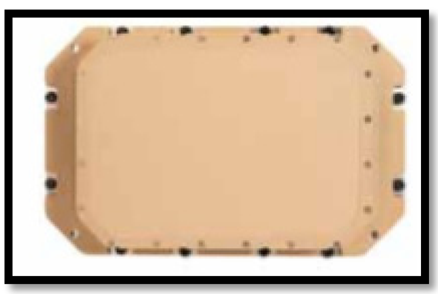

Figure 20. aCHR Single Panel. Source: RADA (2019a).

- **Enhanced Compact Hemispheric Radar (eCHR) (RADA 2019a).** The eCHR (Figure 21) is nearly identical to the aCHR in both design and in capability. The primary differences between the two is in size and weight, with the eCHR consuming approximately one half of a cubic foot more of space and weighing more than 20 pounds less than the aCHR.

Figure 21. eCHR Single Panel. Source: RADA (2019a).

d. Additional Vendors

Defense vendors Blighter, Leonardo, and FLIR each have one radar alternative for consideration.

- **Blighter – A400 (Blighter Surveillance Systems 2017).** The A400 (Figure 22) is a medium-range air security radar capable of detecting both manned and unmanned aircraft. The A400 is capable of being mounted on a vehicle, however the vehicle must be stationary for the A400 to operate. The A400 is not designed to detect rockets, artillery, or mortars.

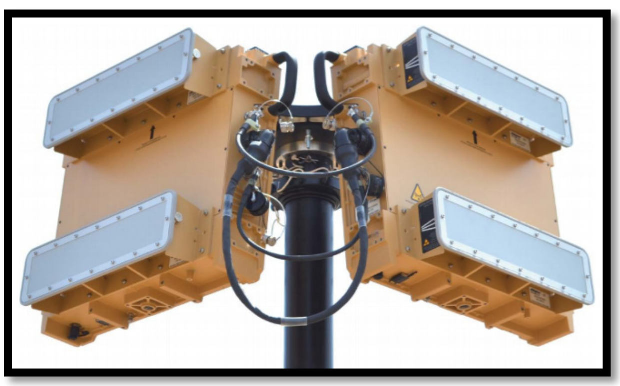

Figure 22. A400 Two Panels on a Mast. Source: Blighter (2017).

- **Leonardo – Osprey (Leonardo 2017).** The Osprey (Figure 23) is a multi-mode surveillance radar designed to be installed on rotary or fixed wing aircraft. The Osprey is capable of detecting targets on land, air, and sea at up to 370 km. The Osprey is the smallest of all the radar alternatives at less than one cubic foot.

Figure 23. Osprey Radar. Source: Leonardo (2017).

- **FLIR – Ranger R20SS (FLIR 2015).** The Ranger R20SS (Figure 24) is a ground-based surveillance radar capable of being mounted on a vehicle. While the Ranger R20SS is designed to detect land or maritime targets, it is also capable of tracking aerial targets if angled correctly. The radar is the second lightest of the 12 alternatives at 38 pounds per panel. Similar to the Blighter A400, the Ranger R20SS requires the vehicle its mounted on to be stationary in order to operate.

Figure 24. Ranger R20SS Radar. Source: FLIR (2015).

2. Data Overview and Estimating Methodology

The product specifications for each radar system in this market study are available on the competing companies' websites. Each of the six vendors presented their product's capabilities in different formats and measurements. The RCCTO provided five categories of interest to compare in order of precedence: panel size, panel weight, detection ranges for three target groups, the field of view (FOV), and power consumption. In order to compare the radars, the data in these categories required a degree of normalization before additive weights and scales could be applied to rank the items.

The panel size represents the physical dimensions of the exterior object that would be mounted to the Stryker vehicle where length, width, and depth are multiplied and converted to cubic feet. SRC did not provide size dimensions for the SR Hawk. To develop a dimension, the panel size for each of the 12 systems was divided by its panel weight. The resulting values were averaged together to arrive at a factor of 0.0256. That factor was then multiplied by the weight of the SR Hawk to provide an estimate of the expected size. The same method was used for the ELM-2138M. The data used in this study also accounts for certain design differences among the various radar alternatives. For example, the panel size and weight for each system represents four panels with the exception of the ELM-2138M. The ELM-2138M's current configuration does not allow for the installation of a separate panel on each side of the Stryker, as this system would require a raised top mount with only two panels. As a result, the size estimation of the ELM-2138M accounts for two panels instead of four.

The detection ranges of interest are for groups 1, 2, and 3 UAVs, RAM, and rotary wing (RW) and fixed wing (FW) aircraft. While all companies provided range data in kilometers, some companies listed different ranges for different sizes of UAV. This study focuses on the detection ranges for standard-sized UAVs rather than ranges for UAVs more unique in size. This is primarily because every vendor listed at least one detection range for a standard-sized UAV, which provides for a more comparative analysis. As such, detection ranges listed in Table 8 reflect the detection ranges of the most standard-sized UAV, regardless of how many different ranges were listed. For example, the aCHR's detection range is listed as 15 kilometers based on its advertised range for a "medium-size

UAV," despite it also being capable of detecting a "nano-UAV" at three kilometers (RADA 2019a).

Only four of the radar data sheets explicitly state a capability to detect RAM. While every aerial threat radar has the capability to detect RAM to a certain degree, radars not specifically designed to do so may be unable to process the data needed to facilitate an engagement sequence. For this reason, detection ranges for RAM were not listed for the majority of radars included in the study.

The Syracuse-based SRC does not provide detection range data for their products. To determine UAV detection ranges for the SR Hawk, the known detection ranges of all radar alternatives was averaged together to produce a 20-kilometer estimate. Detection ranges for the SRC's SkyChaser were determined using an analogous comparison to RADA's RPS-42, as both are similar in size, weight, and capability. Certain vendors did not list a detection range for RW or FW aircraft. For those radars, UAV detection ranges were used instead. It can be reasonably assumed that if a radar is able to detect a UAV at a certain range, it will be able to detect a target with a much larger radar cross-section at the same range. This substitution was made for the SR Hawk, the ELM-2180, the Ranger R20SS, and the Osprey. The Leonardo Osprey's range data appears as an outlier because the system is intended to operate from a rotary wing aircraft. The detection range listed on the radar's data sheet is 200 nautical miles, or 370 kilometers, which is significantly higher than any ground-based radar included in this study (ELTA NA, 2019a).

Field of view consists of elevation and azimuth. Certain radars have a limited elevation based on the mission they were designed to perform. The ELM-2180, for example, was designed to perform ground surveillance, resulting in a maximum elevation of ten degrees. Most radars in this study provide 360-degree coverage through the combined efforts of four radar panels. The ELM 2138M, however, can only provide 180-degree coverage because only two panels can be mounted on the Stryker. This is due to a combination of its significant size and design that requires it to be top-mounted and facing solely in one direction.

The data for all twelve systems is consolidated in Table 8.

