GLOBAL MOBILITY:

ANYWHERE, ANYTIME, ANY THREAT?

COUNTERING THE MANPADS CHALLENGE

by

Jacqueline D. van Ovost, Lieutenant Colonel, USAF

December 2005
Occasional Paper No. 38
Center for Strategy and Technology
Air War College

Air University
Maxwell Air Force Base, Alabama

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
DEC 2005

2. REPORT TYPE

3. DATES COVERED
00-00-2005 to 00-00-2005

4. TITLE AND SUBTITLE
Global Mobility: Anywhere, Anytime, Any Threat? Countering the Manpads Challenge

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air University,Air War College,Center for Strategy and Technology,Maxwell AFB,AL,36112

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**		**55**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

GLOBAL MOBILITY:

ANYWHERE, ANYTIME, ANY THREAT?

COUNTERING THE MANPADS CHALLENGE

Jacqueline D. van Ovost, Lieutenant Colonel, USAF

December 2005

The Occasional papers series was established by the Center for Strategy and Technology as a forum for research on topics that reflect long-term strategic thinking about technology and its implications for U.S. national security. Copies of No. 38 in this series are available from the Center for Strategy and Technology, Air War College, 325 Chennault Circle, Maxwell AFB, AL 36112, or on the CSAT web site at http://www.au.af.mil/au/awc/awcgate/awccsat.htm. The fax number is (334) 953-6158; phone (334) 953-6460.

Occasional Paper No. 38
Center for Strategy and Technology

Air University
Maxwell Air Force Base, Alabama 36112

Disclaimer

Contents

Page

Illustrations

Page

Author

Lieutenant Colonel Jacqueline D. van Ovost is the Standards Branch Chief at the United States Transportation Command Operations Directorate, Requirements Division, Scott AFB IL. She is responsible for deployment and distribution operational processes, standards implementation, and performance monitoring. She is an experimental test pilot and has worked on the C-17, C-141B/C, and C-12J test programs. Colonel van Ovost is a graduate of the U.S. Air Force's Air War College and holds a M.S. in mechanical engineering from California State University, Fresno and a B.S. in aeronautical engineering from the U.S. Air Force Academy. In 2004 she won the Airlift Tanker Association Global Reach Award for her research paper entitled "Anytime, Anywhere, Anythreat? A Fresh Look at Countering the MANPAD Challenge."

Preface

My interest in countering the man-portable air defense system is an outgrowth of my experiences in mobility aircraft acquisition and commanding a tanker squadron during Operation Iraqi Freedom, when a defensive system would have significantly reduced concerns about crew and aircraft vulnerability during combat operations. It is my hope that the extremely talented research and development personnel working on this challenge continue to have the funding and vision necessary to eliminate this concern for future crews and commanders.

I would like to sincerely thank Colonel John Geis of the Air War College Center for Strategy and Technology for his guidance and advice on directed energy technology and the writing of this paper. I also wish to thank the many people who provided information and ideas on defensive system research and programs. I would like to especially thank Lt Col Dennis Card and Mr. Bill Taylor for their expertise and time. Most importantly, I thank my family for their love and support.

Abstract

Man-portable air defense systems are threatening places of the world where mobility operations occur daily and the U.S has spent billions of dollars trying to counter their effects to little avail. The continued ability to project and apply joint U.S. military power is jeopardized without suitable defensive systems for military and civilian mobility aircraft. This paper reviews man-portable air defense system missile and countermeasure capabilities, weapon proliferation trends, and the impact on global mobility operations through 2025. Breakthroughs in laser and microwave weapon technologies are described and represent the best opportunity for transformational progress against these missile threats. Developing these technologies will ensure the U.S. has the capabilities to defeat the projected threats using a mix of ground-based and aircraft-based defensive systems to smartly defend all U.S. and coalition transport and tanker aircraft. This paper recommends changes to strategy, technology development, and doctrine to meet this force protection and projection challenge.

I. Introduction

> *Worldwide, the conclusion is clear: Shoulder-fired, IR-guided missiles currently represent the most potent practical threat to modern aircraft. The losses say this. The ginger tactics used by the United States and its allies over Yugoslavia and Iraq speak volumes. If the enemy has MANPADS missiles then it isn't safe to fly low enough to use many weapons effectively. Put another way, MANPADS has cracked the shell of air superiority.*
>
> —Michael Puttre, *Journal of Electronic Defense*

One of the most credible threats to transport and tanker aircraft is the man-portable air defense system due to threat proliferation and the inability to field an aircraft countermeasures system that can defeat these missiles. The slow-speed and low maneuverability of mobility aircraft combined with their high infrared signature, large size, and flight path predictability make survivability a critical force protection concern. From May to November 2003, there were 19 surface-to-air attacks on aircraft near Baghdad International Airport. On November 22, 2003, after its Airbus 300 aircraft was hit by a man-portable air defense missile on departure from the Baghdad airport, the Belgium-based cargo carrier DHL suspended flights to Iraq.[1] Although not an Air Mobility Command chartered flight, DHL was the only air carrier providing daily mail runs to the troops in Iraq. Further, two more surface-to-air incidents on departure from Baghdad International occurred in December 2003 and January 2004 involving engine strikes on U.S. Air Force C-17 and C-5 aircraft. Both landed safely.[2]

Man-portable air defense system threats are not a Middle-East phenomenon; mobility aircraft face increasing surface-to-air threats in all regions of the world. The Federal Bureau of Investigation (FBI) reports that there have been 29 instances in which civilian transport planes crashed after being hit by shoulder-fired missiles, causing up to 550 deaths.[3] These include attacks on transports in Columbia, Angola, Congo, Chechnya, Sri Lanka, and Kosovo. *Jane's Intelligence Review* reported seven military transports were downed and another one struck by non-state use of man-portable air defense system (MANPADS) missiles from 1996 to 2001.[4]

The nature of the threat environment mobility assets face can be broadly categorized into three levels. The first includes the use of small to medium-caliber automatic weapons, up to 14.5-millimeter heavy machine guns, and infrared (IR) guided man-portable air defense systems.[5] This level is characterized by the use of enemy-controlled agents, sympathizers, and terrorists.[6] The next threat level includes more advanced, short to medium-range radar-guided anti-aircraft artillery and surface-to-air missiles. These systems are associated with regular combat units and more traditional nation-states. The final threat level, consisting of a sophisticated enemy air defense system with integrated high performance surface-to-air missiles and air interceptors, represents a major theater war scenario with a near-peer competitor.[7] Currently only a few nation-states could present this most advanced level of threat.

Global mobility must meet the growing challenges in the first two threat levels to ensure the ability to rapidly deploy U.S. military forces and initiate operations at any base around the globe. Mobility aircraft will not operate under the threat of an integrated air defense system, but must provide support in rear areas. There, the main threats are consistent with the first threat level above. This is also true of peacekeeping or peace enforcement missions where mobility operations abound. While mobility aircraft would not normally be exposed to the second level of threat, two such scenarios are likely. First, special operations missions require the ability to operate covertly, often in higher threat regimes. Second, future ground force maneuver strategies will rely more upon maneuvering in the third dimension using intratheater lift, which will expose transport aircraft to higher threat areas for longer periods of time.

The focus of this paper is the man-portable air defense system, because it is a proven threat to mobility aircraft in these scenarios and remains a compelling threat to all combat aircraft. "Since 1973, 49 percent of aircraft losses in combat worldwide have been attributed to IR-seeking surface-to-air missiles….By some estimates, 90 percent of all the aircraft lost in combat in the last 15 years have fallen to MANPADS missiles."[8] The scope is limited to technological capabilities of the MANPADS achievable by 2025 and possible countermeasures applicable to mobility aircraft, both military and civilian. This discussion assumes MANPADS would be operating independently as described in the level one and two threat environments. Although the focus of this paper is on the infrared man-portable surface-to-air threat, these are not the only threats concerning commanders. Rocket-propelled grenades and anti-aircraft fire also top the list of threats at low altitudes. In the future, enemies with cruise missiles or unmanned aerial vehicles could also strike mobility assets operating at forward bases. While these are credible threats, this paper's focus remains on the infrared guided man-portable air defense system because of their accessibility, portability, low cost, range and accuracy. In addition, the technologies needed to adequately solve the MANPADS threat may evolve to defeat many of these other guided and unguided threats.

Man-portable air defense systems have been a looming mobility aircraft threat for over a decade, yet only 50 percent of the mobility fleet have some type of anti-missile defense system which still require continuous upgrades to match threat evolution.[9] There is a need to aggressively investigate future technologies and possible doctrinal changes to counter the man-portable air defense system threats that jeopardize global mobility capabilities. Specifically, the U.S. air mobility forces must have the technological capabilities and strategies to defeat the projected man-portable air defense system threats of 2025.

This paper begins with a primer on the global mobility system and future concepts of operations focusing on the mobility missions and threats. Contradictions on who is responsible for defense of mobility aircraft while engaged in theater operations will be highlighted. Missiles and countermeasures technologies will then be presented, framing the evolution of current countermeasures technologies and presenting emerging paths to mitigate the MANPADS threat. Finally, two strategies of defensive systems will be analyzed and recommendations proposed.

II. The Threat to the Global Mobility System

Our current strategy and technology efforts have not been able to keep up with surface-to-air threats against mobility aircraft, as evidenced by the December 2003 C-17 MANPADS strike on departure from Baghdad International Airport, despite that aircraft being equipped with a missile warning system and flares. General John W. Handy, commander of U.S. Transportation Command, is not understating the issue by commenting that the danger posed by shoulder-fired missiles "is perhaps the greatest threat that we face anywhere in the world."[10] The United States is now experiencing the effects of multiple transport aircraft and helicopter attacks by man-portable surface-to-air missiles in Iraq. To clearly understand the implication of these threats, it is important to understand the global mobility system and the evolving global mobility concepts of operations. Complicating this is a gap in joint doctrine concerning responsibility for protecting mobility assets from surface-to-air threats. This gap will be discussed and a way forward proposed. The global nature of this man-portable air defense system threat will be discussed along with the strategic and operational implications.

Global Mobility System

The national air mobility system is organized into intertheater, intratheater, and organic theater forces drawing on specialized contributions of its civil and military components.[11] Intertheater forces are those strategic forces, both military and civilian, that provide long-range transoceanic capabilities usually into and out of major air mobility hubs; including the creation of an air bridge using air-refueling assets. Intratheater forces fulfill the theater commander's operational requirements and are considered the spokes emanating from the major hubs to distribute logistics within theater or extend the range of theater-assigned forces through refueling support. Across these two categories lies direct delivery or insertion of logistics across long distances directly to the point of need, bypassing major hubs through airland or airdrop missions.

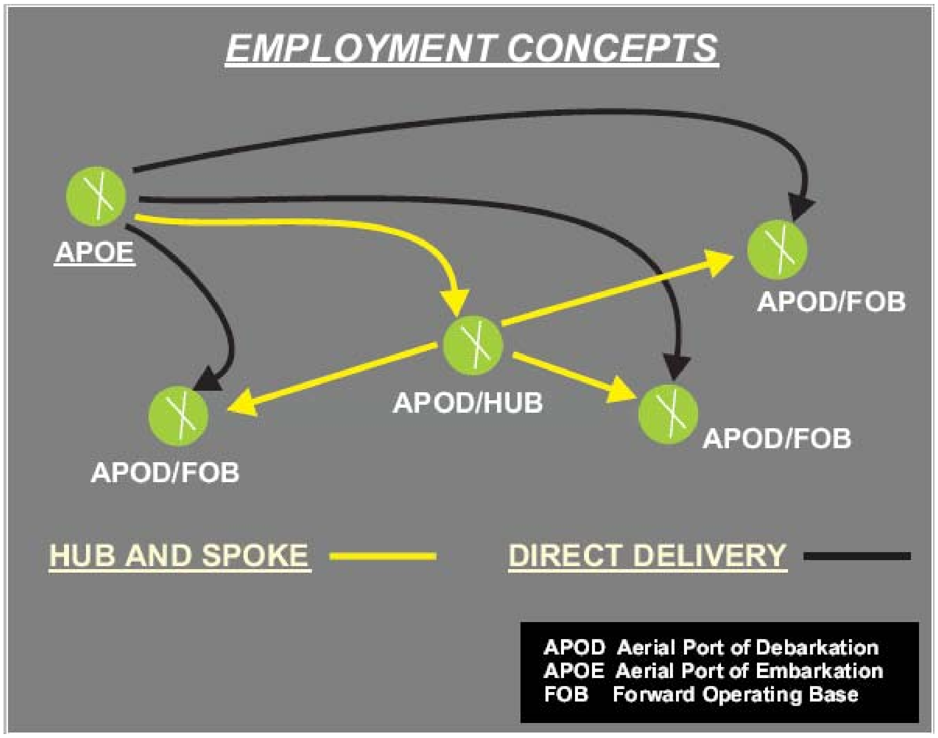

Figure 1. Direct Delivery and Hub and Spoke Employment Concepts[12]

Finally, organic theater assets are those assets that provide specialized internal support to the theater commander, including very important person transport. Together, these forces along with their respective support elements provide the Air Force core competency of Rapid Global Mobility: the ability to rapidly position forces anywhere in the world to ensure unprecedented responsiveness.[13] These resources are applied within the global mobility construct to provide the effect of rapid projection and application of joint U.S. military power—the cornerstone of the evolving global mobility CONOPS.

Global Mobility Concept of Operations

The Air Force is using concepts of operations (CONOPS) to describe the capabilities needed to fulfill global power projection requirements. The goal of these concepts is to "transform the Air Force planning, programming, requirements and acquisition process from a narrow program-centric perspective to a broad capabilities-based systems process."[14] The CONOPS describe how the Air Force could contribute to meeting 21st century military challenges within the context of joint operations and then outline the required capabilities necessary to execute these operations. This is not an operational level but a strategic level analysis of the capabilities needed to solve military challenges in the future.

In particular, the global mobility CONOPS "describes the capabilities required to rapidly plan and mount a global mobility operation - independently, or as part of a joint or coalition effort, and defines the capabilities necessary to open a base and establish the right operational environment for conducting sustained air combat operations."[15] Keys to this challenge are the required capabilities of expeditionary base assessments and force protection as a part of "operationalizing" a base.[16] Overall, these concepts convey how global mobility capabilities should normally be used as an instrument of national power and are therefore the basis of current and future mobility doctrine.

As part of these capabilities, and driven by evolving threats and reduced external infrastructure, the Air Force is turning away from operating large forward logistical bases. To meet the demands of rapid power projection and sustainment, Air Mobility Command (AMC) is using just-in-time delivery to the user, thus minimizing the forward footprint. This concept is also tied to supporting a more continental U.S. (CONUS)-based joint force as it transforms into light, lean, and more mobile force capable of operating at higher tempos. As a consequence, AMC forces are a more critical element of overseas force projection as they continue to perform the range of military operations in both benign and hostile environments. Indeed, the *Airlift 2025* study recommends that the future airlift system should be independent of the theater-basing structure and during a worst-case scenario assumes no intratheater lift capability or major hubs, forcing direct delivery from CONUS to the warfighter.[17] An example is not being able to use the major theater bases in Southwest Asia, such as Dhahran or Riyadh in Saudi Arabia, but directly delivering supplies into Kuwait during Operation Desert Storm. Although this is not the most probable scenario, future rear areas will not necessarily be secure for ports of debarkation and staging areas implying a similar threat and requirement to defend mobility bases in theater.

Who is Responsible to Defend Against These Threats?

Airfield Threat Level Defined

To determine the risk of mobility operations at a specific location, Air Mobility Command performs a detailed threat assessment using Defense Intelligence Agency, regional combatant commander, Transportation Command, and AMC intelligence sources. Specifically for the man-portable air defense system threat, AMC comprehensively analyzes the country specific factors including terrorist groups present, credible capabilities, and internal and external region stability. The next level of analysis is the airfield specific details of location, local security, and man-portable air defense system footprint or threatened area security. Finally, mission frequency and predictability are factored in to determine the overall AMC man-portable air defense system threat assessment as low, moderate, significant or high. This assessment determines whether aircraft with operable defensive systems are required for operations into that airfield and identifies the level of risk to the Joint Force Commander (JFC).

Most AMC operations fall into the joint rear area level I threat category: disorganized forces leveraging enemy agents, sympathizers and terrorists to achieve harassing or anti-access effects. Air mobility operations can expect to encounter this type of threat during stabilized peacekeeping, peace enforcement or humanitarian missions.

Defining Defense Responsibilities: The Gap in Joint Doctrine

Airfield location combined with varied threat levels and types of operations can confuse who is responsible to defend against the man-portable air defense system threat. At issue is the gap between the responsibilities delegated to the local base commander and the JFC during combat operations, or the geographic commander during peacetime. The geographic combatant commander is ultimately responsible for all rear area operations, including protecting U.S. possessions and bases against attack or hostile incursions.[18] The geographic commander can assign responsibility for rear area defense to the JFC. To carry out these responsibilities during combat operations, the JFC can designate an Area Air Defense Commander, normally the Joint Forces Air Component Commander (JFACC), responsible for the security of airspace above the joint rear area. This person develops the area air defense plan, including detailed engagement procedures that provide guidance on positioning joint defenses and employment rules. However, despite being a surface-to-air missile, the MANPADS threat does not fall under the purview of the Area Air Defense Commander, who is focused on the air superiority and theater ballistic missile aspects of the campaign. The following analysis of the air superiority concept will expose the confusion.

