Securing Passenger Aircraft from the Threat of Man-Portable Air Defense Systems (MANPADS)

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Securing Passenger Aircraft from the Threat of Man-Portable Air Defense Systems (MANPADS)

Uche Okpara1* and Vicki M. Bier1

In this article, we develop a model for the expected maximum hit probability of an attack on a commercial aircraft using MANPADS, as a function of the (random) location of the attacker. We also explore the sensitivity of the expected maximum hit probability to the parameters of the model, including both attacker parameters (such as weapon characteristics) and defender parameters (such as the size of the secure region around the airport). We conclude that having a large secure region around an airport offers some protection against MANPADS, and that installing onboard countermeasures reduces the success probability of a MANPADS attack.

KEY WORDS: Attacker location strategy; conditional hit probability; MANPADS; onboard countermeasures; sensitivity analysis

1. INTRODUCTION

Since late 2001, after the terrorist attacks in New York City and Washington, D.C., (1) there has been considerable focus on man-portable air defense systems (MANPADS). After the September 11 attacks, the commercial aviation industry in the United States was effectively crippled for a period of time. On November 28, 2002, an Arkia Boeing 757-300 with 271 passengers and crew was narrowly missed by two SA-7 missiles after it took off from Moi International Airport in Mombasa, Kenya. (2) Also, on November 22, 2003, a DHL Airbus A300 cargo plane with three crew members was hit by a MANPADS missile shortly after it took off from Baghdad International Airport in Iraq; the crew managed to land the aircraft safely in Baghdad. (3) Furthermore, in 2003, the U.S. Department of State estimated that “since the 1970s, over 40 civilian aircraft have been hit by MANPADS, causing about 25 crashes and over 600 deaths around the world.” (2) A successful MANPADS attack on a passenger aircraft would undoubtedly send shock waves through the aviation industry.

In this article, we investigate the factors affecting the probability that an airplane landing or taking off from an airport could be hit by a MANPADS located somewhere near the airport. Section 2 gives an overview of MANPADS and countermeasures, and also discusses some assumptions and choices we made. In Section 3, we model the region of interest around the airport and the aircraft trajectory. We model some characteristics of MANPADS in Section 4. We do not explicitly model the trajectory of the missile fired from the MANPADS, but focus instead on the conditional probability of the missile hitting its target, given the position of the launcher relative to the target. Section 5 postulates some possible strategies available to an attacker in choosing a location from which to fire a MANPADS, represented by probability distributions. The details of our simulation are discussed in Section 6, and the results are discussed in Section 7. We present our observations and conclusions in Section 8; in particular, putting onboard countermeasures in context with...
other protective measures such as perimeter security and preplanned evasive flight maneuvers.

2. MANPADS AND COUNTERMEASURES: OVERVIEW AND ASSUMPTIONS

This section is intended to provide the reader with a summary knowledge of MANPADS and countermeasures, and to clarify some of the assumptions made in this article.

2.1. MANPADS

MANPADS are shoulder-launched surface-to-air missiles (SAMs). A MANPADS usually consists of a launcher and a missile. The missile is made up of three sections:\(^{(4-6)}\)

1. Guidance section: A seeker unit, guidance unit, control unit, missile battery, and control surfaces to provide “in-flight maneuverability.”
2. Warhead section: Explosives (payload); fusing and firing system. The warhead can be detonated by target impact, target penetration, target proximity, or self-destruction (at a set time after launch).
3. Propulsion section: Launch motor; and flight motor. The missile is ejected from the launcher by the launch motor. After the missile has traveled some (safe) distance from the operator, the flight motor takes over and accelerates the missile toward the target.

MANPADS are typically named by their manufacturers; however, those weapons manufactured in countries of the former Soviet Union have also been given reporting names by the North Atlantic Treaty Organization (NATO) and the United States. Where applicable, each MANPADS will be identified by all three names: manufacturing country designation/NATO designation/U.S. designation. An example is the Russian-made 9K32 Strela-2/“Grail” Mod 0/SA-7A and 9K32M Strela-2M/“Grail” Mod 1/SA-7B; and the U.S.-made FIM-43 Redeye.