Table 8. MMHEL Radar Vendor Data

		SRC	SRC	Blighter	ELTA NA	ELTA NA	ELTA NA	FLIR	Leonardo	RADA	RADA	RADA	RADA
		SR Hawk	**SkyChaser**	**A400**	**ELM-2138M**	**ELM-2026B**	**ELM-2180**	**Ranger R20SS**	**Osprey**	**eMHR**	**RPS-42**	**aCHR**	**eCHR**
Panel Size	Cubic Feet	4.8	4	6	4.52	8.2	3.08	6.04	2.2	8.2	5.8	3.64	5.56
Panel Weight	Pounds	180	200	220	176.37	660	88	152	248	356	202.8	299.8	211.64
Detection Range (km)	Group 1-3 UAV	20	30	10	50	15	6	12	370	25	30	15	15
	RAM				15					8.5		4	4
	RW/FW	20	30	10	80	15	6	12	370	30	30	15	15
FOV	Elevation	55	90	90	90	60	10	45		90	80	90	90
	360˚ Coverage	360	360	360	180	360	360	360	360	360	360	360	360
Power	Watts	100	500	96	500	500	90	245	245	590	320	250	250

3. Top-Level Screening Criteria

Three top-level screening criteria were applied to the 12 alternatives to determine their eligibility for further analysis. To be included in the cost effectiveness analysis, each alternative must be capable of performing MSHORAD operations, be able to be mounted on a ground vehicle, and be capable of operating while on the move. Each of these top-level criteria is foundational requirements that are critical to employ the MMHEL as it is intended. Any alternative that failed to meet one or more of these criteria were not selected for further analysis. These alternatives are listed in Table 9.

- **Criterion 1: Perform MSHORAD.** The first and broadest criterion is that the radar is capable of performing MSHORAD operations. In basic terms, radars must be capable of detecting aerial threats. This is the primary function of the MMHEL, making any radar incapable of performing MSHORAD relatively useless. Radar alternatives were considered to possess an MSHORAD capability if they were able to detect one or more of the following: UAVs, RAM, or manned aircraft. The ELM-2180 Watchguard is the only alternative that fails to meet this criterion.
- **Criterion 2: Vehicle-Mounted.** The second top-level screening criterion is that the radar is capable of being mounted on a ground vehicle. As outlined in this report's problem statement, the radar and MMHEL will be mounted on a Stryker, making this criterion a central requirement. The ELM-2180 Watchguard and the Osprey fail to meet this criterion.

- **Criterion 3: On-The-Move Operation.** The final criterion is that the radar is capable of operating from a vehicle in motion. This function is critical to enable offensive operations and to eliminate the current constraints of an off-platform, stationary radar like the AN/TPQ-53. This criterion was the most exclusive, eliminating the SR Hawk (V)2E, the Blighter A400, the ELM-2026B, and the Ranger R20SS from consideration.

Table 9. Screening Criteria Matrix

Vendor	Radar	Criterion 1	Criterion 2	Criterion 3
SRC	SR Hawk (V)2E			x
Blighter	A400			x
ELTA NA	ELM-2026B			x
ELTA NA	ELM-2180	x	x	
FLIR	Ranger R20SS			x
Leonardo	Osprey		x	

x = failed to meet this criterion

4. Cost Analysis

The RCCTO provided cost data for the SRC SkyChaser, Blighter A400, and the RADA RPS-42. A parametric cost estimating method was applied to determine the costs for the remaining radar alternatives. This method used detection range as an independent variable to develop a cost estimating relationship, as detection range was identified as a major cost driver for radar systems. This study uses cost data from three analogous radar systems to generate three separate cost estimates for each of the remaining radar alternatives. These three estimates were then averaged together to produce a single cost estimate for each radar.

The first cost estimate is based on the AN/TPQ-50, which is used as an analogous system because of its similarity to the different radar alternatives and the availability of its cost data in the Army's 2017 budget justification to Congress. The AN/TPQ-50 is an Army vehicle-mounted counter-fire radar. The radar is too large to be mounted on a Stryker in support of the MMHEL; however, the production cost drivers are presumably similar due to its comparable detection ranges and other capabilities. The Army Acquisition Support Center states the AN/TPQ-50 is capable of detecting RAM at ten kilometers (USAASC n.d.). The Army 2017 budget included two procurements for the TPQ-50: one procurement of 46 radars for $74 million to support full rate production and one procurement of 18 radars for $26 million to provide an immediate capability to the European COCOM (Defense Budget 2016). Based on these numbers, the average unit cost for these two purchases is approximately $1.5 million. In order to arrive at a cost factor based on range, the $1.5 million is divided by the ten-kilometer detection range to calculate approximately $152,000 per kilometer.

The remaining two estimates were based on the verified cost data of the SRC SkyChaser and the RADA RPS-42. The RCCTO provided an estimate of $8M for the SRC SkyChaser, which accounted for the four panels required to achieve 360-degree coverage. This estimate is divided by four to arrive at a price of $2M per panel. The $2M is then divided by the SkyChaser's detection range of 30 kilometers, following the same calculation method used with the TPQ-50, to produce a factor of $66K per kilometer. The RPS-42 estimate was based primarily on a report from Arirang News that South Korea purchased ten RADA RPS-42 radars at a cost of $19M (Kim 2014). At a unit cost of $1.9M, the same calculation method used for the previous two estimates was applied using the RPS-42's range of 30 km to produce a factor of $63K per kilometer.

The cost estimates for each system are shown in Table 10.

Table 10. Radar Cost Estimates

	SRC SkyChaser	ELTA NA ELM-2138M	RADA eMHR	RADA RPS-42	RADA aCHR	RADA eCHR
Costs based on AN/TPQ50	$ 4,598,940	$ 7,664,900	$ 3,832,450	$ 4,598,940	$ 2,299,470	$ 2,299,470
Costs based on RPS 42	$ 1,900,000	$ 3,166,667	$ 1,583,333	$ 1,900,000	$ 950,000	$ 950,000
Costs based on Skychaser	$ 2,000,000	$ 3,333,334	$ 1,666,667	$ 2,000,000	$ 1,000,000	$ 1,000,000
Average	$ 2,832,980	$ 4,721,633	$ 2,360,817	$ 2,832,980	$ 1,416,490	$ 1,416,490
Verified Price	$ 2,000,000			$ 1,900,000		

The advanced technologies included in the aCHR and eCHR may increase the costs of those radars significantly. Consequently, these features and their importance must be weighed by the RCCTO to determine their value in meeting the warfighter's needs. While RADA markets these radars as having "unprecedented affordability," the company's marketing representative (email to author, September 6, 2019) declined to share the cost of these radars for this study.

5. Selection Criteria and Weights

A comparison of the six radars under consideration required the development of a decision support aid (DSA) using weights and scales. The DSA, which reflects the radars' quantitative benefit score (Table 11), incorporates the preferences of the RCCTO and normalizes the data so that the radars are ranked according to the best features. Normalization is an important step because simply weighting the data would skew the results. For example, the smallest radar should receive the most favorable score; however, simply multiplying weight by size creates a scenario where the largest radar is scored the most favorably. The DSA normalizes the data by assigning a scale of one to the smallest radar; the scale of the other radars is then calculated by dividing the size of smallest radar by the size of the radar in review. In the case of detection range, the RCCTO prefers the radar with the highest range. Therefore, the radar with the highest range is assigned a scale of one. The scale of the other radars is then calculated by dividing the range of the radar in review by the range of the highest radar. For criteria where several radars have the most preferred value, such as a 360-degree field of view, each radar with the preferred value is assigned the scale of one.