Merely having air superiority does not protect mobility assets from the man-portable surface-to-air system threat. As previously discussed, air mobility forces are normally employed only in the lowest level of threat characterized by disorganized hostile forces potentially brandishing infrared-guided man-portable air defense systems. Global mobility assets are not normally deployed into higher threat level areas where U.S. or coalition forces do not have at least local air superiority. Air superiority is the first priority when the enemy possesses air and missile assets capable of threatening friendly forces. However, in most military-operations-other-than-war cases, there is no air-to-air threat or integrated ground-to-air threat and thus air superiority is assumed. The joint definition of air superiority is instructive:

> Air superiority is that degree of dominance in the air battle of one force over another that permits the conduct of operations by the former and its related land, sea, and air forces at a given time and place without *prohibitive interference* by the opposing force.[19] (*Emphasis added*)

Further, “some enemy aircraft may continue to fly and some enemy missiles may be launched in spite of air superiority.”[20] Air superiority is not a freedom from attack and freedom to maneuver concept. In fact, air superiority is only relevant when discussing operations in a hot combat zone with a potential air-to-air threat or integrated air defense system—not the area in which most mobility assets are threatened by MANPADS.

If the Area Air Defense Commander is not responsible for the MANPADS threat, then security responsibility is assigned to either a component commander in charge of area security or the base commander. The issue boils down to aircraft protection versus air base protection; unless mobility aircraft are directly engaged in combat air operations, their defense falls under the concept of force protection.[21]

Force Protection Assets Provide Ground-to-Air Fire Security

During an operation, the local base or wing commander is responsible for force protection of all assets or units assigned to or transiting the base. If there is no assigned commander, the Expeditionary Mobility Task Force commander or his designate becomes responsible for local force protection of air mobility assets. However, the Expeditionary Mobility Task Force currently has forces capable of security close to the airfield, inside the base perimeter, but not along the flight paths where these missiles would be launched. Under the global mobility CONOPS,

> The airfield security force is responsible for achieving conditions which enable airfield operations within acceptable risk determined by the Joint Force Commander. This includes hostile ground-to-ground, air to ground and ground to air fire effects on the airfield and ingress and egress routes. [22]

The task force commander can request additional security forces from the Air Expeditionary Force Center. However, response depends on the risk assessment and availability of forces. The security resource reality, demonstrated by multiple MANPADS attacks on aircraft near Baghdad International Airport, is that these bases will never have enough security capability to respond to all scenarios; therefore the issue becomes a balance of risk and resource cost.

The local base or expeditionary mobility task force commander does not have direct tasking authority to assign defense duties to the Army unit normally in charge of ground defense. However, this commander may request additional support from the component commander in charge of area security. These ground forces may be available and allocated during major combat operations such as Operation Iraqi Freedom. During peacekeeping or humanitarian operations, however, the Joint Force Commander has to concur that additional security due to the MANPADS threat is needed and is at least as important as his other security needs to allocate necessary resources. In some operations, such as in Afghanistan, U.S. presence is capped at a specified number of personnel, making this choice more difficult.[23]

Air Mobility Command is making progress toward eliminating this force protection seam. Under the evolving “open and establish the airbase” global mobility concept of operation, a new Crisis Response Group (CRG) will be designated and standardized specifically to rapidly respond to contingencies requiring a new expeditionary airbase to be established. The CRG capabilities will include “secure and protect airfields, rapidly open airbases, and perform initial airfield and airbase operations to ensure a smooth transition to subsequent operations.”[24] This unit must be tailored to include sufficient force protection assets to cover aircraft ingress and egress routes, or arrival and departure paths, as determined by Air Mobility Command’s MANPADS threat assessment.

In summary, there is currently no joint doctrine addressing the force protection seams concerning aircraft ingress and egress routing. It is necessary for the JFC to delineate and assign appropriate responsibilities dependent upon the operational conditions. The new global mobility CONOPS takes a stand by designating that the expeditionary mobility task force security team is responsible for aircraft ingress and egress route security and must now obtain trained and equipped force packages to carry out this responsibility. The CRG provides an opportunity for AMC to advocate and resource its own force protection resources to protect air mobility assets.

Responsibilities Determine Countermeasure Approach

The confusion surrounding where airfield operations security responsibility stops and area security begins further muddies who should be responsible to develop and purchase defensive capabilities against the man-portable air defense system threat. Air Mobility Command leads the transport aircraft defense program since they own the majority of those assets. Their approach has been to modify the aircraft with onboard missile detection and countermeasures systems. On-board defensive systems have received a high priority within the command in the past few years, and several programs have funding and aggressive installation schedules. However, decades of research have not produced a foolproof defensive system and it may now be appropriate to develop alternative strategies. Instead of relying solely on aircraft-based countermeasures systems, it is time to overcome the technical limits of onboard systems and explore a defensive system that increases protection of all aircraft within the airfield area.

At issue is the ability to freely operate in the level one and two threat environments found in numerous places around the world where global mobility assets are needed. Without this ability, the flexibility and versatility of mobility operations decreases. Current and future global mobility CONOPS are in jeopardy of being insufficient to meet joint force objectives under the man-portable air defense system threat.

Who Has These Weapons?

MANPADS are widespread and problematic for governments around the world. The magnitude of the threat ensures that daily mobility operations are affected. Without measures to contain this threat, the concern will intensify in the future.

The MANPADS Arsenal

Illegal weapons sales and the unprotected arsenals of failing states combine to make MANPADS relatively cheap and easy to find. Cost estimates vary. For example, *Jane's Intelligence Review* reports the cost of a U.S.-made Stinger missile on the black market is anywhere between $80,000 to $250,000.[25] *National Defense* reports the black markets costs are $5,000 to $30,000 for first generation missiles such as the Russian A-7.[26] With over 150,000 MANPADS in worldwide circulation and another 350,000 in defense inventories, there are plenty for potential adversaries to acquire.[27]

Jane's Intelligence Review reports that 27 terrorist organizations have or are believed to have MANPADS as part of their arsenal.[28] Sub-Saharan Africa, with its porous borders and plethora of terrorist groups, is a hotbed for proliferation. Angola has been particularly active in the use and trade of these weapons. The terror group UNITA fired Stinger missiles at three World Food Program aircraft in June 2001, hitting one. Although the aircraft landed safely, officials were alarmed that the aircraft was struck at 15,000 feet, which is 3,500 feet beyond the weapon's published maximum effective altitude.[29] Africa does not hold a monopoly; Russian mafias have been able to obtain virtually any type of weapon and have a proven smuggling track record.[30]

Among the terror groups that have MANPADS are Al-Qaeda members who have been training with them for decades. A training video was recovered in 2001 detailing how to assemble and use the Russian Strela 2, or SA-7, missile system.[31] It was this missile that was used against the Arkia Airlines Boeing 757-300 departing from Mombassa, Kenya, on 28 November 2002. Al-Qaeda are known to be thorough in their planning, as demonstrated both by launching two missiles at the airliner to increase probability of kill and having a backup team in place five kilometers from another runway in case the departure path changed.[32] Fortunately, the missiles didn't hit the aircraft either because the terrorists engaged the aircraft inside the Strela's minimum engagement range or the aircraft was equipped with infrared countermeasures.[33] Another interesting note is that the missiles were traced back to a lot that was approximately 28 years old, dispelling the notion that these systems could not be used due to expired batteries or degraded propellants.[34]

Older missiles such as the SA-7 are prevalent in the terror inventory and are tail chase systems that lock-on from a rear aspect. However, newer missiles such as the SA-18 Igla are capable of all-aspect engagement. In August 2003 the Federal Bureau of Investigation arrested an alleged British arms dealer in a plot to smuggle an SA-18 and supply 50 more to the U.S. to be used against commercial airliners.[35] These missiles are reported to be widespread on the market, but at this time only one group is reported to have them. The Israeli daily *Maa'riv* reported that Hezbollah had acquired the SA-18, impacting Israeli strategy to protect military and civilian aircraft.[36]

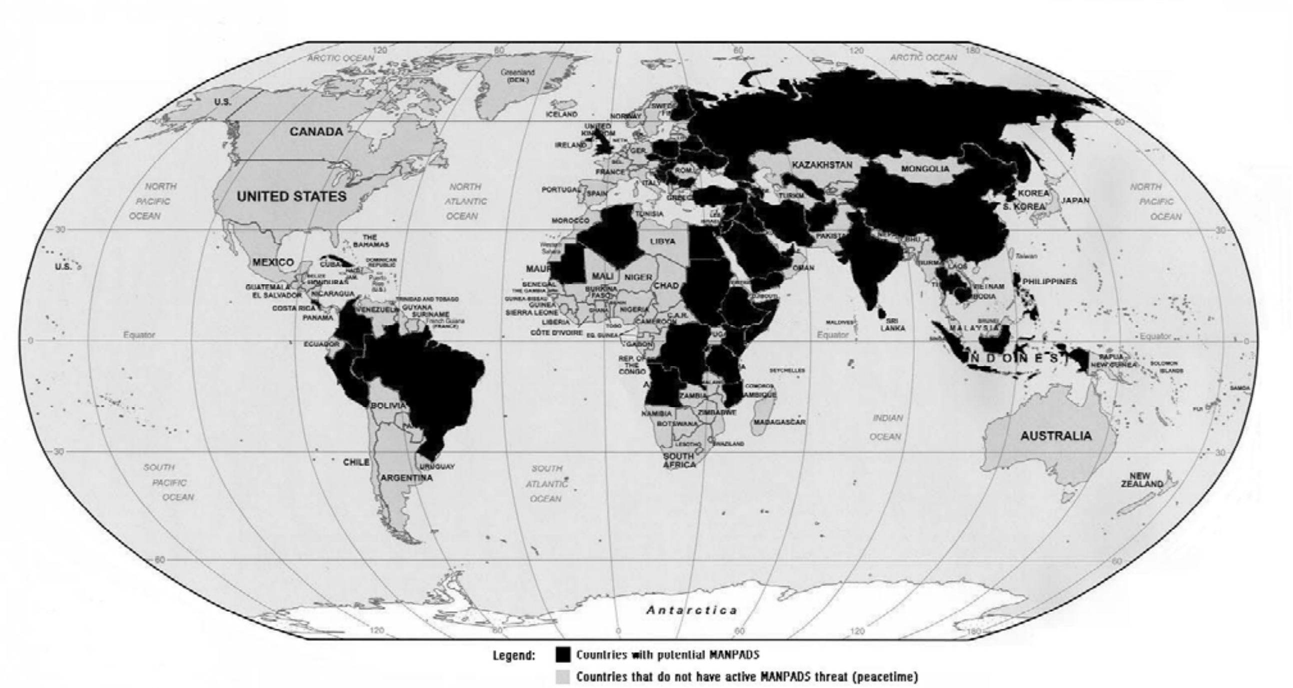

Figure 2. Nations With MANPADS Potentially in the Hands of Terrorists[37]

Figure 2 pictorially displays in black the countries that have had terrorists inside their borders armed with man-portable air defense systems as defined by actual incidents, weapon confiscation, trafficking, or proliferation. Clearly these systems are in the hands of transnational actors and failing states in parts of the world that the U.S. and its allies are engaged in every day and will remain an important part of the national security strategy. These proliferation trends, combined with the inherent vulnerability of heavy aircraft during the takeoff and landing phases, are compelling reasons to aggressively address the MANPADS threat. The implications to theater strategy and operations if Global Mobility operations are limited or prohibited by MANPADS in the future are revealing.

Strategic and Operational Implications

Strategic Implications

Political support for military-operations-other-than-war such as peacekeeping or peace enforcement has traditionally fluctuated with mission success. The American public and the decision-making elite in particular have come to expect minimal, arguably zero, casualties in these types of scenarios.[38] They will certainly not tolerate a man-portable air defense system shoot-down of any aircraft, much less a contracted civilian carrier, during operations that are not of clear vital importance to the U.S. Such an incident could become a catalyst that turns the tide of public opinion and requires politicians to terminate a mission. Indeed, the high probability of a successful shoot-down may convince American leadership to limit military and civilian personnel exposure to this threat, and rely on the other instruments of power to shape the scenario, affecting our national strategy.

Similarly, our coalition and non-governmental partners depend upon secure bases to ensure their own domestic support to assist in operations. A high or significant man-portable air defense system threat is a factor that may keep partners from participating in operations or force them to wait until better conditions appear.[39] For example, humanitarian operations were a strategic objective in Operation Iraqi Freedom (OIF) that commenced before the major conflict ended and were key to stabilizing the Iraqi population. The effort began with military forces but coalition and non-governmental humanitarian operations were quickly incorporated. Often non-government organizations charter civilian aircraft to transport supplies, however, in this case, the threat required military air transports equipped with defensive systems to move the loads. Otherwise, supplies must be ground shipped or opening of relief centers delayed until an adequate distribution chain is secured. The use of coalition and non-governmental partners in operations brings a legitimizing effect that is arguably required in today's political environment. Loss or delay of this aid can affect U.S. foreign policy efforts and ripple into American and allied domestic politics.

The final strategic implication of the inability to counter the man-portable air defense threat is the forward basing decision. As aptly pointed out in the global mobility CONOPS document, "the limited ability to expeditiously deliver combat forces to a conflict is a key equation in the development of courses of action. Although slow delivery of forces may not be a showstopper, the quicker we can deliver force, the greater our chances for deterrence or success."[40] Choosing forward base locations impacts operational reach and directly affects how much joint combat power can be generated over time. Basing further away from the objective area requires longer ground supply lines that are vulnerable to harassing attacks, as experienced during both combat operations and the stabilizing phases of OIF. These strategic implications can limit or eliminate military options and have a far-reaching effect on U.S. actions. For the theater commander, the threat of MANPADS can also operationally limit successful prosecution of the conflict.

Operational Implications

Single or multiple mobility aircraft shoot-downs will cause operational tempo problems due to restricted logistics flow. The loss of a high-value mobility asset means a loss of sortie generation capability and combat personnel. Such a loss would cause a change in tactics that may require longer routes, limit airfield operations such as night only or random times, and limit field operations to only those aircraft that have appropriate defensive capability. As of this writing, these are the types of precautions being taken at Baghdad International with some effect. Further, the lack of missile defensive capability eliminates the ability to use 50 percent of Air Mobility Command's organic fleet and the entire civil reserve air fleet.[41]

The civil reserve air fleet can only fly into non-threatening areas through their contract with AMC and agreements with the Federal Aviation Administration (FAA).[42] Proliferation of the man-portable air defense systems combined with increased worldwide mobility mission tempo will cripple operations due to the loss of contract carriers because of the MANPADS threat. These carriers are a critical part of the air transportation structure. Historically, these aircraft move 93 percent of troops and 41 percent of long-range air cargo for major contingencies.[43] During Desert Storm commercial carriers were able to deliver troops to the forward staging area in theater. Loss of this capability will increase operational risk by slowing the flow of troops and supplies or will require additional military transports to pick up the load, increasing military fleet cost. For example, during Operation Desert Fox, forces transported via commercial carriers had to be trans-loaded at European staging bases into AMC organic lift assets equipped with defensive systems due to the downrange threat.[44] Consequently, combatant commanders must reshuffle airlift priorities of people and equipment since those organic assets must be pulled away from other needs to handle this additional load. Major operational plans require evaluation and restructuring to use contract carriers only into safe transshipment areas overseas.

This combination of operational impacts will increase the time it takes to assemble and sustain forces, potentially requiring the use of other forms of transportation or forward operating locations to meet the JFC's requirements. Unless the U.S. can defeat this threat, MANPADS will drive inefficiencies in the air logistics system. During major force deployments, MANPADS will deny the U.S. the ability to achieve the focused logistics goal of delivering the right items at the right time with full dimensional protection at acceptable risk levels.

Summary and Recommendations

The evolving global mobility CONOPS requires AMC to have the capability to achieve rapid projection and application of joint military power worldwide. Inherent in this capability is the need to open and operate bases as required by the JFC. The CONOPS declares that the Expeditionary Mobility Task Force commander will be responsible for base security, including aircraft ingress and egress routes outside the base perimeter. AMC has taken the lead by standardizing the Crisis Response Group to provide this level of security; however, these force protection resources must be procured, trained, equipped, and made available to AMC.

The Expeditionary Mobility Task Force or base commander must look comprehensively at the base and local area security challenge for aircraft operations. Instead of relying solely on aircraft-based countermeasures systems, the Air Force should fully explore a system that protects the airfield area where the MANPADS risk is highest. This system could essentially form a defensive shield around a main airbase and its flight corridors to protect any aircraft from MANPADS.

Global surface-to-air missile proliferation trends will clearly keep the infrared guided missile threat at the forefront of leadership concerns. Theater commanders down to mobility planners must carefully consider the impact to theater strategy, expeditionary basing, operational maneuver, and tactics.

III. MANPADS Missile and Countermeasures Technologies

Countering the man-portable air defense system (MANPADS) threat is extremely complex; the U.S. is investing billions of dollars in evolutionary on-board countermeasure systems that admittedly cannot defeat all MANPADS. To provide insight into how to successfully defeat MANPADS, this section begins with an introduction to man-portable air defense system mechanics and components. Current and projected missile capabilities are then presented to highlight the growing dangers of this threat. The inadequacies of current countermeasures systems will be reviewed, emphasizing the need for technology leaps to finally get ahead of the missile/countermeasure cycle. Future directed energy programs are outlined as the transformational path forward to finally defeating the MANPADS threat.

MANPADS at Work: Mechanics of the Kill

Why have these systems become so popular? Their main attractions are compactness, weight, and ease of operation. Most are about five feet long, weigh between 10 and 35 pounds, and rest on the shoulder for firing.[45] The missiles can be effective up to approximately 15,000 feet in altitude and three miles in range as designed for fast moving targets.[46] These systems can be assembled and shouldered quickly; some require less than 30 seconds. In addition, these systems are relatively easy to operate. The operator activates the battery-operated MANPADS just prior to engagement to preserve the short battery life. The operator aims the missile at the aircraft and the infrared (IR) seeker detects the aircraft IR signature against the cold sky, usually homing in on the heat emitted by metal parts of the engine and the hot carbon dioxide in the exhaust.[47] As a rough comparison, if the IR signature of an Apache helicopter were a value of one, a C-130 would be a ten and a four-engine jet transport such as the C-17 would be a 100.[48] Some MANPADS automatically calculate where to aim, based on aircraft speed; some have television or infrared scopes to aid in earlier aircraft acquisition; and all can positively lock on to the target prior to launch to increase the probability of hitting the aircraft. After launch, the missile travels quickly and will either directly impact the target, detonate in proximity to the aircraft, or self-destruct after the fly-out period is complete.