2.1.1. Infrared

The vast majority of MANPADS in circulation today are IR MANPADS. IR missiles are fitted with guidance systems designed to track sources of IR emission (e.g., the exhaust of an aircraft engine), and then detonate their warheads on impact or near the source of heat. Since these missiles emit no signal, their guidance systems are sometimes described as “passive IR.” Also, these missiles are sometimes referred to as fire-and-forget because the operator is not involved in tracking the target after the missile has been launched.

a. First generation. These MANPADS came into service in the 1960s and 1970s. They are also referred to as “tail-chase weapons” because they are more effective when used against a receding aircraft—the aircraft’s engine provides IR radiation for the missile’s seeker to use in tracking the aircraft. Due to their almost complete dependence on IR radiation, first-generation IR missiles are less capable of managing background interference (i.e., IR radiation from other sources like the sun) than later generations of IR missiles. As a consequence, some aircraft countermeasures (e.g., decoy flares) are more effective against first-generation IR missiles. Some examples of these weapons are: the Russian-made 9K32 Strela-2/“Grail” Mod 0/SA-7A and 9K32M Strela-2M/“Grail” Mod 1/SA-7B; and the U.S.-made FIM-43 Redeye.

b. Second generation. These MANPADS came into service in the 1970s and early 1980s. One reason that first-generation IR MANPADS are more susceptible to background IR sources is because of heating in the seeker head. This problem is mitigated in second-generation IR MANPADS by the use of coolants (like nitrogen) to cool the seeker head.\(^{(9)}\) This “enables the seeker to filter out most interfering background IR sources as well as permitting head-on and side engagement profiles.”\(^{(7)}\) This means that their capability goes beyond “tail-chasing”; i.e., they can engage an aircraft from any direction (although their capacity to do this is less than that of third-generation IR missiles). Also, some of these missiles are fitted with early (limited) versions of ultraviolet (UV) detectors. Some examples are: the
Russian-made 9K34 Strela-3/"Gremlin"/SA-14; and the U.S.-made XFIM-92A.

**c. Third generation.** These MANPADS came into service in the 1980s and 1990s. They have more sophisticated measures for defeating IR decoys. Their seeker units can typically detect both IR and UV radiation; hence, they are referred to as “two-color” seekers. Also, third-generation missiles can engage a target from any direction (tail-chase, head-on, side-on, and from above or below); hence, they are also referred to as “all-aspect” missiles. Some examples are: the Russian-made 9K38 Igla/"Grouse"/SA-18 and 9K310 Igla-1/"Gimlet"/SA-16; the French-made Mistral; and the U.S.-made FIM-92A,B,C,D,E Stinger.

### 2.1.2. Command to Line of Sight

The CLOS guidance system typically requires the operator to guide the missile to its target. In addition to the missile unit, CLOS systems come with a separate **aiming** unit. The aiming unit consists of two subsystems: a guidance subsystem; and a transmitter subsystem. The technology made available for the operator to use in guiding the missile to its target determines the type of CLOS system.

**a. Manual Command to Line of Sight (MCLOS).** With MCLOS systems, the operator simultaneously tracks both the missile and the target. Here, the guidance subsystem is a small joystick and the transmitter subsystem is a radio transmitter. The joystick is used to steer the missile to the target; the digital instructions from the joystick are delivered to the missile via the radio transmitter. One disadvantage of MCLOS systems is that the radio link between the transmitter and the missile is susceptible to jamming. A wire link is possible, but would be limited by both the length of the wire and possibility of obstacles along the path of the missile. Another disadvantage of MCLOS systems is the considerable training required to master simultaneous tracking of both the missile and its target. An example of an MCLOS MANPADS is the British-made Blowpipe.