Each criterion on the DSA is assigned a weight based on the preferences of the RCCTO. The RCCTO provided the order of precedence as follows: size, weight, range, field of view, and power requirements. Size and weight are the most important with a combined weight of 50 percent because the radar must integrate into the Stryker vehicle without interfering with the vehicle's other components and tactical operations. The radar size received a heavier weighting than radar weight because all radars in the study successfully meet the weight requirements by a significant margin. The detection range weight of 45 percent is divided equally among the UAS, RAM, and aircraft target classes. The field of view is an important metric; however, all radars except the ELM-2138M provide the full 360-degree field of view. The DSA’s weights for FOV are smaller in comparison to other weights due to this strong similarity between the systems. The weight for power is relatively low for three reasons. First, the RCCTO specified that power is not a major concern because of how minor a radar’s power consumption is in comparison to the MMHEL itself. Second, the radar vendors reported this metric in inconsistent terms, with some listing peak power consumption while others listed average power consumption. Finally, each system far exceeds the threshold for power consumption.

Table 11. Radar Benefit Scores

		SkyChaser			ELM-2138M			eMHR			RPS-42			aCHR			eCHR		
	Weight	Raw	Scaled	Wtd	Raw	Scaled	Wtd	Raw	Scaled	Wtd	Raw	Scaled	Wtd	Raw	Scaled	Wtd	Raw	Scaled	Wtd
Size	30%	4.0	0.91	0.27	4.5	0.81	0.24	8.2	0.44	0.13	5.8	0.63	0.19	3.6	1.00	0.30	5.6	0.65	0.20
Weight	20%	200.0	0.88	0.18	176.4	1.00	0.20	356.0	0.50	0.10	202.8	0.87	0.17	299.8	0.59	0.12	211.6	0.83	0.17
UAV Detection Range	15%	30.0	0.60	0.09	50.0	1.00	0.15	25.0	0.50	0.08	30.0	0.60	0.09	15.0	0.30	0.05	15.0	0.30	0.05
RAM Detection Range	15%	0.0	0.00	0.00	15.0	1.00	0.15	8.5	0.57	0.09	0.0	0.00	0.00	4.0	0.27	0.04	4.0	0.27	0.04
RW/FW Detection Rang	15%	30.0	0.38	0.06	80.0	1.00	0.15	30.0	0.38	0.06	30.0	0.38	0.06	15.0	0.19	0.03	15.0	0.19	0.03
FOV - Elevation	2%	90.0	1.00	0.02	90.0	1.00	0.02	90.0	1.00	0.02	80.0	0.89	0.02	90.0	1.00	0.02	90.0	1.00	0.02
FOV - Azimuth	2%	360.0	1.00	0.02	180.0	0.50	0.01	360.0	1.00	0.02	360.0	1.00	0.02	360.0	1.00	0.02	360.0	1.00	0.02
Power	1%	500.0	0.50	0.01	500.0	0.50	0.01	590.0	0.42	0.00	320.0	0.78	0.01	250.0	1.00	0.01	250.0	1.00	0.01
TOTAL	100%			0.64			0.93			0.49			0.55			0.58			0.53

The DSA provides a weighted factor effect for each performance parameter by multiplying the raw data by the scaled value for the radar. The sum of the weighted effects ranks the radars, with the highest sum representing the radar with the greatest benefit to the warfighter. Further analysis is required to determine which radar provides the greatest benefit in terms of cost. The Cost Effectiveness Chart, found in Chapter IV of this report, multiplies the summed benefit factors by the projected per unit price of the radars. The resulting values reflect which radar provides the greatest benefit at the best price. These radars values are then ranked to provide the RCCTO a recommendation based on quantitative analysis. Other factors must be considered in addition to the ranking to determine the best radar to meet the warfighters needs.

6. Benefit Analysis

The benefits of the post-screening radar alternatives include both quantifiable measurements and qualitative attributes. The project team quantified important physical characteristics and performance parameters using a ratio method described in the preceding section. However, there are instances where certain radar alternatives demonstrate unique capabilities that are difficult to quantify. Therefore, this analysis necessarily reviews both quantitative and qualitative characteristics to arrive at a complete overview of the benefits provided by each alternative. While the quantifiable benefits carry more weight, a comparative analysis that includes some discussion of qualitative benefits is useful, especially if there is negligible difference between the quantifiable benefits of competing alternatives (Department of the Army 2013, 48).

a. Quantitative Benefits

The DSA depicted in Table 11 captures the quantitative benefits of the various radar alternatives. The ELM-2138M radar provides the most quantitative benefit with a score of 0.93, largely driven by its high detection ranges across the variety of aerial threats. It also weighs the least; however, this is because it consists of only two panels that afford 180 degrees of azimuth coverage, which fails to meet the 360-degree requirement (ELTA NA 2019a). The SkyChaser has the second highest benefit score at 0.64, primarily due to its relatively low size and weight. The four remaining RADA products have comparable benefit scores, offsetting comparative advantages over each other in size or weight with lower scores in other categories, like detection range.

b. Qualitative Benefits

Each of the post-screening radar alternatives has particular added capabilities that may not be quantifiable but present valuable decision-making considerations to the RCCTO. The SkyChaser, for example, is compatible with existing mission command systems such as the AFATDS, and so provides additional interoperability benefits. It also provides flexibility for the warfighter, as its array is designed to be modular with different mission configurations—for example, the radar panels can be stacked together to provide increased angular accuracy based on mission requirements (SRC Inc. 2017). Likewise, RADA's eMHR provides mission flexibility by offering multiple operating modes on one product, including the ability to tune the radar to mission-dependent sensitivity configurations based on likely threat signatures (RADA 2016).

Mission flexibility is a common theme for RADA's alternatives. For example, the RPS-42 allows for "examination of specific tracks while scanning is continued" (RADA 2019b). Comparable in their quantitative benefits, the aCHR and eCHR have significant qualitative differences. The aCHR adds the capability of tracking ground targets in addition to aerial threats, which provides options to broaden the scope of the MMHEL's use in the future. In contrast, the eCHR is designed to fulfill a Very Short-Range Air Defense (VSHORAD) mission, and so is acutely suited to detect low signature targets like nano-UAVs (RADA 2019a).

Conversely, the ELM-2138M's design is not as flexible. The ELM-2138M is specifically designed to be affixed to the top of a vehicle, therefore increasing the vehicle's tactical profile and possibly obstructing the view of the vehicle commander. This is a potential concern given that the Stryker platform is generally outfitted for combat operations with numerous items on top of the vehicle—ammunition, critical equipment, and counter-sniper netting—which could make the addition of a radar array problematic.

F. CHAPTER SUMMARY

This chapter's objectives were to outline the project team's systems engineering approach, establish traceability between system functions and system requirements, and to detail the process used to develop and execute the preliminary cost effectiveness analysis. The collective intent of these objectives was to provide readers insight into the methodology used by the project team to complete this research effort, which primarily consists of the preliminary cost effectiveness analysis. This analysis began with 12 radar alternatives and ended with 6 alternatives through the application of top-level screening criteria. Each of the remaining alternatives underwent a cost analysis and a benefit analysis, both qualitative and quantitative, to inform the comparison of alternatives. This comparison of alternatives, as well as the complete results of the cost effectiveness analysis, a risk analysis, and a sensitivity analysis, will be addressed in detail in the following chapter.