As the Mombassa incident indicated, one shot is not one kill so what is the real level of risk to mobility aircraft? A definitive analysis on man-portable air defense strikes for all transport aircraft has not been done, but some basic information is available. MANPADS deliver a relatively small, three to seven-pound blast-fragmentation warhead that is approximately one-third the size of the short-range AIM-9M air-to-air missile warhead.[49] The FBI reports that at least 42 civilian transport-type aircraft have been hit and 29 have crashed, for a loss rate of 69 percent.[50] From an overall threat system standpoint, each missile system has a probability of kill based on its ability to detect, track, engage, and kill a specific target. Current estimated manufacturer system probabilities of kill range from approximately 20 percent for the first generation MANPADS, like the Strela, to 75 percent for the latest Russian Igla-S system.[51]

Missile Components: Present and Future

Countering this threat requires an understanding of the system components and future capabilities potential. Figure three depicts the U.S. Stinger MANPADS' major components—a tube launcher, grip stock launching mechanism, coolant, battery, and missile. The launcher may have an electro-optical or infrared (IR) sight to assist in optically aiming the weapon prior to launch and an identify friend-or-foe (IFF) interrogation antenna.

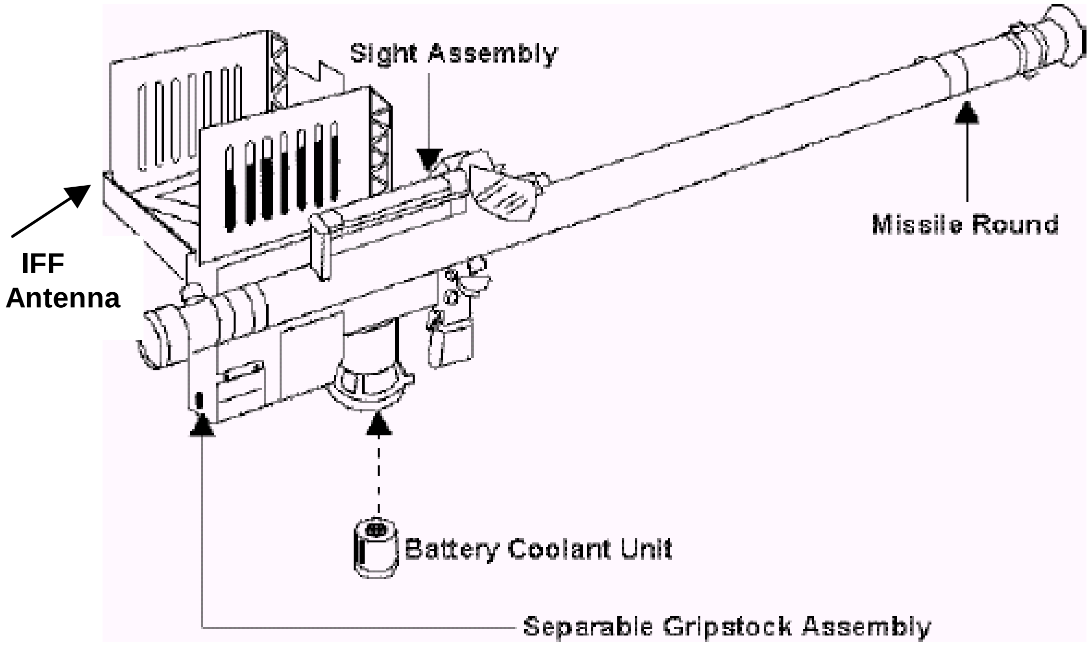

Figure 3. Stinger Launcher Assembly[52]

Figure 4 shows a typical missile with an IR dome, seeker, guidance and control system, warhead, and rocket motor with rollerons for maneuvering and tail fins for stability. Seeker, warhead, and rocket motor technologies are discussed in the remainder of this section.

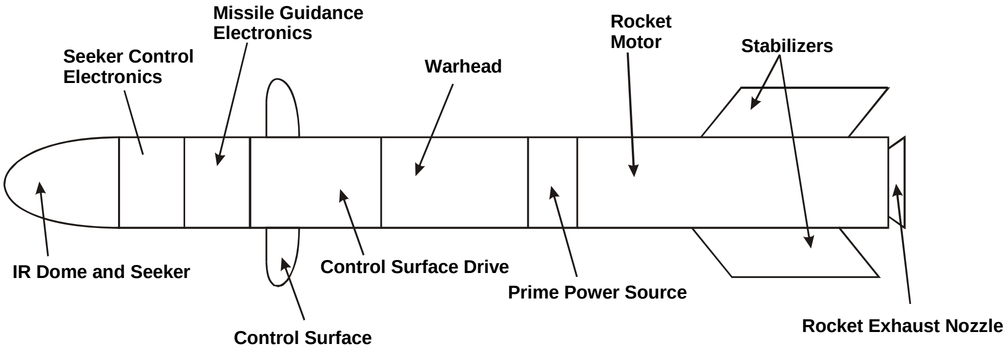

Figure 4. Typical MANPADS Missile[53]

Seeker Technologies

The seeker is the brain of the missile. Designing an infrared seeker or sensor is a trade-off between the sensitivity to detect real targets and minimizing noise, clutter, and countermeasure success. The seeker has three main components: the detector, reticle or imager, and mirror optics. The older, more prevalent missile types have uncooled lead-sulfide IR detectors that home in on targets with signatures in the near-IR band at frequencies of 2 to 2.5 microns. This band corresponds to a peak in hot metal radiation transmitted through the atmosphere. Because solar reflections are strong in this band, seekers must overcome considerable solar interference, meaning they cannot track toward the sun, and a low signal-to-noise ratio or faint tracking signal to successfully find and engage the target. These detectors are most effective on a rear-aspect shot where there is a clear path to the hottest surface: the engine turbine and exhaust area. Modern detectors use lead-sulfide (PbS) or mercury-cadmium-telluride (HgCdTe) materials that operate in the mid-IR band representing a more “signal-rich” environment, as depicted in Figure 5. Mid-IR detectors can observe warm objects, approximately 50 to 200 degrees Celsius; long-IR bands are best for –20 to 100 degrees.[54] A combination of these sensors allows for all-aspect attack, tracking the plume, heated leading edges of the wings, or the contrast of the aircraft itself against the cool sky. However, these modern detectors require cooling to 77 degrees Kelvin, adding weight and complexity to the system.[55] The battery/coolant units only last a short time; for example, the Stinger system lasts 45 seconds. The operator must time the initiation and launch sequence correctly to be successful and have an additional supply of these units available for multiple shot opportunities.

Once the seeker has found the aircraft, it must continuously update the missile flight path to hit the target. Older generation missiles used seekers that tracked hot metal point objects by converting the IR signature into a signal and providing steering commands to center the object in the seeker field of view. The next major leap was the development of pseudo-imagers and

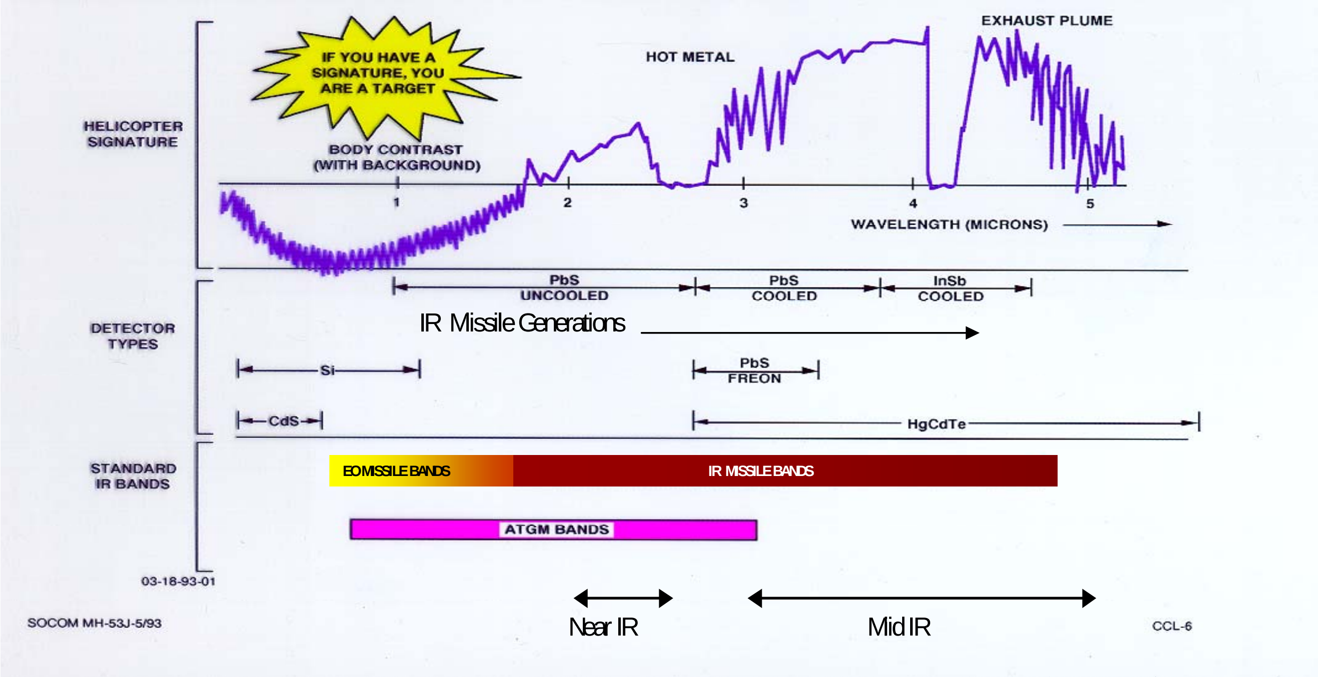

Figure 5. Electro Optical and Infrared Missile Bands[56]

increasing countermeasure resistance by scanning in a special pattern that narrowly focuses the sensor on the target, decreasing any extraneous signals such as sunspots. For example, the Russian Igla SA-16 (9M313 missile) pseudo-imaging two-color seeker operates on both ultraviolet and infrared wavelengths and has special processing logic that compares these emissions to determine if the target is real or a decoy such as a flare. The manufacturer claims these improvements doubled the probability of a kill from 30 to 60 percent.[57]

Another method to track the target is to use laser beam riding for guidance. Saab Bofors Dynamics RBS 70 and the Shorts Starstreak systems use operator-tracking and a rear mounted sensor on the missile to follow the laser beam to the target, making it unjammable from the forward aspect. These systems are currently man-packable, requiring two personnel to move and operate. However, projected advances in technology will make these systems lighter and easier to use. A more dangerous future sensor development would make use of the aircraft's own laser beam jammer countermeasure as a guidance laser to "reverse" track or guide the missile towards the jammer and thus the aircraft.[58]

In the future, hyperspectral imaging, or combining electromagnetic radiation signals from across the electro-optic and infrared (EO/IR) bands, will enhance the ability of a seeker mechanism to characterize or track an aircraft. Hyperspectral imaging and signal processing advances can make use of signals across the electromagnetic spectrum and fuse the data to provide greater detail on objects of interest. Analysis of a range of signals emanating from a single target will enable stronger target signature and tracking capability, and provide increased resistance to countermeasures. Such seekers will not lock on to the brightest point of heat but instead will track the actual aircraft skin signature, making even the most sophisticated flares ineffective. Current research efforts include development of fully staring mid- and long-wave infrared arrays that have improved thermal sensitivity, increased detection range and accuracy, can be made up to 50 percent smaller, and cost less than current imagers.[59] In addition, projected advancements in miniaturization and materials engineering will increase system efficiency and generate less heat, potentially eliminating the bulky cooling system.[60] The bottom line is if an aircraft has a signature, it will be vulnerable. Finally, operator acquisition of the target is getting easier with the addition of strap-on EO/IR sensors. Thermal imaging cameras or night vision devices already enhance earlier target acquisition and the ability to lock-on before launch, increasing system lethality and ease of use.

Warhead Technologies

Warhead technology has evolved from high explosive, to high explosive with fragmentation, to multiple individual penetrators. Examples include the newest Russian MANPADS, the Igla-S, with state-of-the-art, fully digital solid-state electronics that makes the components lighter and allows for an increase in warhead weight. The Igla-S 9M342 missile not only has a high explosives weight but possibly has embedded metal rods to boost missile lethality. The missile also incorporates a laser proximity fuse that can detonate the warhead five meters below the target directing the rods and explosive energy towards the target.[61] The RBS 70 has a shaped charge and over 3000 tungsten pellets of three millimeters diameter and an unjammable proximity fuse.[62] Finally, the shoulder-mounted version of the British Starstreak, fielded in 2000, carries three kinetic energy penetrators. These darts separate from the missile body after the second stage motor is burnt out and use individual guidance and control circuitry with laser beam riding guidance to attack the target. The darts have a delay fuse, allowing target penetration before detonation.[63] Multiple warheads and fragmentation increase the probability of hitting the target. Although recent strikes by the older SA-7 MANPADS against transport aircraft in Iraq have not shot down the aircraft, warhead technology will provide more kill for the kilogram in both the high explosive and multiple warhead capabilities, increasing shoot down probability.

Rocket Motor/Propellant Technologies

Missile range and speed are critical factors in a successful engagement; missile designers are taking advantage of new materials, fuels, and drag-reducing devices to achieve maximum capabilities. Increasing missile range and speed normally translates into heavier missiles and sturdier platforms, thus decreasing system mobility. However, the newer, lighter-weight components can offset the increased fuel weight needed for additional range. In addition, solid rocket fuels are becoming lighter and can be used more effectively. For example, the Igla-1 and S have has a fuel remnants detonation device that ignites remaining rocket fuel with warhead detonation, providing perhaps double the explosives weight to the target.[64]

Most missiles use some type of a boost charge to clear the tube, then the sustainer or second-stage motor fires. The missile boost and sustainment motor EO/IR signatures are a beacon to trigger missile warning systems. Manufacturers are reducing or shielding these signatures to decrease probability of missile detection using new materials or different fuels.

Increases in missile speed and the concealment of missile launch decrease aircraft or countermeasure reaction time and allow engagement of faster aircraft. Newer missiles incorporate a nose-mounted shockwave generator to decrease missile wave-drag, increasing speed and range. The new Igla-S has incorporated many of these technologies to increase range to 6,000 meters, twice the range of first generation missiles, and at speeds up to Mach 1.8.[65] The British Starstreak High Velocity Missile is capable of speeds greater than Mach 4.[66]

Other Missile Improvements

Additional missile system enhancements include integration into short-range defense networks, target interrogation, and ease of upgrades. For example, the Igla-S can be effectively integrated to fit into a short-range defense network through a field notebook computer and a connection to the land forces air-defense system. New MANPADS have identify friend-or-foe (IFF) systems to allow beyond visual identification range engagements and avoid fratricide. Manufacturers are making systems more modular, upgradeable, and interchangeable, extracting additional efficiencies of scale for these systems.

The current and emerging missile technologies described in this section further extend the trend of missile systems staying ahead of the countermeasures developed to defeat them. Enhanced targeting capabilities, coupled with these new missile technologies, continue to place MANPADS in the high threat category for U.S. transport aircraft, reiterating the reason even fighter aircraft stay out of the low altitude environment.

Current Countermeasure Technology Program and Investments

Why haven't developers designed a countermeasures system that is reasonably effective? There is an endless cycle of missile, countermeasure, and counter-countermeasure enhancements but seemingly no leap in technology. Current MANPADS countermeasures focus on defeating an already launched missile; a task measured in seconds. Future countermeasure technology efforts are focused on proactive measures to detect and avoid the threat or disable the missile prior to launch. The elusive leap may come by 2025, when tactical lasers and portable radio frequency weapons capable of generating destructive power may be fielded. Countermeasures technologies and their applications are the focus of the remainder of this section. Two critical countermeasure subsystems are the missile warning system and the countermeasures system. To defeat a missile threat, the missile warning system (MWS) must detect the launch and pass the information to a countermeasures dispenser and/or a pointer-tracker system that directs an active countermeasures system to blind, spoof, or degrade the accuracy of the missile.[67]

Missile Warning Systems

Adequate missile warning systems that can detect a missile launch at long ranges against dynamic ground clutter, solar glint, and various atmospheric conditions have yet to be fielded.[68] Secretary of Defense William Perry experienced this inadequacy first-hand during his C-17 flight into the Balkans when the pilots quickly shut off the missile warning system after a cockpit alert. He queried the crew; they said the system has too many false alarms so they just turn it off.[69]

Reliable early passive detection of a missile IR signature requires high sensor sensitivity to the missile rocket motor exhaust and continuous 360-degree scanning. The missile IR signature is greatest when it first launches out of the tube with the booster motor and second stage ignition, then decreases as the rocket motor burns out. The EO/IR missile warning system has a series of passive sensors mounted around the aircraft scanning the ground and low altitudes trying to detect an actual launch amidst the ground clutter moving rapidly beneath it. If the threat detection threshold is lowered to obtain better sensitivity to identify launches, the false-alarm rate can increase exponentially.[70] Integrating an active sensor system that uses radar to confirm an approaching missile would reduce false alarm rates. Unfortunately, while this system may work for non-combat situations, this may not be suitable for continuous use aboard aircraft in combat situations due to radio-wave emissions revealing the aircraft location.

The ability to passively detect a launch accurately may be enhanced by multi-spectral imaging, or defining the threat by sampling several parts of the electromagnetic spectrum. This can be done by storing the multi-spectral IR launch signatures of all known threat missiles into memory for comparison to confirm launch. This clutter-rejection filter decreases false alarms. However, the more complex the filter signature comparison routine is, the more time it takes to process in a system where tenths of seconds count.