**b. Semi-Automatic Command to Line of Sight (SACLOS).** Here, the operator manually tracks only the target, and the guidance subsystem includes a sighting device (e.g., a TV camera), while the transmitter subsystem is still a radio transmitter. The operator directs the sighting device toward the target while the missile is in flight. The missile’s trajectory is continually updated by guidance commands transmitted from the sighting device via radio link. The SACLOS system is easier to use, and has therefore largely replaced the MCLOS system. An example of a SACLOS MANPADS is the British-made Javelin.

### 2.1.3. Laser Beam Riders (LBR)

LBR systems are similar to CLOS systems in that both come with an aiming unit, and both need the operator to track the target. However, in LBR systems, the operator directs a narrow radar or laser beam at the target; the missile aligns itself within the beam and guides itself to the target. This process is called “beam riding.” LBR systems are not susceptible to radio jamming because there is no radio link from the operator to the missile. Examples of LBR systems are: the British-made Starburst and Starstreak; and the Swedish-made RBS-70.

### 2.1.4. Characteristics

The physical properties of a MANPADS directly affect the performance of the missile. Some of these properties include: maximum effective range, or slant range, or maximum guaranteed firing range (in meters); maximum effective (target) altitude; minimum effective range, or minimum firing range; and minimum effective (target) altitude. Others are: average missile speed (in meters per seconds); missile self-destruct time (in seconds); target tracking rate (in angular degrees/second); total weight (in kilograms); reaction time (in seconds); temperature range of operation (in degrees Celsius); length of launcher (in meters); missile diameter (in millimeters); etc. Not all of the above-mentioned characteristics were considered in this work. The storage condition and age of a missile can also affect its performance, but were not taken into consideration.

### 2.2. Countermeasures

Countermeasures are methods and systems used to counter the effective use of guided missiles, including MANPADS. There are several types of countermeasures.
Table I. Characteristics of Select MANPADS (U.S. Designation Only)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>SA-7B</th>
<th>SA-14</th>
<th>SA-16</th>
<th>SA-18</th>
<th>FIM-92A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum effective range (meters)</td>
<td>800</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>Maximum effective range (meters)</td>
<td>4,200</td>
<td>4,500</td>
<td>5,200</td>
<td>5,200</td>
<td>&gt;4,000</td>
</tr>
<tr>
<td>Minimum effective altitude (meters)</td>
<td>30</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Maximum effective altitude (meters)</td>
<td>2,300</td>
<td>3,000</td>
<td>3,500</td>
<td>3,500</td>
<td>3,500</td>
</tr>
<tr>
<td>Flight speed, average (meters/seconds)</td>
<td>430</td>
<td>470</td>
<td>570</td>
<td>570</td>
<td>700†</td>
</tr>
</tbody>
</table>

This table was created using data from Reference 5. †Data obtained from Reference 9.

2.2.1. Heat Decoys

These are deployed against IR missiles because IR missiles rely on heat signatures to track their targets. A target aircraft discharges objects that produce extremely bright light or intense heat (but with no explosion). This potentially generates fictitious targets, making it difficult for a missile to track the actual target. Examples includes IR chaff and flares.

2.2.2. Electronic Countermeasures

This generally involves any electronic device designed to fool guided missiles. Infrared countermeasures (IRCMs) are designed specifically to counter IR missiles by using a strong source of modulated infrared energy (much stronger than the infrared energy from the target aircraft) that renders the seeker unit of the missile ineffective. Directional infrared countermeasures (DIRCMs) have the added feature of being able to direct the modulated energy to the approaching missile. Large aircraft infrared countermeasures (LAIRCMs) are IRCMs designed to protect large aircraft from MANPADS. Examples of IRCMs are ALO-144 and ALO-24. A combination of heat decoys and electronic countermeasures is also common.

2.2.3. Other Countermeasures

Heat decoys and electronic countermeasures are sometimes referred to as onboard countermeasures (since they are typically installed onboard an aircraft). Other countermeasures may include increased security in and around the airport, and evasive flight maneuvers. These countermeasures are in principle effective against all MANPADS, including CLOS and LBR systems. However, they are not always easy to implement. For example, implementing steep ascent during aircraft takeoff may be uncomfortable for passengers. Also, ensuring that the entire region around an airport is adequately secured may be a very expensive task.