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IV. RESULTS

A. CHAPTER INTRODUCTION

This chapter offers further analysis of the radar alternatives and provides results of the cost effectiveness study. The analysis begins with an assessment of the risk associated with the MMHEL radar alternatives in an effort to better inform the decision process. While a more detailed risk analysis will certainly be necessary following the technological demonstration of initial prototypes in 2021, this assessment highlights top-level risks that should be considered when comparing alternatives and provides suggestions on how to mitigate these risks. A sensitivity analysis of the weighting used in the cost effectiveness study is then presented to highlight how manipulating certain weights may influence the results. The chapter concludes by delivering the results of the cost effectiveness analysis, which establishes the basis for the project team's recommendations provided in Chapter V.

B. RISK ANALYSIS

This section analyzes the top three risks associated with the MMHEL radar alternatives. Blanchard and Fabrycky (2011) explain that a risk analysis is conducted to "determine the ways in which the risk can be eliminated or minimized" and that some potential solutions are "determined through the accomplishment of design trade-offs" (692). Design trade-offs were part of the quantitative analysis presented in Chapter III, which identified areas of uncertainty related to operational performance, suitability factors, and vendor considerations. These primary areas of uncertainty are translated into top-level risks and are discussed in more detail below.

1. Operational Risk: Detection Range

A radar's ability to detect targets at a range that enables the MMHEL to engage prior to itself being engaged is paramount to operational success. From a systems engineering perspective, the range at which a radar can accurately and precisely detect, track, and classify a target represents its relative technical maturity, and also presents the system's foremost technical challenge to overcome. This is largely due to the technical complexity involved in radar target detection, which includes detecting targets from a mobile platform that have a diverse set of radar cross-sections, travel at multiple speeds, are manned and unmanned, and are capable of engaging friendly forces. According to the Department of Energy's *Technology Readiness Assessment Guide*, critical technology elements are at-risk technologies that are essential for the success of a project (DoE TRA 2011, 8). The "at-risk" technology of the radar alternatives is the critical technology element of detection range (DoE TRA 2011).

The detection range requirements specified in Chapter III of this report include UAV, RAM, and both rotary and fixed-wing targets. While no one system met all of the RCCTO's threshold requirements, the only system that met every detection range requirement was the ELM-2138M. As such, the ELM-2138M presents the lowest risk of all the alternatives in this particular area. With the majority of the radar vendors self-reporting detection ranges that fail to meet threshold requirements, the risk of selecting a radar that is unable to provide the warfighter the desired capability is significantly high. This underscores the high level of risk presented by detection range.

From all the specified range requirements, the UAV detection range is the requirement best represented by all systems. RADA's aCHR, eCHR, and eMHR met the 10-kilometer threshold requirement, while the ELM-2138M, RPS-42, and SkyChaser met the 30-kilometer objective requirement. All systems selected for comparison met or exceeded the UAV detection range. Consequently, no radar presents a significant risk for UAV detection.

Rockets, artillery, and mortars (RAM) is not as well represented among the alternatives. The aCHR, eCHR, eMHR, and SkyChaser systems failed to meet the seven-kilometer RAM detection range threshold. As such, these alternatives present a greater risk than the remaining two systems, the RPS-42 and ELM-2138M, which meet and exceed the threshold respectively. This risk is significant because RAM represents one of the fastest moving threat targets with relatively small radar cross-sections.

The radar alternatives appear to be the least technologically mature in the area of manned aircraft detection. The ELM-2138M is the only system that meets the RCCTO requirements for rotary and fixed-wing aircraft detection range. The remaining five systems failed to meet threshold requirements for manned aircraft detection range. As a result, manned aircraft detection is the largest capability gap among the radar alternatives.

While the technical challenges are considerable, the risks associated with a radar's ability to detect, track, and classify targets at an adequate range can be mitigated. One possible mitigation technique is to award the top two competitors with research and development contracts focused on further maturing the technology associated with detection range. Furthermore, a more critical inquiry into the effects of detection ranges on mission accomplishment could drive a revision of desired system requirements and enable the RCCTO to develop a more robust competitive range for MMHEL Radar alternatives. For example, further analysis might prove that an effective detection range for manned aircraft is actually much lower than the current threshold requirement. A revised requirement with a decreased range, which must be supported by thorough analysis, would lower the risk presented by current radar alternatives.

2. Suitability Risk: Reliability, Maintainability, and Availability

A commercial off-the-shelf (COTS) radar solution presents uncertainty related to operational suitability, primarily due to the lack of visibility acquisition professionals have on the solution's development. The *Defense Acquisition Guidebook* defines operational suitability as "the degree to which a system is satisfactorily placed and operated in field use, with consideration given to reliability, maintainability, and availability" in conjunction with other factors (DAG 2018, 21). The risk associated with the operational suitability factors of reliability, maintainability, and availability (RMA) are especially high when a COTS item is integrated with a newly developed system, like the MMHEL. This risk is further elevated by the absence of operational data, resulting in the sole reliance on vendor-reported data to evaluate the RMA metrics of each alternative.

None of the six radar alternatives has been tested with the MMHEL. In one respect, this means each alternative presents an equal level of risk in regard to how integrating with the MMHEL might affect system RMA. Integration issues may also include that every alternative carries a certain level of risk that RMA metrics will be significantly degraded.

This report's "System Supportability Section" highlighted the unique importance of RMA to this system, as the system's projected operational environment will typically be located far from established logistical support. This risk is compounded by the critical assumption that the performance characteristics and physical specifications annotated in the collected vendor data are accurate, and that the radars can perform to those standards in an operational environment. While the vendors of all six radar alternatives report the RMA metrics of their respective radar, determinations of RMA should be "based on data from system use under operationally realistic…environments and planned operating conditions" (21).

The RMA risk presented by both the integration of two different systems and the reliance on vendor-reported data can be reduced through testing and evaluation. While this solution appears obvious, its execution requires thorough planning and preparation. To assist in this, the *DOD Guide for Achieving Reliability, Availability, and Maintainability* recommends that the government organization request radar RMA levels recorded in commercial usage from the vendors being considered (DOD GARAM 2005, 1–19). This data would help clarify the information listed in the radar's data sheet and establish more accurate metrics prior to entering testing. Further analysis could then be conducted to "determine the anticipated changes in RMA when using the COTS in a military application" (1–19). The testing and subsequent evaluation of these radar alternatives will significantly lower the risk associated with the RMA suitability metrics.

Table 12 provides additional suitability factors for the RCCTO to consider prior to selecting an alternative. Each factor presents additional considerations unique to the MMHEL radar.

Table 12. Potential RMA Issues. Adapted from *DOD Guide for Achieving Reliability, Availability, and Maintainability* (2005).