Processing capability must increase to take full advantage of these filters to decrease missile warning false alarm rate. The Defense Intelligence Agency led a collective study on the information technology revolution and predicted a factor of one million further improvement in computing power by 2025, which equates to roughly one thousand times "better than human" processing capability.[71] The processing speed available now and by 2025 will make it possible to run multiple complex filters quickly to further reduce false alarms.[72]

The latest passive sensor missile warning systems combine sensors in the ultraviolet and infrared bands to suppress clutter, increase detection range, and decrease sensitivity to atmospheric conditions, increasing warning system reliability. Elta Electronics, an Israeli firm, is further stressing current processing and fusion capability to reduce false-alarm rate by experimenting with these two bands as sensors that trigger a pulse-doppler radar search if a launch is suspected; the theory being that the enemy has already detected the aircraft and there is no need to conceal position at that point.[73] However, if false alarms cannot be eliminated, the radar becomes a beacon for enemy detection.

Detecting a laser-beam riding missile requires a different type of warning system, adding to warning system cost and complexity. Current technology for this type of threat is a special laser missile warning system. This system warns of laser-guided missiles and laser range finders or designators. However, once the missile is detected, there is currently no countermeasure available. To effectively cover the range of man-portable air defense threats, these warning systems must be effectively integrated to alert the aircrew of the type of threat and cue the appropriate countermeasure, if one becomes available.

Countermeasures

Flares, jammers, and decoys have been used for years to counter man-portable air defense threats with mixed results. One just needs to turn on the news to see the details of the latest MANPADS hit in Iraq or review Russian archives on conditions in Afghanistan in the 1980s to understand the magnitude of the problem. The issues concerning protecting mobility aircraft with large infrared signatures and lethargic maneuvering capabilities become readily apparent. The following discussion summarizes countermeasures evolution and shortfalls.

The function of a flare or jamming system is to fool the missile into locking on to another signal or cause a break-lock away from the target. The level of jamming or flare signature required to defeat the threat is based the hottest signature of the target aircraft. The IR output of a jammer or flare is a multiple of this signature and is referred to as the jammer-to-signal (J/S) ratio. While flares are very effective against first generation infrared missiles, newer missiles are not easily fooled by a flare burst that emits an IR signature within a single band and travels away from the original intended target. Therefore, newer flare dispensers now use a "cocktail" of multiple types of flares in an effort to more accurately model the aircraft signature. Flare burn patterns can also be varied in an attempt to fool the threat sensor.

The key to successful use of reactive flares is adequate warning of the threat type and direction to achieve adequate miss distance and for flares to fully ignite, and dispensing the flares from well-paced dispensers to ensure the missile sees and reacts to them. Proper flare ejection sequence and timing is a function of the type of threat. Ejecting the flares too early may allow the incoming missile to reject the pattern and reacquire the target, while ejecting them too late may cause the flares to be outside the missile field of view and have no effect. Proper use of the integrated missile warning and flare countermeasure system requires the pilots to allow a computer to determine the best flare sequence, with intelligence data determining the "menu" of responses.

Preemptive flare dispensing is one way to keep the missile from initial lock-on, potentially preventing a launch from occurring. However, preemptive flare use would have to start upon entering the threat envelope and continue until exiting the envelope. This would cause excessive use of flares, which unless managed appropriately, would result in the aircraft exhausting its supply prior to exiting the threat area.

Another, more critical issue for routine operation of pyrotechnic decoy flares is the collateral damage caused by starting fires when dispensed close to the ground, especially over urban areas. A current technology breakthrough is the use of pyrophoric materials that self-ignite when exposed to oxygen, providing better signature matching than the hot pyrotechnic flares. Instead of burning, these materials rapidly oxidize when exposed to the air, virtually eliminating the ground fire possibilities and allowing for covert dispensing.[74] Unfortunately, increasingly sophisticated MANPADS signal processing and filter routines will be capable of rejecting flares even if they are perfectly spectrally matched to the target signature.[75]

Therefore, a lamp-based or laser jamming system is preferable. The lamp-based systems utilize mechanically generated codes in sequence, essentially flashing on and off in specific patterns, to defeat the threat.[76] One advantage of these jammers is you have continuous jamming power available, unlike flares that must be reloaded. Lamps have a broad radiation pattern that emits energy over a wide angle. A high-intensity, mirrored flash lamp can counter many of the MANPADS threatening smaller transport aircraft like the C-130. However, this system's jammer-to-signal ratio is not powerful enough to protect a large aircraft like the C-17 at short range.[77]

Both the lamp-based and laser jamming systems require an up-to-date library of threat-seeker codes to ensure all codes are represented in the jamming sequence or are available for the closed loop jammer system.[78] These codes represent the optimum jamming patterns of energy necessary to defeat the missile seeker systems and must be programmed into the countermeasure unit. As new missile seekers are developed, these systems must be updated to ensure the missile can be defeated.

Using a laser instead of a flash lamp increases the level of jamming power available to generate the miss distances needed to protect large aircraft.[79] The laser directs modulated energy into the missile dome, interfering with its tracking mechanism by introducing errors and thus driving it off course. To be most effective, the laser must jam inside the missile field of view. Jamming outside this "cone" is not efficient, requiring more power the further off-missile axis the laser beam enters the seeker. In addition, this energy has to be directed at the correct wavelength for the type of missile it is trying to defeat; therefore, the system either jams on a generic wavelength at higher power or utilizes multiple wavelengths repeated in a sequence. Increasing jamming power on the correct wavelength drives the missile off faster. To jam the most common MANPADS, a multi-band laser capable of covering the two to five micron wavelength bands is needed with approximately three to five watts in each missile band to protect a C-17.[80]

The Large Aircraft Infrared Countermeasures (LAIRCM) program has successfully demonstrated the capability to protect the C-17 against infrared guided missiles using a mid-IR band laser.[81] The program has further demonstrated a closed-loop system which adapts to the detected threat by classifying and precisely jamming the threat in its unique sensor wavelength, thus placing more power faster on the seeker head and driving the missile off in less time.[82] The interrogator laser receives reflections from the missile seeker that provides unique signatures to compare against the database. The closed-loop system eliminates the need to sequence through multiple potential threats and begins tailored jamming immediately. This threat-adaptive system combines the latest developments including using a two-color IR missile warning system with staring focal plane array sensor/processor subsystem, large array IR track camera, laser-specific gimbals, closed loop IR signal processing, and a countermeasure-effectiveness assessment capability, backed up with flares.[83]

These breakthroughs provide a tremendous near-term capability that represents billions of dollars and years of countermeasures investments by the government and industry. However, these are still reactive systems that require a missile to be in the air before any action can be taken. As the missile sensors become more capable, databases must be updated or new countermeasures developed to defeat them. Success is measured in seconds, and the pilot never knows until the endgame whether the missile was defeated or it is time to brace for impact. Researchers have now become more proactive in this kill chain and are developing technologies to reach out and touch the man-portable air defense system while the missile is still in the tube.

Mid-Term Countermeasure Technologies-MEDUSA

The Defense Advanced Research Projects Agency (DARPA) is leading a program that could revolutionize this “cat and mouse” game. The key to future aircraft survivability depends on understanding and engaging or avoiding multi-spectrum threats. The Multifunction Electro-optics for Defense of U.S. Aircraft (MEDUSA) program is a future generation laser-based multi-spectral system providing both self-protection and offensive functions from a single set of electro optic sensors. The program goal is to move from a reactive posture to a capability to proactively deny launch and put threat EO/IR systems at risk.

The MEDUSA program aims to negate all ground-based and airborne EO/IR threats by sensing that it is being observed and determining the best way to eliminate the threat. MEDUSA would use a highly sensitive search laser, hyperspectral imaging, and new techniques to distinguish the threat from ground clutter. If MANPADS can be detected prior to the aircraft entering the missile system’s lethal range, then the pilot would be alerted to avoid the threat. If the threat is not sensed in time to avoid the lethal window, the next opportunity is to defeat the acquisition and track sensors before missile launch. The last option is to defeat the sensor after launch—a problem resembling current system efforts, whether it requires defeating the missile sensor or beam riding system.[84] Because newer missile imager seekers utilize several frequency bands to lock on to the aircraft, defeating them may require destructive laser energy at each wavelength. The Special Projects Office estimates the solid-state laser power requirement to search, classify, and counter these imagers to be 20-30 watts.[85] The challenge will be to design a multifunctional laser or system of lasers that can adequately perform the search, classification, and jamming functions in several wavelengths in a small, affordable package.[86]

Although designed more for tactical aircraft use, these technologies will make large aircraft defensive systems cheaper, lighter, and more effective. Technology development under the MEDUSA program includes search lasers, active clutter measurement, tracking and steering, identification, missile warning and countermeasures.[87] One example of the innovations DARPA is working on is in the area of beam steering. Their steered agile beam program objective is to develop miniaturized components that can steer a laser beam without heavy mirrors or gimbals. Breakthroughs in micro-electromechanical systems (MEMS) technologies are expected to make this possible. DARPA's goal is to decrease the total weight of beam steering systems from 200 pounds to fewer than 6 pounds per aircraft with the ability to conform to the aircraft skin. The outcome could be an all-electronic laser countermeasures system comprised of solid-state components, more precise steering capability, and decreased reaction time with the ability to steer a laser beam over a 90-degree arc in less than a millisecond.[88] But even if all these component technologies were to achieve their goals, the system as currently designed will still use flares as the fourth and final layer of defense, clearly an indication of the complexities in solving the MANPADS problem.

The search for a better solution to defeat the MANPADS threat is not a U.S.-only obsession; other countries are trying to grapple with balancing multi-spectrum threat probability against cost. For example, Australia is trying to put a comprehensive protection system on their C-130J aircraft. Under the Echidna program, BAE Systems Australia was awarded a contract for design of an integrated radar-warning receiver and laser warner, countermeasures dispenser, radar jammer, lamp-based infrared countermeasures, and a towed radio-frequency decoy for their new C-130J transports.[89] The cost for incorporating all these systems is quite high and reflects government concern and commitment to protecting their assets.

Future Programs: Hard-Kill Lasers

Current countermeasure systems are based on defeating the threat through the electromagnetic spectrum by attacking the tracking algorithms or jamming the missile. Because each sensor can operate in a different wavelength, several different countermeasures or capabilities to defeat sensors in all wavelengths are required. What has not been seriously proposed, due to lack of mature technology, is a laser that immediately destroys unidentified missiles by imparting enough thermal energy to damage one of the systems or explode the warhead or rocket fuel. Unlike low-power laser jamming, which must be done in the correct wavelength and with the right waveforms for maximum effectiveness, this is a brute force kill that requires no advance or instant information on the type of missile. The countermeasure system's problems are reduced to detecting, tracking, and imparting energy somewhere on the missile to achieve the desired effects. An advantage of a hard-kill system is that it would be effective against all MANPADS, including the laser beam riding missiles and future seeker/guidance technologies.

While this class of laser certainly makes the system more flexible, the power requirements to achieve these effects are high. There is no set power level threshold that defines high-energy lasers; average powers of tens of kilowatts to megawatts are generally considered high power.[90] Two types of lasers, chemical and solid-state, will be considered in this paper for MANPADS defense. Of the two, chemical lasers have achieved megawatt-class power levels.[91]

Chemical Lasers

There has been a steady stream of successes using chemical lasers to track and destroy objects. For example, the U.S. Army and Israeli Ministry of Defense choose Northrop Grumman's Mobile Tactical High Energy Laser (M-THEL) as the design concept for short-range defense against ground-to-ground projectiles. The system as demonstrated consisted of a fixed structure containing a command and control element, radar to acquire and track incoming targets, a pointer-tracker subsystem to direct the energy, and a chemical laser. System components are quite large, but the end game projects the laser to fit on a ten-ton truck in as little as four years.[92] It has already proven the ability to detect, track, and engage by shooting down 28 Katyusha rockets, fired singly and in salvos, and five artillery projectiles.[93] The system is currently programmed to only engage the Katyusha rocket, providing a level of safety against engagement of friendly airborne platforms or projectiles.

Chemical lasers obtain power through chemical reactions in a supersonic gas mixture; the volume and weight requirements of such a system make it prohibitive to place on a mobility aircraft without very significant useful load penalties. The megawatt-class chemical laser being developed for theater missile defense neatly fills an entire Boeing 747-400 freighter, which describes the magnitude of the problem. Another disadvantage is the laser has a limited "magazine" of shots, requiring chemical reload. Technical advances in adaptive optics, handling and disposal of chemical effluents, and laser cavity size and pressure requirements will be required to significantly decrease its footprint.

The new Advanced Tactical Laser (ATL) program will investigate the feasibility of a smaller tactical chemical laser on an airborne platform with power levels from tens to a few hundreds of kilowatts.[94] Boeing won the advanced demonstrator contract that places a chemical laser on a Special Operations C-130 and plans to demonstrate tactical effects in the 2006-2007 timeframe.[95] The laser has already demonstrated 16 kilowatts of power in the laboratory. Their goal is to fit the system into a footprint the size of a 20-foot shipping container or four pallet positions. They have also designed a closed loop core, to decrease waste heat, and sealed the exhaust system allowing for a more compact and self-contained unit.

As part of this concept, the government performed an analysis of how tactical lasers could meet multiple, full-spectrum mission needs across the services. According to Boeing, although the sensors and specifications vary, all requirements relied on the same basic laser capability to generate 100 to 300 kilowatts of optical power.[96] Scaling from 16 to 300 kilowatts is not an easy leap and will be even more challenging to place it in a smaller package. Getting rid of chemical storage, mixing, and waste, and decreasing thermal waste would make this a much more compact and attractive system for on-board use. These challenges are why solid-state laser technology is so appealing.

Solid-State Lasers

The solid-state laser provides the most promise for a compact, durable weapon for integration into a future combat system for short-range air defense.[97] Solid-state lasers obtain power from "optically pumping or exciting rare earth elements embedded in a crystalline or glass medium to an excited state at a higher energy level and then decay to a ground state."[98] Currently, these lasers have large components but do not require complicated chemical reaction components or storage. The "magazine" is limited only by the electrical power necessary to obtain the excited states and not by how much chemical is available.

A capable defensive system would require a high-power, possibly 100-kilowatt, laser that delivers energy onto the missile to explode it at a range of up to 5 miles.[99] Researchers at Lawrence Livermore Laboratories have demonstrated a solid-state laser system conversion of one-megawatt input to a 13-kilowatt laser beam that can essentially vaporize metal. In fact, the system burned a 1-centimeter diameter hole through a 2-centimeter thick stack of steel in 6 seconds.[100] Their program goal is to develop a battery-powered version that mounts on a hybrid-electric Humvee where the battery and vehicle generator power both the laser and the vehicle using diesel fuel. Their efficiency goal is ten percent; producing a 100-kilowatt laser beam with that same one-megawatt of input power.[101] Further, Major General John Urias, Deputy Commander of Space and Missile Defense Command, believes a solid-state battlefield laser is probably eight years away.[102]

However, this high power, solid-state system does have significant technical obstacles ahead. First, scaling the solid-state laser to the 100-kilowatt power level is a challenge due to waste heat removal. While chemical laser heat is dispersed through the flowing gases; the waste heat from the solid-state laser remains in the laser medium, destroying laser beam quality. Currently, heat removal is done physically with water or air or by limiting laser operation to short bursts. Researchers must determine a way to increase wall-socket efficiency, or the ratio from input to output power, and further reduce waste heat through a heat sink or other heat diffusing methods.

Another major issue with the solid-state laser is the need to make affordable and efficient high-power laser diodes to pump up to the excited states necessary for lasing. This pumping process currently increases the temperature in the lasing medium unacceptably, further degrading beam quality. The sheer numbers of diodes are staggering. Pumping a 100-kilowatt laser at ten percent efficiency requires a million diodes—approximately three times the world's yearly production. At around $100 per watt, this is an expensive element of the solid-state laser.[103] Researchers at Lawrence Livermore Laboratories are experimenting with a modular packaging technology, water-cooling techniques, and the use of silicon substrates to produce the smallest, most powerful, and least expensive laser diode pumps available. Their designed diode cost per watt is less than one third that of its nearest competitor. Their next step is to use these diodes to power a one-megawatt solid-state heat capacity laser.[104] The manager of Raytheon's high-energy laser program predicted even greater breakthroughs in the next several years, bringing the cost per watt down to five dollars.[105]

One way to scale up solid-state laser power without excessive heat is through fiber optics. Researchers at the University of Southhampton have successfully demonstrated a one-kilowatt single-mode high power fiber laser with a very high beam quality.[106] Realistically, a few kilowatts per fiber is considered possible and although that seems small, the goal is to combine, or bundle, many single-mode fiber lasers to get enough total power to be tactically useful.[107] Fiber lasers have high wall-socket efficiency, approximately 20 percent, and a large surface-to-volume ratio, which simplifies heat removal.[108] These lasers would be lighter, scalable, more flexible in packaging, and would generate less heat. These are near-term goals; fiber lasers could be an integral part of tactical laser weapons in the future.

With any laser system, adaptive optics will be critical to system performance. Adaptive optics focuses the beam onto the target with minimal diffraction by compensating for atmospheric disturbance; otherwise, the beam would scatter and become less effective. Deformable mirrors with hundreds of tiny actuators that can reshape the mirror have been successfully used for this purpose. The solid-state laser offers an additional advantage to the chemical laser since it operates at a lower wavelength, which simplifies the optical system by allowing the beam to focus on the required spot size with smaller optics.[109] In addition, the airborne laser program is already demonstrating technological advances in atmosphere characterization and adaptation, increased optical pointing and tracking accuracies, and beam handling at high power levels. All these technologies will be required to produce a more responsive, compact, high-quality laser beam, and given the current technology investments, trends certainly point to having a hard-kill laser capable of countering any MANPADS by 2025. A high power laser may have the capability to engage any projectile headed for the aircraft, such as a surface-to-air missile or rocket-propelled grenades, greatly enhancing aircraft defense.