2.3. Assumptions

Although there are various possible attack scenarios using MANPADS, we focus on the single-attacker, single-target, single-shot scenario. This provides a base scenario that can be further expanded in future work. The 9K32M Strela-2M/"Grail" Mod 1/SA-7B was used as our base MANPADS. First, it is the most widely deployed of all MANPADS (in at least 71 countries(5)). Second, it is a fire-and-forget missile, which means that much less training is required (compared to CLOS and LBR systems) to be proficient in its operation. Third, it is the most cloned/reverse-engineered of all MANPADS; sophisticated variants have been cloned in China, Pakistan, and Egypt.(5,10) The results in this work are not restricted to the SA-7B. In our sensitivity analysis, key parameters were varied beyond the range of most MANPADS (compare Tables I and II); for example, the maximum range was varied from 1 meter to 8,400 meters. Thus, the choice of a different MANPADS would affect only the base case, not the sensitivity analyses. However, not all missile characteristics were quantified in this study (e.g., age, storage, and maintenance of the missile; sophistication of the missile’s seeker unit; etc.), and the operator of the MANPADS was assumed to be proficient.

3. REGION OF INTEREST AND AIRCRAFT TRAJECTORY

Fig. 1 shows the basis of our model. In particular, we consider a circular region $I$ with an airport at the center, $c$, and an aircraft $A$ with a straight flight trajectory, $c - w$. We are interested in the probability that a missile fired from a MANPADS $M$ positioned at a particular location in the region $I$ would hit the aircraft $A$ at some point along its trajectory $c - w$. $I$ is the overall region of interest (with radius $r_I$), in the sense that an attacker located outside the region $I$ would have a negligible probability of hitting an aircraft taking off from or landing at point $c$. There is a secure region $S$ of radius $r_S$ at the center...
of the region of interest; we assume that the probability of an attacker being inside the secure region $S$ is negligible, although this assumption could easily be altered if desired.

Actual take-off and landing trajectories of aircraft can be quite complex, and depend on factors such as aircraft design (for example, wing area, engine size, etc.), length of runway, quantity of fuel, size of payload, and aviation regulations. For reasons of parsimony, we adopt a simple parametric model based on the Weibull cumulative distribution function. The Weibull function is a convenient choice because of the flexibility provided by the shape and scale parameters. In particular, we model the altitude $h_A$ of an aircraft $A$ at a horizontal distance $r_A$ from its take-off point by:

$$h_A(r_A) = C_A(1 - \exp\{-(r_A/k_A)^\gamma_A\}),$$  \hspace{1cm} (1)

where $C_A$ is the cruising altitude of the aircraft $A$, and $\gamma_A$ and $k_A$ are the shape and scale parameters of the aircraft’s trajectory, respectively. For constant values of $k_A$ and $C_A$, greater values of the shape parameter $\gamma_A$ correspond to steeper trajectories. Fig. 2a illustrates this for three different values of $\gamma_A$. Similarly, $k_A$ represents the distance from the take-off or landing point at which the aircraft would be at approximately 63% of its cruising altitude $C_A$. Thus, for constant values of $\gamma_A$ and $C_A$, greater values of $k_A$ correspond to less steep trajectories. Fig. 2b illustrates this for three different values of $k_A$. In our model, the landing trajectory is assumed to follow the same functional form as the take-off trajectory, except for the obvious difference in direction (and, possibly, different parameter values).

4. MANPADS CHARACTERISTICS

4.1. Parameters of MANPADS

MANPADS can be characterized by several parameters. We use $R_{\text{max}}$ to denote the maximum effective range; i.e., the maximum range beyond which the MANPADS is no longer highly effective against its intended target. Several factors determine this range, including the rate of consumption of the missile propellant, and the target acquisition system of
the MANPADS. The SA-7B, for example, has a maximum effective range of 4,200 meters (see Table I).