Factor	Discussion
Environment	If the environment of the Army application is more severe than the commercial application, reliability may be significantly less in the intended Projected Operational Environment (POE).
Integration	The radar solution may require new or different support requirements. Special support equipment such as interface adaptors or cabling may be necessary for sustainment of the radar. The RCCTO may consider a thorough analysis and risk assessment associated with the potential impacts of integrating the radar into the POE.
Maintenance	The only military repair is to remove a failed radar from the MMHEL system and replace it with a new radar. The manufacturer must do all maintenance of the radar for two reasons: • Vendors are likely to not sell the data needed to conduct repairs to the radar • Maintenance attempts by the user are likely to void the warranty
Long-term support	A vendor is not obligated to support the radar for a specific length of time. They may not provide notice of plans to discontinue supporting an item. The Army may: • Choose to make a lifetime buy • Identify another COTS item that may be a suitable substitute
Warranty	Warranties for commercial items are usually null and void if the user attempts to modify or repair the item. The RCCTO may consider asking the chosen vendor if their existing policy allows for the return and replacement of faulty radars. This becomes significantly more important if the radar should fail while deployed to an overseas location.

3. Vendor Risk: Foreign-Based Options

The RCCTO issued a Broad Agency Announcement (BAA) for several advanced research initiatives, including air and missile defense and counter-A2AD capabilities (FBO 2019). The BAA specifies that foreign firms should contact the RCCTO prior to submitting proposals. This could potentially be in part because of the risk associated with contracting with foreign-based companies to produce defense systems. One such risk is supply chain management. It is significantly more difficult to enforce standards within a company's supply chain if the majority of the transactions occur overseas. A second risk is access to sensitive or classified information. Additional processes must be emplaced when working with a foreign-based company to safeguard any information that the company cannot legally view. The inability to access this type of information may also inhibit the company from performing to their ability. Finally, contracting with a foreign-based company presents risks related to public policy. Defense acquisitions procedures are unique in that certain business decisions are influenced more by public policy than in gaining a profit. Contracting with a foreign-based company instead of a domestic company, which may help create jobs and stimulate the economy, exposes the program to potential scrutiny from external parties. These external parties could include a congressman who represents a district that would benefit from a defense contract, or protests from a domestic company that was competitive for the contract. These are the three primary risks associated with foreign-based vendors.

The six systems selected for comparison are produced by three vendors. Of the three, RADA is the only foreign-based company. RADA, who produces the eMHR, RPS-42, aCHR, and eCHR, is an Israeli-based defense contractor. As such, the RADA alternatives present the highest level of risk in this particular area. ELTA North America, which produces the ELM-2138M, is an American subsidiary of the Israeli company ELTA Systems Ltd. As a result, the ELM-2138M contains the second highest level of risk in this area, albeit significantly lower than the RADA products. The SkyChaser, produced by the American company SRC, presents the lowest risk.

The risk associated with contracting with RADA has already been significantly mitigated through the company's establishment of U.S.-based subsidiaries. RADA established a U.S. subsidiary, RADA Technologies LLC, in March 2018 as part of a joint venture with the American-based company Saze Technologies Inc. (RADA 2018). This risk can be even further mitigated by partnering RADA, if selected, with an American-based defense company. A similar approach was taken by the Israeli defense company Rafael Advanced Defense Systems Ltd., that partnered with the American defense company Leonardo DRS to manufacture and deliver the Trophy Active Protection System (APS) for several M1 Abrams tanks (Freedberg 2019). Not only did this help streamline communications between the defense acquisition community and the vendors, it also simplified the supply chain management process and benefited the sustainment effort as a whole. The American-based subsidiaries and the frequency with which contracts are awarded to foreign-based vendors makes this risk the lowest of the three presented in this section.

C. SENSITIVITY ANALYSIS

This section analyzes the sensitivity of the data results based on the selection criteria and their associated weights. According to Blanchard and Fabrycky (2011), a sensitivity analysis centers on a fundamental question: "how sensitive are the results of the analysis to possible variations of these uncertain input factors?" (589). In this study, the "uncertain input factors" are the weights associated with the selection criteria used to compare the competing MMHEL Radar solutions. The weights do not represent objective, scientific facts but are reflective of a decision maker's preference and the warfighter's needs. Therefore, the RCCTO and other decision makers must be informed on whether the overall results of this cost effectiveness analysis are changed by manipulating the relative importance of the selection criteria; and, if so, to what degree these changes occur. Consequently, this section puts forth three possible weighting variations alongside the RCCTO's weights to analyze the impact on the overall outcome of a quantitative comparison. Finally, the sensitivity analysis concludes by testing the effect that cost has on the overall outcome.

1. Possible Variations

The relative weights and outcomes of the possible variations are captured in Table 13. The first scenario is reflective of the sponsor's input and serves as a comparative baseline. According to the RCCTO, size and weight are highly valued because of the limited space available on the Stryker's exterior and the technological challenge of including all the system's requirements within specified physical restrictions. Therefore, the weight of those two attributes is a combined 50%, followed by detection range and, lastly, the more standard attributes such as power and field of view. As a result, two of RADA's products, the aCHR and eCHR, rank first and third respectively, while ELTA North America's ELM-2138M ranks second.

In a second scenario, all selection criteria are set to equal weighting. This scenario does not consider one attribute any more important than another, therefore complementing the first scenario's baseline. As a result, the top three radar alternatives remain unchanged; although, the ELM-2138M slips to third because the equal weighting of the attributes mitigates its comparative advantage in detection range. This indicates that the results will not significantly change if decision makers determine that all attributes are equally important.

Detection range is the system attribute most closely linked to technical maturity, and as such could be considered the most important selection criteria. Therefore, the third scenario illustrates the impact of detection range on the overall outcome. Reflective of the need for superior detection range in an era of near-peer competition, the third scenario allocates a combined 75 percent of the weight to detection range. Under this weighting scheme, the ELM-2138M's superiority in raw detection ranges propel it to first, while the two RADA products trail at a distant second and third. However, similar to the second scenario, the top three alternatives remain the same.

The A2AD environment requires responsiveness and rapid target acquisition from its weapons systems, making it feasible to consider a 360-degree coverage capability as equally important as detection range. Accordingly, the fourth scenario assigns a weight to Field of View-Azimuth that is equal to the aggregated weight of the detection ranges. As a result, RADA's aCHR, eCHR, and RPS-42 are ranked first to third respectively. As expected, this manipulation in weighting of the Field of View-Azimuth attribute dropped the ELM-2138M to fifth in the ranking. Of the three additional scenarios, this scenario resulted in the most significant changes, which highlights the sensitivity of the comparatively small Field of View-Azimuth weighting of the RCCTO's scale.