Lasers do have limitations, a prime one being atmospheric degradation of performance due to moisture and particles. Although missile IR seeker performance is also degraded under these conditions, a defensive system must be capable of operating under the harshest conditions. The Navy abandoned laser-based defense as a primary method to counter incoming missiles due to scattering and thermal blooming from water vapor, dust, and atmospheric turbulence. Their researchers have turned to microwave physics to provide the Navy primary defensive capabilities against any electronic target. This radio frequency technology may also be integral to a complete aircraft defensive system.

Radio Frequency Weapons

Radio frequency weapons, or high power microwaves, would complement a laser-based countermeasures system during atmospheric conditions that degrade lasing capabilities. These microwave systems can produce either narrowband beams in longer pulses or wideband beams in very short pulses, also called ultra-wideband. Narrowband beams can efficiently couple energy into the target if the target antenna geometry or sensor frequency is known. Ultra-wideband weapons produce a pulse over a much wider band of frequencies, and although not as efficient as focusing power in a narrow band, this method ensures some energy will couple onto the target to achieve effects.[110] At sufficient power levels, high power microwave systems can lock-up or cause permanent damage to electronic circuitry, without needing any specific advance knowledge of the threat.

A tactically useful high power microwave weapon would produce a series of intense, short pulses of very high power microwave energy, causing the inbound missile to react by locking up or resetting the guidance system or causing severe changes in flight path. Any of these effects may cause missile structural failure or drive the missile away from the target. High power microwave systems could engage not only man-portable air defense missiles but also all incoming missile types that have guidance packages or fins requiring electronics such as radar guided missiles or potentially the laser beam riding missiles.

It is difficult to protect electronic components since microwaves attack through any conduit. “Back-door entry” can occur through antennas, optical windows/domes, electrical wiring, or seams in metal, and can travel deep inside the system. Hardening a missile against high-power microwaves is possible but not practical at this point. Shielding all electrical systems would require a protective wire mesh enclosure, called a Faraday Cage, which would add bulk and complexity to any system.

The distance to the target and the power level transmitted by the source essentially determine the effects of a microwave weapon. The microwave power applied to unprotected electronics is roughly inversely proportional to the square of the distance between the microwave generator and the missile, meaning either the high power microwave system must be close to the missile, or gigawatt to terawatt levels of power are needed to achieve effects at significant distances. These power levels can currently be achieved. For example, one gigawatt of power can be generated for a few nanoseconds in a package that weighs less than 45 pounds. Another microwave source is capable of radiating 20 gigawatts of power and weighs 400 pounds.[111]

Radio frequency weapons are called area weapons since they illuminate every object downrange within the footprint of the beam, potentially causing collateral damage. Researchers can use special antennas to propagate these beams in the tens of degrees range to minimize the affected area and maximize power on target.[112] However, systems onboard the aircraft as well as anything along the beam's path could still be damaged. Extensive use of commercial off-the-shelf electronics in military systems provides many "openings" for microwaves to attack; purchasing all hardened systems would be cost-prohibitive. Additional research into antennas and electronics hardening technology is required to make this an effective weapon and avoid suicide and fratricide events. Even if the military hardening challenges are solved, there may be complicated weapon rules of engagement to minimize civilian system damage, reducing the capability of the weapon system.

Summary and Recommendations

MANPADS performance trends of increased seeker sensitivity throughout the spectrum, robust countermeasures resistance, earlier target detection and lock-on, increased warhead lethality, longer range, faster speed, and smaller launch signature are alarming to defensive system experts and require increased attention by Air Force leadership. Although defensive systems have previously not been given due priority on weapons systems, recent attacks by older generation MANPADS and the promise of more lethal systems in the future have placed development of effective missile countermeasure systems higher in the resource priority list.

The United States is developing the right technologies in the areas of countermeasures systems and has placed proper focus on multi-spectrum missile warning systems and closed-loop laser jammers. The bulk of the countermeasures research is reactive in nature and focused on defeating missile tracking capability. However, technology breakthroughs allow for mid to long-term proactive technologies that identify and mitigate the threat before launch, providing additional layers of defense.

The use of high power lasers to defeat MANPADS by imparting energy somewhere on the missile instead of jamming it is the next leap in capability and will allow immediate detonation of unidentified inbound missiles. Research in high power laser programs such as the Airborne Laser is being leveraged to advance chemical laser technologies and produce a laser that could be mounted in mobility aircraft if the cost and risk balance were favorable. The Advanced Tactical Laser program is also developing high-power lasers capable of disrupting or destroying missiles instead of jamming seekers. From a ground defense perspective, the Mobile Tactical High Energy Laser program has seen success in tracking and destroying some classes of rockets, proving a robust tracking and targeting capability under strict time constraints.

Solid-state lasers are more compact and durable than chemical lasers, but are not as powerful. Unfortunately, the electrical power needed to drive a solid-state laser is five to ten times as much as the output laser power, making these systems inefficient and causing thermal waste heat problems. One way to beat the heat is through fiber lasers. Researchers have demonstrated a one-kilowatt single-fiber laser that could be bundled with many other fibers to produce a more efficient, tactically useful weapon. However, unless advances can be made in decreasing laser beam distortion due to moisture and particulates, radio frequency weapons should also be proposed as a complementary system during poor atmospheric conditions. High power microwave systems can couple energy onto the missile, affecting all electronics and causing the missile to miss the aircraft. This system's major drawback is collateral damage due to the indiscriminate microwave beam affecting all objects in its path. For a high power microwave weapon to be effective on the battlefield, additional research in antennas and electronics hardening is required. In this author's opinion, the high-energy laser and high power microwave system developments represent the best opportunity for transformational progress against the man-portable air defense system and the first time countermeasures will exceed missile capabilities.

IV. Two Strategies to Defeat MANPADS Threats

If future operations require mobility aircraft to operate at forward, bare bases and the Army plans on leveraging air mobility for vertical maneuver, it is clear these assets must be adequately protected from the threat. However, is it necessary that all mobility assets be equipped with on-board defensive systems? If threats deny sanctuary for logistics build-up, will the U.S. install defensive systems on civil reserve air fleet (CRAF) aircraft? Is the addition of defensive systems on CRAF aircraft even possible or will Air Mobility Command have to use rear bases for them that are a continent away? Is there a better balance between mission capability and cost?

Answers to these dilemmas may lie in a new concept, a ground-based defensive system. This alternate strategy to an aircraft-based system has become feasible with the latest laser technologies and deserves further consideration and development. As laser capabilities finally begin to fulfill the prophecies of their proponents, laser effectiveness as a viable ground-based defense alternative will be undeniable and even preferable. On-board countermeasure capabilities will be reviewed, followed by a description of the essential elements and feasibility of a ground-based system as applied to the various mobility missions. Results will show that the best strategy is not a singular one but a mix of on-board and ground-based defensive capabilities to ensure unimpeded access to critical forward basing.

Aircraft-Based Countermeasures System

Protection of mobility assets using on-board countermeasure systems was a natural outgrowth of fighter aircraft countermeasure strategies. As transport aircraft became more exposed to the threat, air mobility leaders called for enhanced on-board protection. The defense industry focused on solving the larger signature problems these transports have and developed new countermeasure systems. Emerging proactive countermeasure technologies provide the promise of achieving parity with MANPADS capabilities. In the future, advances in multi-spectral detection capability combined with high-power laser technologies will greatly reduce, if not eliminate, the risk of operating under the future MANPADS threat. This projected system would be combined with enhanced situational awareness capabilities in the cockpit, such as an integrated on-board sensor system fused with datalink information, to ensure full-spectrum protection and power projection through continued global mobility responsiveness.[113]

The question of whether all mobility aircraft require the latest laser jammers or future defensive systems is best answered by analyzing mission risk. In the *Air Force 2025* study, the worst-case scenario required direct delivery of logistics and no forward staging due to multiple threats. However, even in the future, intertheater hubs will remain a critical part of the logistics flow, just further away for most scenarios. For example, the U.S. may not be able to use Osan

Air Base, Korea, or Yokota Air Base, Japan, as staging bases for a North Korean conflict, but should be able to use Guam. From there, intratheater assets could deliver the supplies forward. However, the growing proliferation of MANPADS virtually guarantees that aircraft transiting these main hubs will require some type of defense. A review of the types of mobility operations should highlight whether it is cost effective to outfit all mobility assets with state-of-the art defensive systems or use those resources to reduce risk through a ground-based system.

Intratheater and Direct Delivery Air Mobility Operations

Aircraft supporting intratheater and direct delivery operations that are exposed more frequently and over longer periods of time to the MANPADS threat would require an on-board defensive system. Intratheater and direct delivery missions distribute logistics to the forward troops by transiting bases that are closer to or inside the combat zone during a level one or two threat scenario. These missions may require flight at lower altitudes for tactical operations such as airdrop and low-level ingress/egress. Most special operations missions would also fall into this category. A ground-based system could be set up to protect the forward airfields. However, these aircraft would remain vulnerable while transiting over unsecured areas at low altitude. Therefore, a robust on-board defensive system would be required for aircraft performing these types of missions. Air Mobility Command’s Electronic Warfare roadmap projects outfitting approximately two small-scale contingencies’ worth of mobility assets, consisting of 137 aircraft including C-130s, C-17s and tankers, that could perform these missions with the laser-based jammers by fiscal year 2011. The roadmap further describes a need for a full-spectrum defensive system capable of countering radio frequency, infrared and command line-of-sight weapons.[114]

If the capabilities of a high-power laser defensive system are needed for full-spectrum protection on-board the aircraft, will the system be feasible in terms of cost, capability, weight, and volume? High-energy laser costs are hard to estimate, but will probably be an order of magnitude more that the laser-based jammer. The system potential is also enormous; Boeing’s Advanced Tactical Laser research program will attempt to demonstrate precision effects against ground targets several miles away with a 50 to 70 kilowatt sealed chemical laser system. Future applications become unlimited using a scalable laser against ground and air targets. However, when it comes to performing the mobility mission, the system may be too bulky or the weight penalty too high to be practical. The planned chemical laser demonstration on a C-130 will require at least 67 percent of its cargo floor capacity, or four of six pallet positions, and approximately 25 percent of its cargo weight capacity.[115] If the system were placed on a C-17, it would use 22 percent of its cargo floor capacity, still a significant portion. This has clear implications for theater mobility strategy; the system may allow lower-risk access but the price will be degradation in mission capability for an already “high demand” asset.

At a minimum, the number of aircraft necessary to provide intratheater and direct delivery capability to fulfill our National Military Strategy requirements should be outfitted with on-board defensive systems. These theater requirements should be determined in light of our expeditionary force structure and sister service needs, taking into account the potential for reduced mission capability due to the size and weight of the system.

Intertheater Air Mobility Operations

Intertheater missions are long-range, heavy load movers and represent the backbone of Air Mobility Command. Assets include heavy lifters, both military and civilian, and air refueling aircraft that that augment both the heavies and fighters into the theater. These aircraft normally land at bases capable of efficiently offloading and servicing these aircraft, transloading cargo and personnel to both ground and air intratheater transportation assets, and storing supplies.

The robust forward operating locations normally associated with intertheater operations are located outside the combat zone, normally in a lower threat area. However, insurgents, transnational actors, and sympathetic groups in the region may have access to man-portable air defense systems and an intent to harm our personnel, raising the local threat level as forces arrive. This reaction to United States presence, especially in Southwest Asia, is not uncommon.

If the AMC Threat Working Group, in conjunction with the Transportation Command Joint Intelligence Center, makes the decision to require aircraft defensive systems while operating at this forward location, many of today's aircraft could not be used. By FY11 the AMC Electronic Warfare roadmap will add another 137 aircraft to the 600 aircraft that currently have some type of missile defense system.[116] These 137 systems will be laser jammers, with the remainder mainly flare-based systems that will only decrease in effectiveness as newer surface-to-air missiles are proliferated. Replacing these older systems and updating the 900 military aircraft mobility fleet with laser-based jammers is an affordability issue for AMC and the Air Force.[117]

The production cost for these jammers is roughly $2 million per aircraft.[118] Installation costs vary by airframe, and there will be additional routine maintenance costs. With aggressive cost reduction measures, it may be possible to reduce the production cost by 50 percent, but the total cost will still require hard tradeoffs by the Air Force at a time when recapitalization and personnel programs are the highest priority. These costs represent the current laser-based jammer, which has outstanding capabilities but still will not defeat laser beam riding surface-to-air missiles. Those must be avoided or the defensive system must evolve to the high-power hard-kill laser system.

One idea to reduce costs is to develop a pod-mounted defensive system that would be installed on the aircraft only if the threat level requires a defensive system. Air Mobility Command would pre-install fittings onboard most mobility aircraft and place these pods in storage. When the threat level increases, AMC would pull these aircraft and install the pods. This would clearly be less expensive than outfitting the entire fleet. However, if an aircraft that had the fittings but not the defensive pod installed encountered a MANPADS, the political fallout of not having the system onboard would be stiff. What commander would choose not to have these pods all the time if the aircraft were capable of using them?

The civil reserve air fleet is currently restricted to low threat areas; installation of defensive systems on this extensive fleet for higher threats would be problematic from several aspects. These aircraft are normally chartered on a volunteer basis. However, if the U.S. Transportation Command calls up any one of the three stages of this fleet, they are required to participate within the limits of the CRAF agreement. Stage one has approximately 80 passenger and wide-body cargo aircraft. Stage two has approximately 120 aircraft, with the remaining approximately 700 aircraft in stage three. Stages one and two were activated during Desert Storm; in April 2003 stage one was activated for the second time in history to support OIF.[119]

To fully outfit each civilian aircraft with laser-jammers would be cost prohibitive and hard to manage from a logistical and legal standpoint. Even if the government paid for the installation, the recurring maintenance and drag penalties would further strain the airline industry. Complicating the issue is the specific aircraft tails designated for civil reserve service fluctuates. Carrier tail management becomes an issue if only certain tails are modified with these defensive systems and must be rotated off the line to fly military charter missions. The pod-mounted system may be an alternative to a permanently mounted system. However, the tails would still need to be managed since the pre-installation kit would only be on a portion of the fleet. In addition, agreements concerning war risk insurance and accepting flights into higher risk areas would have to be renegotiated with the carriers, insurance companies, and the FAA.

Finally, these forward operating locations not only accept U.S. troops and supplies but also coalition and non-governmental organization transports, smaller intratheater transports, and host nation aircraft. This could account for any number of aircraft on different missions; all have an infrared signature that could be targeted. If a coalition or host nation aircraft is targeted, it could have a far-reaching effect on coalition participation or the support of the host nation. The U.S. could not require them to have defensive systems; in some cases the U.S. may not even be able to share the threat intelligence. Therefore, ensuring protection of these aircraft, which is the responsibility of the local commander, would be troublesome.

There is a need for onboard defensive systems to fulfill the global mobility mission. However, a cost and capability balance must be struck between outfitting all national air mobility system assets with aircraft defensive systems and just outfitting those aircraft more exposed to the threat during intratheater and direct delivery operations. To protect intertheater, host nation, and coalition aircraft that will only transit major airports hubs under the MANPADS threat, it is more feasible to have a ground-based system set up at these major aerial ports.

Ground-Based Countermeasures System

For strategic mobility aircraft that can choose low threat ingress routes into a level one or two threat area, a ground-based hard-kill laser countermeasures system may achieve the same defensive effects in a more cost effective manner. Intertheater missions are at risk for this type of threat on approach or departure below 15,000 feet, which is below the normal cruising altitude for these aircraft. If a ground-based defensive system were set up to cover the approach and departure corridors and the airfield, there would be a reduced requirement to incorporate man-portable air defense system countermeasures on these transiting aircraft. This proposed system could be packaged as part of every Global Mobility Task Force operation, as the threat requires. This system would limit the number of aircraft needing onboard laser-jamming systems to those venturing outside the protective “bubble” of bases covered by the ground-based system. Strategic airlift, air refueling, contract carrier, operational support, non-governmental agency, and coalition aircraft would all be protected using a single comprehensive system. A ground-based protection system would ensure the geographic commander has the full benefit of a flexible mobility force to meet his requirements.

This system could evolve from the Army’s Mobile Tactical High Energy Laser Program (M-THEL) and microwave weapon research. A high power laser and microwave system could provide a shield of protection over the approach and departure corridors near an expeditionary base. The ground-based laser system would not be a missile jammer, but a hard-kill system designed to disrupt or destroy the missile by imparting energy onto it.[120]

Figure 6. Mobile Tactical High Energy Laser Concept[121]

Northrop Grumman has already proposed a megawatt-class chemical laser similar to the M-THEL to the Department of Homeland Security for civilian airliner defense against man-portable air defense systems.[122] The system could be designed as fixed or mobile with the ability to handle multiple salvos of missiles. Pat Caruana, Northrop Grumman Vice President, stated that given the resources they could field such a system in five years.[123] Northrop Grumman caveats this technology as being part of a layered defense system, including aircraft-mounted laser-based jammers. Analysis of the feasibility of a ground-based system requires a more in-depth look at the components and how the system would operate on an airfield.

Ground-Based Defensive System Components

Engaging the missile is extremely time critical since it may take a few seconds to impart enough energy on the missile to destroy it. The THEL program demonstrated kills at or near the apex of projectile flight, which is the relative position the target aircraft would be located. Therefore, the ground-based system needs an additional “look-down, shoot-down” capability for earlier missile detection and potentially providing a better angle to engage the missile. This system could utilize missile-warning systems and relay mirrors mounted on aerostats located along projected flight paths to reflect laser energy onto a target not in immediate, direct field of view of the ground laser.

As mentioned in section three, it is challenging to design a missile warning system with a low false-alarm rate, especially in an urban environment. The advantage to a statically mounted system is that it is not meant to be stealthy nor will it have to adapt to scanning from a moving aircraft. It would be exposed to less vibration and environmental effects than when attached to an aircraft, allowing for lighter and more precise components. Since the missile warning system would be mounted on a tethered aerostat, ground clutter information for that specific area could be linked to the clutter rejection routine to further reduce false alarms. The high-energy laser beam director uses reflective optics that can additionally provide detailed identification of the target, virtually eliminating fratricide. From a sensor standpoint, the Israeli two-color infrared/low light ultraviolet sensor system combined with pulse Doppler radar would be an optimum near-term solution to minimize false alarms.[124] The same advanced technologies developed from the proactive defensive system programs, such as highly sensitive search lasers and hyperspectral imaging, would benefit this missile warning system by providing a warning to the pilot and security forces if an active missile system emerged within range of the flight path area. Proactive warning, or the ability to inform the pilot to maneuver to avoid the threat, will be a critical layer of defense for close-in or fast missiles.

The "look down, shoot-down" capability would come from a twin-mirror bifocal relay system that receives and re-targets the laser beam. The Naval Postgraduate School and Air Force Research Laboratory's Optical Relay Spacecraft Laboratory are doing research on bifocal mirror tracking and targeting technologies to enable a space-based laser relay.[125] The U.S. Missile Defense Agency is discussing the feasibility of mating this aerospace relay mirror system on a high altitude airship as part of a sensor platform for detecting and tracking ballistic and cruise missiles. The first test in late 2006 will redirect a low-power beam of 500 watts from a ground-based laser to actively track objects in space.[126] This system could be adapted to the lower atmosphere to fill an airbase self-defense role. Although operating in the part of the atmosphere with the most moisture and particulates, this system would only have to relay off of an aerostat at 15,000 feet or less. The system would have two telescopes mounted on the airship, one to capture the laser beam and one to redirect it. Beam quality would probably have to be measured both by the laser and by the airship relay optics to ensure the beam maintains its quality while slicing through dense air twice. In addition, the relay mirror system would have to be scaled to handle the expected 100-kilowatt ground laser. Optical mirror relay and missile warning systems would form the heart of a comprehensive laser and microwave air base defense system.

Air Base Defensive System

A comprehensive base defense system could be set up surrounding an expeditionary air base, in particular covering the approach and departure paths to detect and counter inbound surface-to-air missiles. This portable system would be modular and tailored to each airbase layout considering terrain, urban areas, natural clutter, probable threat type, and potential firing locations. Aircraft approach and departure routing would be altered to ensure maximum defensive coverage. Missile-warning systems could be attached to tethered aerostats staggered in altitude and position around the airfield for best field of view of aircraft flight paths below 15,000 feet. Having been used for years as EO/IR imaging and airborne early warning platforms, aerostats are capable of 30-day endurance at medium altitudes and have secure fiber optic communications links. While there would be a flight safety issue with deploying these systems close to the air base, their positions could be relayed to the aircraft situational awareness systems or identified to the pilots on approach.

The laser and microwave components would be mobile and could be placed on the ground for easier access to power. Analysis of the terrain and atmospheric conditions would determine how many ground units would be required for adequate coverage of the base and aircraft approach corridors. If the runway or threat type changed, these systems could be moved to different positions for optimal coverage. The fratricide concern of the high power microwave system "firing" towards the missile and thus the aircraft remains. If it is not possible to increase pointing capability of the microwave system, an alternate option would be to mount it on the aerostats to emit down and away from the aircraft. However, that could place ground-based electronics at risk. An optimum elevation solution would have to be designed to minimize collateral damage and maximize kill capability and an aerostat matched to that need.

Though weight would be an issue, aerostats can carry fairly heavy payloads. For example, a TCOM 32 meter long aerostat can carry over 750 pounds to 3,000 feet. Larger aerostats, such as the TCOM 71 meter long aerostat can handle 3,000 pounds up to 15,000 feet.[127] The goal must be to assemble components that are as light as possible since a 71 meter long aerostat is cumbersome to maneuver and launch, compared to smaller aerostats. This expeditionary system must be mobile and require the minimum amount of personnel to operate.

In accordance with current global mobility CONOPS, an Air Force security team would control these systems through the base defense operations center. Due to the extremely short response times needed, this system would be fully automatic. The defense system would include an intrusion detection system around the base perimeter, around the components, and possibly even much further out, dependent on host nation cooperation. Current intrusion detection systems can alert security forces on unusual activity in the visible band. Future intrusion detection devices will use the entire spectrum to classify targets and alert security personnel. Ground sensor data, including airport radar, would be fused with tethered airborne sensor data and a current threat database to provide a complete operating picture for the security forces. The system as described further enhances proactive warning capability to detect a missile system prior to launch.

If appropriately funded and developed, this ground-based system could be deployed with every expeditionary airbase by 2025. However, the proposed ground-based countermeasures system requires much additional research and development to determine feasibility. It must undergo rigorous testing and demonstrate high reliability before it will be accepted in the countermeasures community. And it must balance cost and risk, both of which are not static proposals. This solution is not a panacea, but it provides an alternate to the traditional aircraft-based system. Aircraft that will also be used for direct delivery or intratheater transportation will still need additional on-board protection to perform those roles outside the protected areas.

Summary and Recommendations

The two strategies of aircraft- and ground-based defensive systems are not mutually exclusive but complementary in achieving the desired effect of full dimensional protection. Organic air mobility assets assigned to intratheater and direct delivery missions may be exposed to the threat over a longer period of time while performing airdrop or operations into austere bases. Further, the future Army concept of operations may drive additional intratheater airlift requirements or, more precisely, additional maneuver in the battle area, affecting mobility aircraft tactics and defense. Theater requirements for these types of missions should be determined and the assigned mobility assets must be protected by full-spectrum aircraft-based defensive systems or the ability to support the joint fight will be in jeopardy.

Having capabilities relevant to both strategies, laser and microwave systems represent a leap in technology that will maintain our military dominance in the future if appropriately developed. Two major programs, the Boeing Advanced Tactical Laser and Northrop Grumman’s Mobile Tactical High Energy Laser, are developing key technologies to make relatively small laser systems capable of achieving a wide range of effects. Both programs are being funded; the Air Force is funding Boeing’s tactical laser prototype, and the Army is funding the ground laser as part of their transformation to the Objective Force.

Air Mobility Command needs to leverage these efforts early to understand what these effects can do for mobility aircraft and air base defense. It is imperative to understand the capabilities and limitations of these emerging technologies and get involved in developing joint requirements that will cover the MANPADS threats as well as other emerging base defense threats. Using modeling and simulation, AMC should analyze whether these concepts are feasible for transport and tanker aircraft missions and what type of coverage a ground-based system would need. To develop the cost benefit analysis, AMC should simulate closure rates, with and without a ground-based defensive system, against a fleet mix that may or may not have capable on-board defensive systems, probable future threat, and potential bases in use for the major operations plans. In addition, the complex transportability issues of these systems should be analyzed, as this would be a component of the initial deployment package to open the airbase.

The proposed comprehensive ground-based countermeasures system should be assigned as a joint Army and Air Force program with the Air Force as the lead service. The Army brings expertise in the short-range air defense and the Tactical High Energy Laser program while the Air Force has the expertise in the Airborne Laser, tactical laser, aircraft defense, and airfield flight operations. The goal should be to develop a joint, deployable, full-spectrum defensive system using spiral development to take advantage of breakthrough technologies. This system would evolve to be multifunctional, protecting the forces from surface-to-air missiles, cruise missiles, uninhabited aerial vehicles, and artillery.

V. Conclusions and Recommendations

The challenge of the global mobility CONOPS is to maintain the ability to deploy U.S. military forces and initiate operations anywhere, anytime, and under any threat to meet the JFC's requirements. MANPADS are a verifiable threat to these operations; recent strikes on military and commercial transports in Iraq demonstrate that the U.S. does not have adequate defensive systems. A combination of technologies to protect mobility assets from the man-portable air defense system threat has emerged, but a full understanding of how they can be leveraged to carry out the global mobility mission has not yet been achieved.

MANPADS missile technologies and fielded systems have been consistently ahead of countermeasure capabilities. Missile seekers will evolve into fully staring focal plane arrays capable of imaging the aircraft across the electromagnetic spectrum. Warheads are becoming more lethal, and their range and speed have increased. Manufacturers' estimates of future MANPADS kill probability range from 75 to 90 percent when deployed by a trained operator under designed conditions.[128] Further, missiles with laser beam riding guidance currently cannot be defeated. Implications of the looming MANPADS threat range from a strategic consequence of deciding not to deploy forces to an operational consequence of additional closure time needed to achieve effects. The lure of numerous, forward bases closer to the combat zone is even more appetizing to an enemy armed with MANPADS.

Air Mobility Command's focus has been on reactive, aircraft-based defensive systems to counter these widely proliferated systems. These defensive systems are not adequate for the existing threat and require enhanced missile warning and countermeasures capabilities. In the future, missile-warning systems must improve by leveraging multi-spectral imaging, quantum leaps in processing speed, and complex clutter-rejection filters. The flare-based countermeasures have evolved from pyrotechnic decoy flares to multi-spectral pyrophoric flares that essentially rust when exposed to oxygen, making them covert and safer to use. However, not all missiles can be fooled with flares. Therefore, lamp- and laser-based jamming systems are the current countermeasures favorite, and the near future will bring closed-loop laser jammers capable of driving the missile off faster, ensuring greater miss distances. Some of the most exciting technology breakthroughs are in the areas of proactive countermeasures, or the ability to locate and defeat the missile before it launches, while still in the tube. A proactive countermeasures system could be the first stage of a powerful hard-kill laser system capable of defeating all radio frequency, infrared, and laser beam riding missiles without requiring prior knowledge of the threat.

Most research into the design of a high-energy laser has focused on chemical and solid-state lasing capabilities. Two chemical laser programs experiencing success are the ground-based megawatt-class Mobile Tactical High Energy Laser and the hundreds of kilowatt-class aircraft-based Advanced Tactical Laser. The ground-based laser has demonstrated the capability of shooting down multiple Katyusha rockets; the Army is continuing funding for further research into the system to meet projected ground defense requirements. The aircraft-based laser is funded as an advanced demonstrator to prove defensive and offensive tactical effects packaged into a C-130. Technological challenges facing these programs to make the systems useful on the battlefield are chemical storage, mixing, and thermal waste management.

Solid-state lasers would be more compact and durable than chemical lasers, not requiring chemical handling and thus having a deep magazine limited only by the input power source. These lasers are currently not as powerful, having only been demonstrated at less than 20 kilowatts. To scale up to 100 kilowatts would require increasing wall socket efficiency and drastically reducing thermal waste. Fiber optic lasers may provide that technology path, since fibers are more efficient and have a large surface-to-volume ratio to simplify waste heat removal. Fiber lasers have been demonstrated at a one-kilowatt power level, however higher power levels are possible by combining several single-mode fibers into one coherent laser beam. Unfortunately, lasers have a weakness—moisture and particulates degrade the laser beam.

To ensure reliability under all conditions, a radio frequency weapon such as the high power microwave system could be integrated into a comprehensive defensive system. Microwaves are not susceptible to atmospheric effects, but they are limited in range. This weapon would attack the missile with high-energy microwave pulses that would disrupt the electronics and cause the missile to lose tracking ability, guidance control, or possibly prematurely detonate the warhead. There is a significant collateral damage issue that must be overcome by advances in electronics hardening and beam control to make a high power microwave weapon feasible. Any use of a microwave weapon would entail complicated rules of engagement to minimize civilian or friendly military electronic systems.

The man-portable air defense system threat near the airports is not negated under the umbrella of air superiority but is an integral part of force protection at the base level. As such, the geographic combatant commander is ultimately responsible to provide for the security of all forces that are part of the operation, both U.S. and coalition. This responsibility is delegated to the local base commander, normally the senior officer of the first on-scene command and control unit. Expeditionary base standup is a core competency for Air Mobility Command; therefore, the commander will most likely be from the mobility task force. The global mobility CONOPS has further designated the deployed Expeditionary Mobility Task Force commander as responsible for aircraft ingress and egress route security, as well as the base perimeter. To fulfill this requirement, Air Mobility Command has designated the newly standardized Crisis Response

Group as being responsible for "opening the airbase" and providing recommendations on the appropriate security forces and equipment to provide this capability under all threats.

These additional area security requirements shed a new light on strategies to provide aircraft defense. The sheer numbers of mobility aircraft, both military and civilian, make aircraft-based countermeasure systems an affordability issue for the Air Force, as demonstrated by the current lack of on-board defensive systems on mobility aircraft. A balance must be struck between exposure to projected threat, consequences of being attacked, and cost. For aircraft on intratheater and direct delivery missions that expose the aircraft and crew to extended low-level operations over potentially hostile terrain, an aircraft-based countermeasures system is clearly required. This system must be capable of negating radio frequency, infrared, and command line-of-sight weapons. The remainder of the military tanker and transport, civil reserve air fleet, theater support, coalition, and host nation aircraft may be protected by a ground-based defensive system modeled after the Mobile Tactical High Energy Laser program and augmented with a high power microwave system for all-weather condition protection. This automatically operated system would consist of a ground-based laser and high-power microwave system weapons, advanced optics and missile warning systems mounted on tethered aerostats, and a full array of ground sensors including intrusion detection devices and radar. As a natural extension of the global mobility CONOPS, mobility task force security assets should operate the system, unless higher threat levels require area defense by the Army.

To take advantage of these systems and get in on the ground floor, AMC needs to comprehend the capabilities of ongoing aircraft-based and ground-based directed energy development programs, and inject the need to counter MANPADS into the joint requirements process. The command should perform several analyses to determine the protected area requirements and the feasibility of these concepts for transport and tanker aircraft and should evaluate future force closure capability given the projected force composition and on-board defensive capabilities. This full-spectrum ground-based defensive system should be assigned as a joint Army and Air Force program with the Air Force as the lead service. The Army brings expertise in the short-range air defense and the Tactical High Energy Laser program while the Air Force has the expertise in multiple directed energy programs including the Airborne Laser and tactical laser. The Air Force also has the operational insight on aircraft–based defensive capabilities and expeditionary airfield operations. The goal should be to develop a joint, deployable, full-spectrum defensive system to provide a defensive shield around the airbase environment, leveraging spiral development to take advantage of breakthrough technologies. System capabilities would evolve to be multifunctional, protecting the forces from surface-to-air missiles, cruise missiles, uninhabited aerial vehicles, and artillery.

In conclusion, United States air mobility forces have access to the technological capability and strategies to defeat the projected man-portable air defense system threats of 2025. Exploiting these capabilities requires an understanding of future threats and the different strategies to counter them. The best protection for all mobility assets, both military and civilian, is through a mix of ground-based and aircraft-based MANPADS countermeasures systems. Ground-based countermeasures systems would defend the intertheater hubs where military, civilian, and coalition strategic transport and tanker assets transit. Aircraft-based countermeasure systems capable of countering the full spectrum of threats to mobility aircraft are required for intratheater and direct delivery missions. The time has come to break the aircraft-based paradigm and embrace the potential cost-effective solution of a portable ground-based system.

Glossary

ATGM	Anti-Tank Guided Missile
ATL	Advanced Tactical Laser
AU	Air University
AWC	Air War College
CADRE	College of Aerospace Doctrine, Research and Education
CdS	Cadmium Sulfide
CRAF	Civil Reserve Air Fleet
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
EO	Electro-optical
FLIR	Forward-looking Infrared
HgCdTe	Mercury cadmium telluride
IFF	Identify Friend or Foe
InSb	Indium Antimony
IR	Infrared
LAIRCM	Large Aircraft Infrared Countermeasures
MANPADS	Man-Portable Air Defense System
MEDUSA	Multifunction Electro-optics for Defense of U.S. Aircraft
MEMS	Microelectromechanical Systems
M-THEL	Mobile Tactical High Energy laser
PbS	Lead Sulfide
UNITA	National Union for the Total Independence of Angola
USAF	United States Air Force

Appendix A

List of Nations with MANPADS

The following is a list of nations with man-portable air defense systems (MANPADS) as depicted on Figure Two. This is not in any way an indication of the current MANPADS threat level, as determined by Air Mobility Command. It is a list of countries that historically have had actors that have demonstrated capability and intent to target aircraft with MANPADS[1]

Afghanistan
Algeria
Angola
Armenia
Belarus
Bosnia-Herzegovina
Brazil
Bulgaria
Cambodia
Chechnya
China
Columbia
Costa Rica
Croatia
Cuba
Czech Republic
Democratic Republic of Congo (Zaire)
Egypt
Ethiopia
Finland
Former Soviet Republic of Georgia
Hungary
India
Indonesia
Iran
Iraq
Israel
Kashmir
Kenya
Kosovo
Lebanon
Mauritania
Mozambique
N. Korea
Northern Ireland
Palestine
Peru
Philippines
Poland
Rwanda
Saudi Arabia
Slovakia
Somalia
Sri Lanka
Sudan
Syria
Tajikistan
Tanzania
Thailand
Turkey
U. A. E.
U.K.
Ukraine
Uzbekistan
Yemen
Yugoslavia

---

[1] Multiple sources. Thomas B. Hunter, “The Proliferation of MANPADS,” *Jane’s Intelligence Review*, September 2001, 42-45; Michal Fiszer and Jerzy Gruszczynski, “On Arrows and Needles,” *Journal Of Electronic Defense*, December 2002, 51-52; British American Security Information Council (BASIC) EU and U.S. Cooperation on Arms Export Controls in a Post 9/11 World: Session 3 Discussion Paper, “Man-Portable Air Defense Systems,” 23 January 2003, n.p. Available from http://www.basicint.org/WT/armsexp/MANPADS.htm.