Table 13. Weighting Sensitivity Analysis

RCCTO WEIGHTING

	Weight
Size	30%
Weight	20%
UAV Detection Range	15%
RAM Detection Range	15%
RW/FW Detection Range	15%
FOV - Elevation	2%
FOV - Azimuth	2%
Power	1%
TOTAL	100%

	BENEFIT	RANK
SkyChaser	0.080	4
ELM-2138M	0.098	2
eMHR	0.052	6
RPS-42	0.073	5
aCHR	0.103	1
eCHR	0.093	3

EQUAL WEIGHTING

	Weight
Size	13%
Weight	13%
UAV Detection Range	13%
RAM Detection Range	13%
RW/FW Detection Range	13%
FOV - Elevation	13%
FOV - Azimuth	13%
Power	13%
TOTAL	100%

	BENEFIT	RANK
SkyChaser	0.082	5
ELM-2138M	0.090	3
eMHR	0.064	6
RPS-42	0.085	4
aCHR	0.118	1
eCHR	0.116	2

RANGE MOST IMPORTANT

	Weight
Size	5%
Weight	5%
UAV Detection Range	25%
RAM Detection Range	25%
RW/FW Detection Range	25%
FOV - Elevation	5%
FOV - Azimuth	5%
Power	5%
TOTAL	100%

	BENEFIT	RANK
SkyChaser	0.057	5
ELM-2138M	0.100	1
eMHR	0.056	6
RPS-42	0.059	4
aCHR	0.074	2
eCHR	0.073	3

RANGE EQUALS COVERAGE

	Weight
Size	5%
Weight	5%
UAV Detection Range	14%
RAM Detection Range	14%
RW/FW Detection Range	14%
FOV - Elevation	5%
FOV - Azimuth	42%
Power	1%
TOTAL	100%

	BENEFIT	RANK
SkyChaser	0.088	4
ELM-2138M	0.082	5
eMHR	0.077	6
RPS-42	0.090	3
aCHR	0.117	1
eCHR	0.116	2

The final component of sensitivity analysis investigates the impact of the cost estimates used in the comparative analysis. Since the majority of costs are based on analogous estimates, this scenario mitigates any bias by assuming all costs are equal. Therefore, the cost sensitivity solely compares benefit scores using the RCCTO-informed attribute weighting. As a result, the ELM-2138M ranks first among the alternatives due to its comparative advantages in detection range, while SRC's SkyChaser ranks second driven by its relatively smaller size and lighter weight. However, RADA's aCHR still ranks in the top three alternatives. The complete results are illustrated in Table 14.

The analogous cost estimates based off the AN/TPQ-50 are from 2016. This means current estimates based on that data could potentially be inflated if the cost per kilometer range has since decreased due to market competition and maturity of technology. Comparisons of the verified prices of the SkyChaser and RPS-42 from 2019 against the analogous cost estimates of those systems indicate that the competitive market of on-the-move radars may well be starting to drive down prices. For example, the SkyChaser's average price according to the analogous cost estimate is 42 percent higher than the actual price that the RCCTO provided. Likewise, the RPS-42's analogous cost estimate is 49 percent higher than the verified purchase made by South Korea (Kim 2014). Subsequently, this study uses the verified prices for the SkyChaser and RPS-42 in its comparative analysis, which arguably provides them an advantage over other radars, where the study relied on an unverified analogous cost estimate due to a paucity of publicly available information.

Table 14. Cost Sensitivity Analysis

	BENEFIT	RANK
SkyChaser	0.641	2
ELM-2138M	0.927	1
eMHR	0.493	6
RPS-42	0.554	4
aCHR	0.581	3
eCHR	0.526	5

2. Critical Factors

Detection range is the most critical factor in affecting the outcome of the MMHEL Radar comparative analysis. The sensitivity analysis indicates that manipulating the weight of the detection range affects the ranking of benefit scores more than any other selection criteria. Whereas RADA's aCHR ranks first in three of the four selection criteria sensitivity scenarios, it moves to second when the detection range is weighed as most important. The driver of this divergence is the variability between the raw detection ranges of the various radar alternatives. While the size and weights of all the radar alternatives are comparable, the ELM-2138M's UAV detection range is more than three times that of the aCHR. Therefore, when the detection range is considered most important and weighed as such, the ELM-2138M predictably outranks the RADA alternatives as the top-choice radar.

Cost is the second critical sensitivity factor. When costs are assumed equal, the ELM-2138M again outranks the RADA alternatives by almost twice the benefit score. However, the ELM-2138M's cost estimate is more than three times more expensive than RADA's aCHR and eCHR. Therefore, when cost estimates are applied the ELM-2138M's comparative benefit advantages are nullified by its cost.

D. RESULTS

The results indicate that the aCHR radar is the most cost-effective of the radar alternatives. While all the radar alternatives included in this study present unique capabilities, the aCHR provides the highest overall benefit at the lowest cost to the government. Figure 25 depicts the results of the cost-effectiveness analysis. Certain radars offer a greater benefit than the aCHR, but also have a significantly higher cost. The ELM-2138M, for example, provides a benefit score of 0.927, almost twice as high as the aCHR's score of 0.581. However, the ELM-2138M's cost estimate of $9.4 million is also almost twice as high as that of the aCHR. Therefore, acquisition decision makers must determine if the ELM-2138M's superior benefits are worth increased investment.

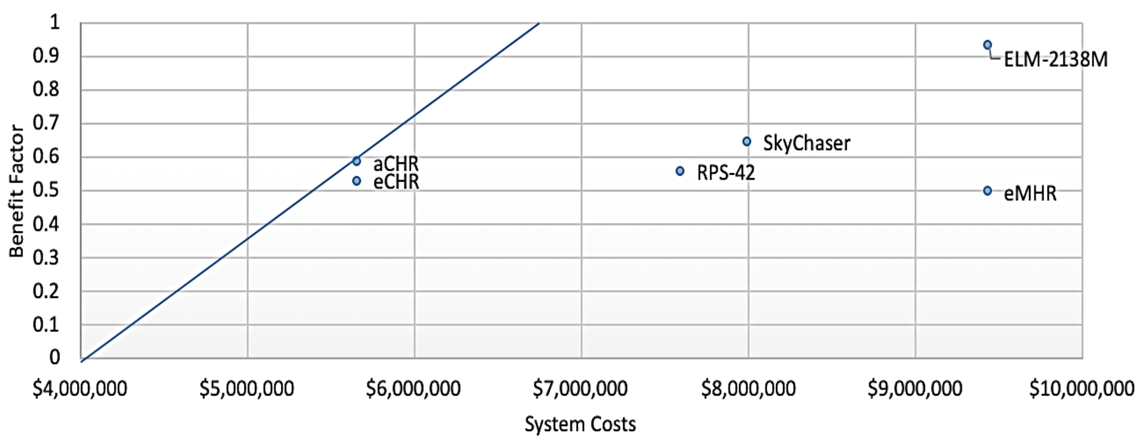

Figure 25. Cost Effectiveness Chart

1. Key Findings

This aCHR provides the best value to the RCCTO for a relatively small, on-the-move, technologically mature, and cost-effective MMHEL Radar system. The aCHR ranked in the top three of all alternatives in all five decision-making scenarios in this analysis, scoring the highest in three of those five scenarios. Still, the aCHR's cost estimate is assumed from analogous estimates and should be re-evaluated against comparative systems when verified cost estimates become available. The ELM-2138M provides the greatest detection range of all the alternatives; however, the scope of this study does not include an analysis of the MMHEL's physical dimensions and whether the ELM-2138M's top-mounted design would interfere with the laser's operation. Therefore, a determination that the ELM-2138M can provide 360-degree coverage if mounted counter-directionally on multiple vehicles requires further analysis and testing. If unresolved, the ELM-2138M can be eliminated from the comparative analysis altogether, leaving the aCHR as the prime candidate.