Notes

[1] John C.K. Daly, “The Threat of Surface-To-Air Missiles,” *The Washington Times*, 28 November 2003, n.p., on-line, Internet, 30 November 2003, available from http://washingtontimes.com/upi-breaking/20031128-040741-3314r.htm. According to Bob Hudson, Headquarters U.S. Air Force, Operational Requirements, video confirms two missiles were fired at DHL, an SA-7 and an SA-14.

[2] The U.S. Air Force will only confirm these aircraft were engaged by “hostile fire” although news reports maintain these strikes were by surface-to-air missiles. Both aircraft were equipped with missile defensive systems. Bob Hudson, Headquarters U.S. Air Force, Operational Requirements, interview by author, 27 January 2004.

[3] David Isenberg, “Missiles with a Sting in the Tail,” *Asia Times*, 16 August 2003, n.p., on-line, Internet, 13 November 2003, available from http://www.atimes.com/atimes/Front_Page/EH16Aa02.html.

[4] Thomas B. Hunter, “The Proliferation of MANPADS,” *Jane’s Intelligence Review*, September 2001, 44.

[5] Paolo Quaranta, “Survivability and Self-protection Systems for Military Airlifters,” *Military Technology* 26, no. 9 (2002), 81.

[6] Joint Publication 3-10, *Joint Doctrine for Rear Area Operations*, 28 May 1996, I-5.

[7] Quaranta, 81.

[8] Michael Puttre, “Facing the Shoulder-Fired Threat,” *The Journal of Electronic Defense* 24, no. 4 (April 2001), 39.

[9] 100 percent of C-17s (105) and 90 percent of C-130s (approximately 500). Sandra I Erwin, “Man-Portable Missiles Imperil Both Military and Civilian Aircraft,” *National Defense* 88, no. 597 *(*August 2003), 28.

[10] Paul J. Caffera “A Proposal to Protect Troops On Civilian Planes,” *San Francisco Chronicle*, 30 September 2003, 7.

[11] Joint Publication 3-17, *Joint Doctrine and Joint Tactics, Techniques, and Procedures for Air Mobility Operations*, 14 Aug 2002, I-3.

[12] Ibid., IV-12.

[13]Headquarters United States Air Force, Transformation Division, *The U.S.AF Transformation Flight Plan FY03-07*, no date, iv.

[14] “Global Mobility Concept of Operations,” Draft Version 3.4, 15 January 2004, 1.

[15] Ibid., 56.

[16] Base assessment is an analysis of the base to identify potential threats and determine if it meets the intended air operations requirements and is suitable for force beddown. Key to this discussion is designing perimeters, identifying force protection asset layout and operational zones, and determining countermeasures.

[17] Lt Col James A. Fellows, LCDR Michael H. Harner, Maj Jennifer L. Pickett, and Maj Michael F. Welch, “Airlift 2025, The First With The Most,” Executive Summary, 17 June 1996, n.p., on-line, Internet, 19 January 2004, available from http://www.au.af.mil/au/2025.html.

[18] Joint Publication 3-10.1, *Joint Tactics, Techniques and procedures for Base Defense*, 23 July 1996, II-1.

[19] Joint Publication 1-02, *Department of Defense Dictionary of Military and Associated Terms*, 12 April 2001, as amended through 17 December 2003, p. 28.

[20] Air Force Doctrine Directive 2-1.1, *Counterair Operations*, 26 April 2002, 2.

[21] Air Force Doctrine Directive 2-4.1, *Force Protection*, 29 October 1999, 3.

[22] “Global Mobility Concept of Operations,” 39.

[23] In Operation ENDURING FREEDOM, the army had a cap on the number of personnel in the country of Afghanistan. Although this particular cap was mandated by the Secretary of Defense, similar caps have been placed on U.S. forces by host nations to minimize U.S. presence, improve host nation political legitimacy, or for security concerns.

[24] “Air Force Contingency Response Group Operational Concept,” Draft Version 4.3, December 2003, 1.

[25] Hunter, 42.

[26] Erwin, “Man-Portable Missiles Imperil Both Military and Civilian Aircraft,” 21.

[27] David A. Kuhn, “Mombassa attack highlights increasing MANPADS threat,” *Jane’s Intelligence Review*, February 2003, 28.

[28] Kuhn, 28.

[29] No specific information was provided concerning this increase in missile capability. This author suspects the details of this event are classified. Hunter, 42.

[30] Ibid., 44.

[31] Kuhn, 30.

Notes

[32] Ibid., 28.

[33] Several authors posit that this airliner did have infrared countermeasure jamming capability, as some of the Israeli airliners have. Although this was not an El Al airliner, some of which are known to have these systems, this particular aircraft may have carried Israeli dignitaries earlier in the week that could have required such systems. Ibid., 28.

[34] Ibid., 29.

[35] Isenberg, n.p.

[36] Bill Sweetman, "The Enemy Down Below," *Air Transport World* 40, no. 9 (September 2003), 34.

[37] See Appendix A for the country list. Multiple sources. Hunter, Thomas B. "The Proliferation of MANPADS," *Jane's Intelligence Review*, September 2001, 42-45; Fiszer, Michal and Jerzy Gruszczynski "On Arrows and Needles," *Journal Of Electronic Defense*, December 2002, 51-52; British American Security Information Council (BASIC) 23 January 2003 EU and U.S. Cooperation on arms export controls in a post 9/11 world: Session 3 Discussion Paper: "Man Portable Air Defense Systems"; 10 January 2004 n.p. on-line at http://www.basicint.org/WT/armsexp/MANPADS.htm.

[38] For a further analysis of casualty-phobia implications, the author suggests Dr Jeffrey Record, *Failed States and Casualty Phobia, Implications for Force Structure and Technology Choices* (Maxwell AFB, Ala.: Air War College, December 2000).

[39] Evidence of this includes the extensive use of land-based transportation of coalition members and cargo from Kuwait instead of direct flights into Iraq. If Air Mobility Command deems the airfield is a high or significant threat requiring use of aircraft defensive systems, then coalition partners without this capability must be accommodated by another transportation mode or reprioritizing U.S. lift assets. This author contends that the MANPADS threat, especially after the DHL airline incident, caused nations to rethink their own organic transportation plans, forcing them to rely on U.S. airlift assets or convoy force protection.

[40] "Global Mobility Concept of Operations," 3.

[41] 100 percent of C-17s (105) and 90 percent of C-130s (approximately 500). Erwin, "Man-Portable Missiles Imperil Both Military and Civilian Aircraft," 28.

[42] Thomas A. Freese, *Force Protection and Strategic Air Mobility: The MANPAD Challenge* (Newport, Rhode Island: Naval War College, 5 February 1999), 6.

[43] "Civil Reserve Air Fleet Stage I Activation Announced," News Release, U.S. Department of Defense, 8 February 2003, online, Internet, 6 October 2003, available from http://www.defenselink.mil/news/Feb2003/b02082003_bt064-03.html.

[44] Freese, 11.

[45] Isenberg, n.p.

[46] Maximum specifications for MANPADS currently on the market. Ibid., n.p..

[47] The seeker detects energy in one of three IR bands; near, mid or far. The strongest aircraft signatures are in the mid IR band, approximately three to five micron wavelength. Dave Adamy, "EO/IR, Part 2-IR-Guided Missiles," *The Journal of Electronic Defense* 24, no. 4 (April 2001), 64.

[48] Puttre, "Facing the Shoulder-Fired Threat," 40.

[49] The AIM-9M warhead is approximately 20.8 pounds. The SA-7 warhead is 2.6 pounds and the Stinger warhead is 6.6 pounds.

[50] Linda Jacobson, "The MANPAD Threat: A Current Assessment," *Flightline*, Fall 2003, 25.

[51] Michal Fiszer and Jerzy Gruszczynski, "On Arrows and Needles," *Journal Of Electronic Defense* 25, no. 12 (December 2002), 49.

[52] Marine Corps Warfighting Publication (MCWP) 3-25.10, *Low Altitude Air Defense Handbook*, 12 June 1998, 2-2.

[53] Bill Taylor, EO/IRCM Tutorial, Sensors Directorate, Air Force Research Laboratory, Wright Patterson AFB, Ohio, 19 May 2001.

[54] James Grove Chem, "Thermal Imagers and Camouflage," n.p., on-line, Internet, 21 January 2004, available from http://www.btinternet.com/~jmcgroves/thrmalim.htm.

[55] Adamy, 64.

[56] Taylor, 7.

[57] Roy Braybrook, "Land-based Vshorad and Shorad Systems," *Armada International* 26, no. 2 (April-May 2002), 48.

Notes

[58] Puttre, “Facing the Shoulder-Fired Threat,” 45.

[59] Rupert Pengelley, and Mark Hewish, “In the Heat of the Night,” *Jane’s International Defense Review* 34 (October 2001), 50.

[60] Nitrogen cooling will be necessary to overcome the inherent thermal noise limitations of these infrared sensors and to increase sensor sensitivity and range. One promising area of materials engineering exploits quantum principles within semiconductor materials. Quantum dots are engineered to manipulate specific wavelengths of light to increase the detector’s sensitivity. This produces infrared sensing systems that perform well at near-room temperatures. “Uncooled Photonic Devices Shine,” *Signal* 57 no. 5 *(*January 2003), 31.

[61] Fiszer and Gruszczynski, 52.

[62] Braybrook, 51.

[63] “Starstreak Close Air Defense Missile, United Kingdom,” n.p., on-line, Internet, 21 January 2004, available from http://www.army-technology.com/projects/starstreak.

[64] Fiszer and Gruszczynski, 50.

[65] Ibid., 52.

[66] “Starstreak Close Air Defense Missile, United Kingdom,” n.p.

[67] Sean Carroll, “Protecting Large Aircraft,” *The Journal of Electronic Defense* 22, no. 9 (September 1999), 46.

[68] Puttre, “Facing the Shoulder-Fired Threat,” 42.

[69] Ibid., 43.

[70] Carroll, 47.

[71] According to the author, a 1,000 times better improvement equates to human processing speed. His presentation describes a one million improvement and a 100 million improvement in processing speeds by 2025. This author chose to use the more conservative one million figure as a basis for this analysis. Dennis M. Bushnell, “Future Strategic Issues/Future Warfare [Circa 2025],” Military Analysis Network, on-line, Internet, 23 February 2004, available from http://www.fas.org/man/eprint/FutureWarfare.ppt.

[72] Puttre, 43.

[73] Ibid., 43.

[74] Ibid., 41.

[75] Ibid., 42.

[76] Carroll, 46.

[77] “Cost, capability gains drive EW advances,” *Interavia* 57, no. 661, March 2002, 38.

[78] Michael Puttre, “LIFE Closes the Loop,” *The Journal of Electronic Defense* 24, no. 7 (July 2001), 25.

[79] “Protecting the Big Boys: Directed IR Countermeasure for Large Aircraft,” *Journal of Electronic Defense* 23, no. 12 (December 2000), 48.

[80] Ibid., 49.

[81] “Cost, capability gains drive EW advances,” 38, and “U.S. Air Force Successfully Completes Live-Fire Tests of Large Aircraft Infrared Countermeasures System,” Northrop Grumman Capitol Source, on-line, Internet, 6 October 2003, available from http://www.capitolsource.net/press_releases/laircm_livefire.html.

[82] “Protecting the Big Boys: Directed IR Countermeasure for Large Aircraft,” 50 and Puttre, “LIFE Closes the Loop,” 24.

[83] Puttre, 24.

[84] John F. Carr, Lt Col Gregory J. Vansuch, Dr Duane A. Warner, and William R. Taylor, “The Future of Combat Aircraft Survivability,” *Aircraft Survivability*, Summer 2003, 29.

[85] Lt Col Gregory Vansuch, Program Manager, Special Programs Office, fact sheet, subject: Multifunction Electro-Optics for Defense of U.S. Aircraft (MEDUSA), 12 August 2002.

[86] Carr, Vansuch, Warner, and Taylor, 30.

[87] Carr, Vansuch, Warner, and Taylor, 28-29.

[88] “Uncooled Photonic Devices Shine,” 31.

[89] Brendan P. Rivers, “By Merit Raised,” *The Journal of Electronic Defense* 24, no. 8 (August 2001), 45.

[90] Elihu Zimet, “High-Energy Lasers: Technical, Operational, and Policy Issues,” *Defense Horizons*, no. 18, October 2002, 1.

[91] Ibid., 4.

[92] Gopal Ratnam, “U.S. Army Moves Ahead on Laser Weapon,” *Defense News*, 10 March 2003, 4.

Notes

[93] "U.S. Army Selects Northrop Grumman Design Concept for Mobile High-Energy Laser Weapon for Tactical Missile Defense," Grumman News Release, 21 August 2003.

[94] Zimet, 6.

[95] Boeing "Advanced Tactical Laser Demonstration Program" pamphlet, no date, on-line, Internet, 28 January 2004, available from http://www.boeing.com/news/feature/wsc2002/press_kit/product_cards/atl_demo_ac130u.pdf.

[96] Don Slater, "The 10-Mile Laser," *Threshold*, Spring 2000, n.p., on-line, Internet 9 December 2003, available from http://www.engineering atboeing.com/articles/10MileLaser.jsp.

[97] "Directed Energy Weapons: Fact or Fiction?" *Military Technology* 27, no. 4 (2003), 81.

[98] L.N. Durvasula, DARPA Tactical Technology Office, Fact Sheet, "Fiber Lasers," 31 July 2002, n.p.

[99] Jim Wilson, "Beyond Bullets," *Popular Science Magazine*, no 4 (2003), n.p., Online, Internet, available at http://www.popularmechanics.com/science/military/2003/4/beyond_bullets/index.phtml.

[100] "Bright Future for Compact Tactical Laser Weapons," *Science and Technology Review*, Lawrence Livermore National Laboratory, October 2002, n.p., online, Internet, 16 November 2003, available from: http://www.llnl.gov.str/October02/October02.html.

[101] Ibid., n.p.

[102] Ratnam, 4.

[103] Sandra Erwin, "Tactical Laser Weapons Still many Years Away," *National Defense* 87, no. 589 (December 2002), 33.

[104] "SiMM is Anything But Simple," *Science and Technology Review*, Lawrence Livermore National Laboratory, October 2002, n.p. online, Internet, available from http://www.llnl.gov.str/October02/October02.html.

[105] Erwin, "Tactical Laser Weapons Still many Years Away," 33.

[106] Single mode fiber lasers with higher output powers are available commercially today, however the beam quality factor is not low enough to achieve desired effects. Michael Hatcher, "Single-Fiber Laser Hits One Kilowatt Output," *Optics.org* News, 6 February 2004, online, Internet, 28 August 2003, available from http://optics.org/articles/news/9/8/23/1.

[107] Andrew Scott, Photonics Business Group, QINETIQ, "Novel Technologies for Future Directed Energy Systems," presentation to the 2004 Directed Energy Weapons Conference, London, England, 20 January 2004.

[108] Durvasula, n.p.

[109] Zimet, 4.

[110] Ira W. Merritt, *Proliferation and Significance of Radio Frequency Weapons Technology*, Joint Economic Committee Hearing, 25 February 1998, 3.

[111] Colonel Eileen M. Walling, *High Power Microwaves: Strategic and Operational Implications for Warfare*, (Maxwell AFB AL: Air University, February 2000), 9.

[112] Lieutenant Colonel John A. Brunderman, "High Power Radio Frequency Weapons: A Potential Counter to U.S. Stealth and Cruise Missile Technology," Air War College Paper (Maxwell AFB AL, 1999), 16.

[113] Air Mobility Command has identified enhanced situational awareness as a future mobility aircraft requirement. In the same vein that MANPADS are more effective with an integrated cuing system, enhanced situational awareness brings real time mission and threat data into the cockpit allowing pilots and other decision makers to react in an evolving, dynamic environment. The purpose is to integrate on-board sensors with off-board datalink information under near-real time conditions for display in a two-pilot cockpit. The system will be capable of fusing sensor information in all bands. Datalink will allow the aircraft to transmit collected threat information to other aircraft and command and control. High confidence-level intelligence will allow pilots and command and control to make accurate real-time decisions on airlift and air refueling flow, ensuring logistics gets to the user.

[114] Ken Heran, Air Mobility Command Combat Tactics, interviewed by author and provided Air Mobility Command shell Electronic Warfare Vision slides, 4 November 2003.

[115] Boeing, "Advanced Tactical Laser Demonstration Program," pamphlet, n.p.

[116] Ken Heran, Air Mobility Command Electronic Warfare Roadmap Briefing, 14 December 2003.

[117] There are approximately 990 aircraft in Air Mobility Command's inventory, including special mission aircraft, which carry important personnel needing defensive capability. As the KC-135s convert to KC-767s, and the C-130s are right-sized, the inventory will decrease. Geographic commander special mission aircraft are not included. However, U.S.-based special mission aircraft may not need to be modified and approximate the number of theater assets that would require the system.

[118] Isenberg, n.p.

Notes

[119] "Civil Reserve Air Fleet Stage I activates for only second time in history," *Airman*, April 2003 Web Edition, on-line, Internet, 6 October 2003, available from http://www.af.mil/news/airman/0403/world7.html.

[120] Laser jamming from the ground is a higher technical risk option due to high power levels required to jam the missile off-axis instead of inside the narrow missile field of view, which is the vantage point if the jammer were located on the aircraft. Therefore, the ground systems are based on a high-energy laser that imparts thermal energy onto the missile to disrupt or destroy it.

[121] Grumman artist conception of the Mobile Tactical High Energy Laser system, on-line, Internet, 26 January 2004, available from http://www.northropgrumman.com/missiledefense/galleries/MTHEL.html?PageID=5491&SiteSectionID=0.

[122] "HORNET Commercial and Military Aircraft Defense System," Northrop Grumman Space Technology, 14 November 2003, on-line, Internet, 29 January 2004, available from http://www.northropgrumman.com/missiledefense/ProgramInfo/HORNET.html.

[123] Shaun Waterman, "3 Firms Tapped for Anti-Missile Project," *The Washington Times*, 6 January 2004, n.p., on-line, Internet, 29 January 2004, available from http://washingtontimes.com/upi-breaking/20040106-064321-5282r.htm.

[124] Puttre, "Facing the Shoulder-Fired Threat," 43.

[125] Barbara Honegger, "Navy, Air Force develop laser-retargeting technology," *Air Force Link*, 20 June 2002, n.p., on-line, Internet, 9 December 2003, available from http://www.af.mil/news/Jun2002/n20020620_0996.shtml.

[126] Michael Sirak, "DoD eyes laser relay mirror trial on airship," *Jane's Defense Weekly* 40, no. 4 (30 July 2003), 9.

[127] TCOM Product Line information sheet for the 32M Mid-Sized Aerostat and 71M Premier Aerostat, 6 February 2004, n.p., on-line, Internet, no date, available from http://www.tcomlp.com/products.htm.

[128] Manufacturer best claims are 75 percent for the Russian Igla S and 90 percent for the U.S. Stinger MANPADS.

Notes

Bibliography

Books

Geis, Lt. Col. John P. II. *Directed Energy Weapons on the Battlefield. A New Vision for 2025.* Maxwell AFB, Ala.: Air War College, April 2003.

McCarthy, Captain William J. USN. *Directed Energy and Fleet Defense: Implications for Naval Warfare*. Maxwell AFB, Ala.: Air War College, February 2000.

Shlapak, David A. and Alan Vick. *Check Six Begins on the Ground: Responding to the Evolving Ground Threat to U.S. Air Force Bases***.** Santa Monica, Calif.: RAND, January 1995.

Walling, Col. Eileen M. *High Power Microwaves: Strategic and Operational Implications for Warfare*. Maxwell AFB, Ala.: Air War College, February 2000.

Periodicals

Adamy, Dave. "EO/IR, Part 2- IR Guided Missiles." *The Journal of Electronic Defense* 24, no. 4 (April 2001): 64-65.

Braybrook, Roy. "Land-based Vshorad and Shorad Systems." *Armada International* 26, no. 2 (April/May 2002): 37-53.

Caffera, Paul J. "The Vexing Problem of Protecting Airliners from MANPADS." *Aircraft Survivability*, Spring 2003, 13-16.

Carr, John F., Lt Col Gregory J. Vansuch, Dr Duane A. Warner, and William R. Taylor. "The Future of Combat Aircraft Survivability." *Aircraft Survivability,* Summer 2003, 28-32.

Carroll, Sean. "Protecting Large Aircraft." *Journal of Electronic Defense 2*2, no. 9 (September 1999): 45-50.

"Cost, Capability Gains Drive EW Advances." *Interavia* 57, no. 661 (March 2002): 37- 38.

Czarnecki, Greg. "Improving Aircraft Survivability." *Aircraft Survivability*, Spring 2003, 32-33.

Daniel, Donald C. "The Air Force: Science, Technology, and Transformation." Defense Horisons 27 (May 2003): 1-6.

Erwin, Sandra I. "Future Anti-Missile Research Directed to Countermeasures." *National Defense* 86, no. 574 (September 2001): 16-17.

Erwin, Sandra I. "Man-Portable Missiles Imperil Both Military and Civilian Aircraft," *National Defense 88*, no. 597 (August 2003): 28-29.

Erwin, Sandra I. "Tactical Laser Weapons Still Many Years Away," *National Defense* 87, no. 589 (December 2002): 32-33.

"Europe Closing the Gap." *Interavia*, November/December 2002, 33-35.

Fiszer, Michal and Jerzy Gruszczynski. "On Arrows and Needles, Russia's Strela and Igla Portable Killers." *The Journal of Electronic Defense* 25, no. 12 (December 2002): 46-52.

Froh, Richard. "Man-Portable Air Defence Systems (MANPADS) – What Future?" *Military Technology* 25, no. 7 (2001): 40-46.

Goodman, Glenn W. Jr. "Infrared Countermeasures." *Armed Forces Journal International* 139, no. 12 (July 2002): 66-67.

Hewish, Mark. "Vital in Combat." *Jane's International Defense Review*, February 2001, 49-56.

Hunter, Thomas B. "The Proliferation of MANPADS." *Jane's Intelligence Review*, September 2001, 42-45.

Notes

Jacobson, Linda. “The MANPAD Threat: A Current Assessment.” *Flightline.* Fall 2003, 25-28.

Jolley, Joseph P. “ MANPADS Study: A Brief Synopsis.” *Aircraft Survivability,* Spring 2000, 30-32.

Keirstead, Burt and Jay Herther. “Aircraft Survivability in the 21st Century-ATIRCM.” *The Journal of Electronic Defense* 15, no. 5 (May 1992): 55-56.

Kuhn, David A. “Mombasa Attack Highlights Increasing MANPADS Threat.” *Jane’s Intelligence Review*, February 2003, 26-30.

“Life Closes the Loop.” *The Journal of Electronic Defense* 24, no. 7 (July 2001): 24-25.

Owen, Lt Col Robert C. “The Airlift System, a Primer.” *Airpower Journal.* Fall 1995: 1-12.

Pengelley, Rupert and Mark Hewish. “In the Heat of the Night.” *Jane’s International Defense Review,* October 2001, 49-50.

“Protecting the Big Boys: Directed IR Countermeasures for Large Aircraft.” *Journal of Electronic Defense* 23, no. 12 (December 2000): 47-50.

Puttre, Michael. “Facing the Shoulder-Fired Threat.” *The Journal of Electronic Defense* 24*,* no. 4 (April 2001): 38-45.

Puttre, Michael. “LIFE Closes the Loop.” *The Journal of Electronic Defense* 24, no. 7 *(*July 2001): 24-25.

Puttre, Michael. “Patterns of Protection.” *The Journal of Electronic Defense* 24, no. 8 (August 2001): 48-52.

Quaranta, Paolo. “Survivability and Self-Protection Systems for Military Airlifters.” *Military Technology* 26, no. 9 (2002): 80-84.

Rivers, Brendan P. “By Merit Raised.” *The Journal of Electronic Defense* 24, no. 8 (August 2001): 42-46.

Rivers, Brendan P. “Protecting the Sky Trains.” *The Journal of Electronic Defense* 26, no. 6 (June 2003): 55-59.

Sherman, Kenneth B. “Countermeasures: Have They Moved Out For Good?” *The Journal of Electronic Defense* 23, no. 8 (August 2000): 41-45.

Sherman, Kenneth B. “Seeing (Infra) Red.” *The Journal of Electronic Defense* 24, no. 8 (August 2001): 54-55.

Sherman, Kenneth B. “What’s New in EO/IR Countermeasures.” *The Journal of Electronic Defense* 24, no. 11 (November 2001): 49-51.

Sirak, Michael. “DoD eyes laser relay mirror trial on airship.” *Jane’s Defense Weekly* 40, no. 4 (30 July 2003): 9.

Sweetman, Bill. “The Enemy Down Below.*”* *Air Transport World* 40, no. 9 (September 2003): 34-36.

Taylor, Bill. “Pre-Emptive Vs. Reactive Infrared Countermeasures.” *The Journal of Electronic Defense* 23, no. 3 (March 2000): 33-37.

“Uncooled Photonic Devices Shine.” *Signal* 57, no. 5 (January 2003): 31-37.

Wollmann, Gerd. “Directed Energy Weapons: Fact or Fiction?” *Military Technology* 27, no. 4, (2003): 80-85.

Zimet, Elihu. “High-Energy Lasers: Technical, Operational, and Policy Issues.” *Defense Horizons* 18 (October 2002):1-8.

Notes

Reports

Freese, Thomas A. *Force Protection and Strategic Air Mobility: The MANPAD Challenge*. Newport, RI: Naval War College, 1999.

Hanley, Major James N. *Force Protection of Strategic Airlift Forces in the Operations Other Than War Environment.* Fort Leavenworth, Kansas: Command and General Staff College, 14 December 1995.

Lester, Col (Sel) Rick W., Jacobsmeyer, CDR Steven M. (USN), Miller, Lt Col Michael M., Bigham, Maj Jim C. Jr., Tanous, Maj Stephen M. "*Counterair: The Cutting Edge.*" Research Report for *Air Force 2025.* Maxwell AFB, Ala.: August 1996.

Unpublished Papers

Brunderman, Lieutenant Colonel John A. "High Power Radio Frequency Weapons: A Potential Counter to U.S. Stealth and Cruise Missile Technology." Maxwell AFB, Ala.: Air War College, 1999.

Manuals, Instructions, Directives, and Other Publications

"Air Force Contingency Response Group Operational Concept," Draft Version 4.3, December 2003.

Air Force Doctrine Directive 2-1.1, *Counterair Operations*, 26 April 2002.

Air Force Doctrine Directive (AFDD) 2-4.1, *Force Protection*, 29 October 1999.

Boeing Advanced Tactical Laser Concept Demonstration Pamphlet. 6 February 2003.

Durvasula, L.N. DARPA Tactical Technology Office. Fact Sheet. Subject: Fiber Lasers. 31 July 2002.

"Global Mobility Concept of Operations," Draft Version 3.4, 15 January 2004.

Headquarters United States Air Force, Transformation Division, *The USAF Transformation Flight Plan FY03-07*, no date.

Joint Publication (JP) 1-02, *Department of Defense Dictionary of Military and Associated Terms*, 12 April 2001, as amended through 17 December 2003**.**

Joint Publication (JP) 3-10. *Joint Doctrine for Rear Area Operations.* 28 May 1996.

Joint Publication (JP) 3-10.1. *Joint Tactics, Techniques and procedures for Base Defense*. 23 July 1996.

Joint Publication (JP) 3-17. *Joint Doctrine and Joint Tactics, Techniques, and Procedures for Air Mobility Operations.* 14 Aug 2002.

Marine Corps Warfighting Publication (MCWP) 3-25.10. *Low Altitude Air Defense Handbook.* 12 June 1998.

Vansuch, Lt Col Gregory. Program Manager, Special Programs Office. Fact Sheet. Subject: Multifunction Electro-Optics for Defense of U.S. Aircraft (MEDUSA). 12 August 2002.

Computer Network

Bayles, Fred. "Guarding Against Missiles." *USA Today*. 13 April 2003. On-line. Internet, 4 October 2003. Available from http://www.usatoday.com/money/biztravel/2003-04-13-antimissile_x.htm.

Boeing "Advanced Tactical Laser Demonstration Program" Pamphlet. No date. On-line. Internet, 28 January 2004. Available from

Notes

http://www.boeing.com/news/feature/wsc2002/press_kit/product_cards/atl_demo_ac130u.pdf.

"Bright Future for Compact Tactical Laser Weapons." *Science and Technology Review*. Lawrence Livermore National Laboratory. October 2002. On-line. Internet, 16 November 2003. Available from: http://www.llnl.gov.str/October02/October02.html.

Bushnell, Dennis M. "Future Strategic Issues/Future Warfare [Circa 2025]." Military Analysis Network. On-line. Internet, 23 February 2004. Available from http://www.fas.org/man/eprint/FutureWarfare.ppt.

Chem, Dr. James Grove. "Thermal Imagers and Camouflage." On-line. Internet, 21 January 2004. Available from http://www.btinternet.com/~jmcgroves/thrmalim.htm.

"Civil Reserve Air Fleet Stage I Activation Announced." News Release, U.S. Department of Defense, 8 February 2003. Online. Internet, 6 October 2003. Available from http://www.defenselink.mil/news/Feb2003/b02082003_bt064-03.html.

Daly, John C.K. "The Threat of Surface-To-Air Missiles." *The Washington Times.* 28 November 2003. On-line. Internet, 30 November 2003. Available from http://washingtontimes.com/upi-breaking/20031128-040741-3314r.htm.

DARPA, 2002 Projects Summary: High Power Fiber Lasers. 24 October 2003. On-line. Internet, 21 January 2004. Available from http://www.darpa.mil/tto/programs/hpfl.html.

"Directional Infrared Countermeasures System (DIRCM) Fact Sheet." Northrop Grumman Corporation. On-line. Internet, 6 October 2003. Available from http://www.northropgrumman.com/tech_cd/es/es_dircm_fact.html.

Fellows, Lt Col James A, LCDR Michael H. Harner, Maj Jennifer L. Pickett, and Maj Michael F. Welch. "Airlift 2025, The First With The Most." 17 June 1996, n.p., On-line. Internet, 19 January 2004. Available from http://www.au.af.mil/au/2025.html.

Hatcher, Michael. "Single-Fiber Laser Hits One Kilowatt Output." *Optics.org* News. 6 February 2004. On-line. Internet, 28 August 2003. Available from http://optics.org/articles/news/9/8/23/1.

Honegger, Barbara. "Navy, Air Force develop laser-retargeting technology." *Air Force Link.* 20 June 2002. On-line. Internet, 9 December 2003. Available from http://www.af.mil/news/Jun2002/n20020620_0996.shtml.

"HORNET Commercial and Military Aircraft Defense System." Northrup Grumman Space Technology. 14 November 2003. On-line. Internet, 29 January 2004. Available from http://www.northropgrumman.com/missiledefense/ProgramInfo/HORNET.html.

"Infrared Countermeasures Systems." Global Security.Org. On-line. Internet, 6 October 2003. Available from http://www.globalsecurity.org/military/systems/aircraft/systems/ircm.htm.

Isenberg, David. "Missiles with a Sting in the Tail." *Asia Times*. 16 August 2003, On-line. Internet, 13 November 2003. Available from http://www.atimes.com/atimes/Front_Page/EH16Aa02.html.

Killingsworth, Paul S. "Flexbasing: Achieving Global Presence for Expeditionary Aerospace Forces." On-line. Internet, 6 October 2003. Available from http://www.rand.org/publications/MR/MR1113.

"Large Aircraft Infrared Countermeasures (LAIRCM)", Military Analysis Network. On-line. Internet, 6 October 2003. Available from http://www.fas.org/man/dod-101/sys/ac/equip/laircm.htm.

“Large Aircraft Infrared Countermeasures (LAIRCM)” Northrop Grumman Capitol Source. On-line. Internet, 6 October 2003. Available from http://www.capitolsource.net/programs/laircm.html.

“Man Portable Air Defense System (MANPADS).” Global Security.Org, On-line. Internet, 6 October 2003. Available from http://www.globalsecurity.org/military/intro/manpads.htm.

Northrup Grumman Mobile Tactical High Energy Laser System, Photo Gallery. On-line. Internet, 26 January 2004. Available from http://www.northropgrumman.com/missiledefense/galleries/MTHEL.html?PageID=5491&SiteSectionID=0.

“Prepared Testimony of Dr. Robert DelBoca Before the House Transportation and Infrastucture Committee Aviation Subcommittee, March 20, 2003.” *Northrop Grumman Capitol Source*. On-line. Internet, 6 October 2003. Available from http://www.capitolsource.net/homeland/delboca_testimony.html

“SiMM is Anything But Simple.” *Science and Technology Review*. Lawrence Livermore National Laboratory, October 2002. n.p. Online. Internet. Available from http://www.llnl.gov.str/October02/October02.html.

Slater, Don. “The 10-Mile Laser.” Threshold, Spring 2000. On-line. Internet, 9 December 2003. Available from http://www.engineering atboeing.com/articles/10MileLaser.jsp.

“Starstreak Close Air Defense Missile, United Kingdom.” On-line. Internet, 21 January 2004. Available from http://www.army-technology.com/projects/starstreak.

TCOM Product Line information sheet for the 32M Mid-Sized Aerostat and 71M Premier Aerostat. On-line. Internet, no date. Available from http://www.tcomlp.com/products.htm.

“U.S. Air Force Successfully Completes Live-Fire Tests of Large Aircraft Infrared Countermeasures System.” Northrop Grumman Capitol Source. On-line. Internet, 6 October 2003. Available from http://www.capitolsource.net/press_releases/laircm_livefire.html.

“Viper Mid-Infrared Laser”, Air Force Research Laboratory. On-line. Internet, 6 October 2003. Available from http://www.afrlhorizons.com/Briefs/Sept03/ML0305.html

Waterman, Shaun. “3 Firms Tapped for Anti-Missile Project.” *The Washington Times.* 6 January 2004. On-line. Internet, 29 January 2004. Available from http://washingtontimes.com/upi-breaking/20040106-064321-5282r.htm.

Wilson, Jim “Beyond Bullets,” *Popular Science Magazine*, 2003, no 4, n.p., online, Internet, available at http://www.popularmechanics.com/science/military/2003/4/beyond_bullets/index.phtml.

Lectures and Addresses

Durvasula, Dr L.N. Tactical Technology Office, Defense Advanced Research Projects Agency. Lecture. Defense Advanced Research Projects Agency 2002 Symposium, Anaheim, California, 31 July 2002.

Heran, Ken. Air Mobility Command Electronic Warfare Roadmap Briefing, 14 December 2003.

Scott, Andrew. Photonics Business Group, QINETIQ. “Novel Technologies for Future Directed Energy Systems.” Presentation to the 2004 Directed Energy Weapons Conference. London, England. 20 January 2004.

Taylor, Bill. Infrared Countermeasures Tutorial. (FOUO) Information extracted is unclassified.

Thompson, Loren B. “MANPADS: Scale & Nature of the Threat.” Briefing. 12 November 2003.

Notes

“U.S. Army Selects Northrop Grumman Design Concept for Mobile High-Energy Laser Weapon for Tactical Missile Defense.” Northrup Grumman News Release, 21 August 2003.

Public Documents

Merritt, Ira W. *Proliferation and Significance of Radio Frequency Weapons Technology*. Joint Economic Committee Hearing. 25 February 1998.

Newspapers

San Francisco Chronicle, 30 September 2003.
Defense News, 10 March 2003.