2. Relevant Observations

The sensitivity analysis indicates that the relative difference in benefit score between the top three radar alternatives is highly dependent on the weighting scheme. For example, under the RCCTO's given weighting, the percentage difference in benefit provided between the highest-ranked alternative, the aCHR, and the third-ranked, the eCHR, is only ten percent. Likewise, under the equal weighting scheme, the percentage difference between RADA's top two systems is only two percent, but this difference increases to 31 percent between the aCHR and the third-placed ELM-2138M. This result repeats itself when the weight of the detection range is equal to the weight given to coverage—the difference between the top two systems is negligible, but the difference between the top system and the third-ranked system is considerable. When detection range is considered the top priority, the ELM-2138M provides a benefit score that is 35 percent greater than the second alternative, the aCHR. Finally, when costs are assumed equal, the benefit of the ELM-2138M is 60 percent greater than the second-ranked alternative. Therefore, due to the variability in relative differences between these scenarios, a decision maker presented with these radar alternatives must ensure the pedigree of the available raw data and consider the weights used to evaluate the relative importance of the system attributes.

V. RECOMMENDATIONS AND CONCLUSIONS

A. RECOMMENDATIONS

The project team has three recommendations. First, given the current available data as illustrated in Chapter IV of this report, the project team recommends that the RCCTO procure RADA's aCHR for the MMHEL's TRL 7 technology demonstration. While other systems, most notably ELTA NA's ELM-2138M, provide more benefit, the aCHR provides the best value while also meeting all threshold requirements except for detection range. The aCHR's detection range, while failing to meet the threshold requirement for RAM and manned aircraft, is likely to improve in the future as technology matures. Additionally, no radar system included in this study met all of the RCCTO's threshold requirements, including the ELM-2138M, which presents significant compatibility challenges with respect to the Stryker platform due to its top-mounted design and inability to provide 360-degree coverage. Furthermore, the express intent of the MMHEL project is eventually to equip multiple Strykers in a BCT with the MMHEL capability, thus necessitating an inexpensive solution. The aCHR helps to achieve this overarching goal due to its relatively low cost.

The team's second recommendation is for the RCCTO to conduct further testing to verify the raw data reported by the vendors. The project team acknowledges that the MMHEL cost-effectiveness analysis relies on two fundamental assumptions. First, the study uses raw data from contractor fact sheets. Therefore, reporting bias certainly affects the pedigree of data, because objective third party testers have not verified the accuracy of the contractor data. Similarly, the project team relied on historical costs of analogous radar systems or contractor quotes to arrive at a cost estimate for most of the MMHEL Radar alternatives. While these cost estimates are certainly informed, they are inevitably imprecise. Consequently, the project team recommends that the RCCTO take steps to confirm the veracity of the data used in their own cost-effectiveness analysis. Developmental and operational testing can verify and validate the figures provided by the contractor fact sheets, while also illuminating qualitative benefits or shortcomings that are not addressed in this project's analysis. Likewise, the team recommends that the RCCTO commission a more detailed cost and price analysis of the various alternatives, as this project's sensitivity analysis indicates that variances in cost estimates can affect the overall outcome of the cost-effectiveness study.

Finally, the project team recommends that the RCCTO revisit its weighting of the desired system attributes to ensure that they accurately reflect the decision maker's priorities. The sensitivity analysis indicates that the weighting of detection range is a critical factor in affecting the outcome of a MMHEL Radar comparative analysis, and so careful consideration must be paid to its relative importance. If it is later decided, for example, that 360-degree coverage is more important than what is currently reflected in the weighting scheme, or that size is not as important as originally thought, results of the analysis will be significantly different.

B. CONCLUSION

1. Summary

Lieutenant General (LTG) L. Neil Thurgood, the director of the RCCTO, instructed his organization to leverage industry partners for new radar technology alternatives in support of the MMHEL rapid prototyping effort, to include its TRL 7 technical demonstration scheduled in the third quarter of FY21. The decision aligns with the office's mission, which in part, states that it will "produce or acquire materiel solutions consistent with the Army's modernization priorities that maximize Soldiers' capabilities to deploy, fight, and win on future battlefields" (The Army RCCTO 2019). During a meeting with the project team held in June 2019, LTG Thurgood suggested that an academic research and analysis effort to assist the RCCTO in finding an effective radar solution would benefit his team by making an informed buying decision while maintaining their accelerated timeline objective. This capstone project was created as a result of that meeting and subsequent lines of communication were established between both parties to begin the collaborative effort.

The result of this report is a recommended radar solution for the RCCTO to consider. The intent is to recommend a radar solution that effectively addresses this project's problem statement: the U.S. military lacks a radar capable of guiding the Multi-Mission High Energy Laser that is compact and inexpensive enough to equip select

Strykers in an SBCT with the capability to engage targets on the move. This project had three objectives. The following is a brief review of how this project addressed each objective.

2. Project Objectives

a. Inform the Army's Search for an MMHEL Radar

The project's first objective was to inform the Army's ongoing search for a compact, vehicle-mounted radar that enables the use of the MMHEL. The capstone team began this effort by framing the project through the consolidation of relevant background information related to previous high-energy laser development efforts and current radar assets to illustrate accurately the capability gap. The team first documented the Army's past development of the Tactical High-Energy Laser (THEL) and its most glaring limitation. The system was a physically large, fixed-site weapon that relied on a separate radar, positioned within relative proximity, to achieve target detection for the THEL. This system was defensive in nature due to its stationary position. The research was then focused on current radar assets within a Stryker Brigade Combat Team (SBCT) that could support an MMHEL-equipped Stryker platform. Significant limitations were identified with the two radar types that are organic to an SBCT. First, the radars must be stationary to be operated, which severely constrains a Stryker's ability to employ the MMHEL while maneuvering within its desired battlespace. The second issue is that the limited number of radars available to the SBCT places a constraint on when and where the radars are employed. As previously stated in Chapter I, these systems are used to protect mission command nodes and headquarters elements within the Brigade. These identified limitations, in combination with the research gathered on the THEL, presented a clear capability gap.

The research was then centered on the Army's need to further develop its laser technology by focusing on the size-to-capability ratio with the intent to utilize the weapon on a Stryker platform. The significance of this need was evident once the team illustrated how the MMHEL Radar system would nest within the current National Security Strategy (NSS). Figure 3 (MMHEL Radar Traceability Diagram) in Chapter II depicts how the

MMHEL provides a unique Mobile Short-Range Air Defense (MSHORAD) capability at the tactical level that also supports efforts at the operational and strategic level. This user need directly supports one of the six Army modernization priorities and can ultimately be traced to requirements outlined in the National Security Strategy.

The RCCTO provided summaries of recent demonstrations using a Mobile Experimental High-Energy Laser (MEHEL) on a Stryker vehicle using 5-kW and 10-kW lasers as a proof of concept. These events helped define the system's key performance parameters, which included the radar's performance requirements used to achieve this objective. Additionally, the RCCTO shared their follow-on plan to conduct a TRL 7 technical demonstration in 2021 utilizing a 50-kW laser integrated with a radar solution chosen from alternatives outlined within the research and analysis from this study. The objective to inform the Army's ongoing search for a compact, vehicle-mounted radar that enables the use of the MMHEL was achieved by first identifying the capability gap, defining the user need, and obtaining the system's key performance parameters. Second, the project outlined the mission success requirements that an MMHEL radar must achieve for its mission to be considered successful. In short, the mission success requirements comprise the four basic functions that the radar must perform to be effective, which are to detect, classify, and track targets, as well as interoperate with the MMHEL. The capstone team effectively linked the operational needs, as stated by the warfighter, with meaningful system requirements that systems engineers can use to evaluate the form and function of any proposed MMHEL Radar solution.

b. Assist in Addressing Larger Issue of U.S. Military's Potential Deficiencies in an A2AD Environment

The project's second objective was to assist in addressing the larger issue of the U.S. military's lack of a mobile, ground-based mechanism for defeating a near-peer air threat in an A2AD environment. The team's Design Reference Mission (DRM) produced a comprehensive and realistic operational scenario that illustrated how the MMHEL could be employed to address this issue. The DRM provided the means for achieving this project objective by providing a detailed narrative illustrating the employment of the MMHEL as a supporting ground-based asset in an A2AD environment. Additionally, the DRM serves to enable further scenario-based wargaming, modeling and simulation exercises, and foundational planning for operational test events to address further this project objective.

A mission background and Projected Operational Environment (POE) were created to present a realistic near-peer threat comprised of A2AD systems in a multi-domain environment. The mission background states the benefits of the MMHEL being employed in such an environment and how it can enable the U.S. Army to defeat its peer adversary. The POE offers an operational-level scenario overview and detailed operational situations (OPSITs), which introduce necessary variables to highlight the radar's critical attributes.

Near-peer threat details were researched and compiled to inform the system's potential operational scenarios. The near-peer threat details included tier one, two, and three unmanned aerial systems, rotary and fixed-wing aircraft, and several rockets, artillery, and mortar systems, all of which could reasonably be encountered in an A2AD environment. This assisted in illustrating how the MMHEL could serve as a viable solution to the need for a mobile, ground-based mechanism capable of defeating aerial threats.

c. Generate Viable Radar Alternatives and Provide a Recommendation

The project's final objective was to generate a list of viable radar alternatives and provide a recommendation to the RCCTO of the optimal solution. The capstone team applied systems engineering concepts to develop the functional hierarchy and system tradeoff considerations. The functions and tradeoffs that were identified will comparatively inform necessary criteria used for upcoming test and evaluation of the radar's performance. Additionally, the effectiveness analysis in this study focused on the requirements and critical technical parameters provided by the RCCTO. This analysis reviewed ten radars that six different companies submitted in response to a request for proposal (RFP) in 2018. Through market research, the team identified two additional radars that became available in September 2019. Preliminary, top-level screening eliminated six radars because of the radars' inability to perform the MSHORAD mission while mounted on a moving ground vehicle.

The RCCTO emphasized their need to find a best-value radar which presented several challenges due to the limited availability of individual unit pricing for certain alternatives. The costs for three radar systems were estimated using parametric techniques. Specifically, the analysis used verified costs from multiple "on-the-move" mounted radar systems to calculate a price-per-kilometer of range. This factor, multiplied by the range for the systems with unknown costs, provided an estimation that was formulated to identify the best-value radar. The RCCTO also shared their prioritization of requirements that guided the capstone team's benefit weighting used in the effectiveness calculations. The data was normalized to compensate for combining attributes where preferential differences exist.

The analysis then focused on generating multiple scenarios to determine how sensitive the results were to variable changes based on the inherit uncertainty of weighting criteria. In every scenario, RADA's aCHR and eCHR radars were among the top three alternatives. The available marketing data suggests that the main difference between the aCHR and the eCHR is size and weight; however, further research may provide more insight on the performance differences between the two radars. The cost for both systems was recorded as equal in the cost effectiveness calculations because RADA would not provide their pricing data. The weighted scenarios also showed that the ELM-2138M performed well, but presented two notable limitations. First, this radar cannot provide a 360-degree FOV for its host platform. The ELM-2138M can only achieve this requirement using multiple vehicles operating together, with the system being mounted counter-directionally on each vehicle to provide the necessary coverage. The second limitation is that the panels are too large to be mounted on the side of a Stryker. This system's top-mount design would interfere with the MMHEL, and would inhibit other mission essential equipment from being stored on the top of the vehicle. The analysis suggests that if these limitations were perceived as acceptable risk, the ELM-2138M's raw benefit score is 60 percent greater than the aCHR due to its superior detection range capability.

This project objective was achieved by incorporating the analysis mentioned above with identified areas of risk associated with the MMHEL radar alternatives to help inform the decision process. This analysis focused on operational risks related to range requirements, suitability risks related to reliability, maintainability, and availability (RMA), and foreign vendor risks that applied to five of the radar alternatives. The intent of the risk analysis was to highlight assumptions related to the most significant uncertainty identified from our research and to provide suggestions on how to mitigate such uncertainties. As a result of this analysis, the team presented a list of six viable radar alternatives and recommended the aCHR as the optimal solution.

3. Areas of Future Research

This report serves as a critical step forward in the process of equipping multiple Strykers in a BCT with the capability to engage and destroy a wide variety of aerial threats using the MMHEL system. Due to the limited scope of this research effort, the project team recommends the areas of opportunity outlined in the following subsections for continued research using this project as a foundational reference. These recommendations are aligned with a variety of systems engineering management course materials to allow for the direct application of learned concepts and relevant tools.

a. Modeling and Simulation

The Design Reference Mission presents just one perspective on how the MMHEL Radar may interact with its operational environment. Therefore, model-based systems engineering techniques provide multiple pathways for future research projects. Specifically, a model of the MMHEL Radar, and a simulation of its interactions with its projected operational environment, holds great promise for further informing the Army's ongoing search for a compact and on-the-move radar capable of guiding directed energy weapons. This recommended area presents an underlying opportunity to collaborate with the Modeling Virtual Environments and Simulation (MOVES) Institute at the Naval Postgraduate School. Leveraging the institute would facilitate achievable solutions while providing focused expertise and mentorship throughout the project.

b. Test and Evaluation

The project team readily acknowledges that the analysis in this report relies on publicly available, contractor-furnished data that has not yet been subjected to government tests. Therefore, as the RCCTO transitions a mature MMHEL capability to a program office, future research can lend support to the acquisition decision-making process by constructing developmental and operational test scenarios. These scenarios can assist with the verification of any alternative's ability to meet the warfighter's requirements. Specifically, applications from the Naval Postgraduate School course SE4354, System Verification and Validation, may be utilized to assist the future program office with developing objective, defendable, repeatable, and traceable evaluations.

c. Decision-Making Support Analysis

Finally, the work undertaken by the RCCTO to develop the MMHEL is undoubtedly a long-term effort that is strictly focused on a limited quantity of prototype models in the near term. Therefore, future research can aid in the evaluation of FY23 MMHEL Radar alternatives by providing system life-cycle analyses focused on the alternatives' associated production learning curves and economies of scale. This recommended analysis may also be applied to MMHEL system quantities to assist the program office with its preliminary cost, schedule, and performance planning.

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