$R_{min}$ is the minimum range below which the MANPADS is not highly effective against its target. Factors that determine this distance include the type of guidance system and the minimum safe distance for missile detonation. The SA-7B has a minimum range of 800 meters. Note that to protect the user, MANPADS are made so that the warhead will not detonate within a certain distance from the launching point. $H_{max}$ is the maximum altitude (vertical distance) beyond which the MANPADS is no longer highly effective in hitting its intended target. Above $H_{max}$, the propulsion system of the missile begins to succumb significantly to the earth’s gravitational pull, which degrades the effectiveness of the missile. The SA-7B has a maximum altitude of 2,300 meters.

$H_{min}$ is the minimum altitude below which the MANPADS is not highly effective in hitting its intended target because the guidance system is more likely to be hampered by terrestrial structures (trees, houses, hills, etc.). The SA-7B has a minimum altitude of 30 meters.

We will refer to the region beyond $R_{min}$ and above $H_{min}$, but within $R_{max}$ and below $H_{max}$, as the hit zone. Thus, a MANPADS is not highly effective against a target outside its hit zone, but can be much more effective against a target well within its hit zone. In Fig. 3, the straight-line distance of 100 meters between $M$ and $A_1$ is less than the value of $R_{min}$ for the SA-7B (800 meters), so the target $A_1$ is outside the hit zone of an SA-7B located at $M$. Conversely, target $A_2$, located 900 meters away from $M$ and at an altitude of 50 meters, is within the hit zone of an SA-7B located at $M$ because the straight-line distance of 900 meters is greater than $R_{min}$ (800 meters) and less than $R_{max}$ (4,200 meters), or in other words within the slant range of the missile, and the altitude of 50 meters is greater than $H_{min}$ (30 meters) and less than $H_{max}$ (2,300 meters).

4.2. The Conditional Hit Probability

We define the conditional hit probability, $P_C$, as the probability of a MANPADS hitting its target in a single shot, given the relative positions of the MANPADS and the target. We assume (conservatively) that every hit will lead to the destruction of the target—or, equivalently, that a hit is a success even if the aircraft is not destroyed. In reality, the probability of destroying a target will also depend on factors such as the type of target, the explosive power of the missile, what part of the target the missile hits (especially for large targets), etc.

In Section 4.2.1, we compute the straight-line distance, $d_r$, between a MANPADS $M$ and an aircraft $A$, and express the conditional hit probability as a function of $d_r$. Initially, we consider the case where $R_{min}$ is zero, and then extend to positive values of $R_{min}$. Section 4.2.2 incorporates the effects of vertical distance on the conditional hit probability. Finally, in Section 4.2.3, we model the effect of onboard countermeasures on the conditional hit probability.

4.2.1. Conditional Hit Probability as a Function of $d_r$

Using cylindrical coordinates, let the MANPADS $M$ be located at point $m = (r_m, \phi_m, h_m)$, and let its target aircraft $A$ be located at $a = (r_a, \phi_a, h_a)$. Let $d_h$ and $d_g$ be the vertical distance (or height) and horizontal (or ground) distance, respectively, between points $m$ and $a$. Then the vertical distance is simply $d_h = h_a - h_m$, where we assume $h_a \geq h_m$, and the horizontal distance is given by:

$$d_g = \left[ r_m^2 + r_a^2 - 2r_mr_acos(\phi_m - \phi_a) \right]^{1/2}.$$  

The straight-line distance, $d_r$, between $m$ and $a$ is given by $d_r(m, a) = [d_h^2 + d_g^2]^{1/2}$, or:

$$d_r(m, a) = \left[ r_m^2 + r_a^2 - 2r_mr_acos(\phi_m - \phi_a) + h_m^2 + h_a^2 - 2h_m h_a \right]^{1/2}.$$  

If the region of interest is assumed to be level, then $h_m = 0$ (this assumption neglects the possibility of hilltop or rooftop launch locations; however, this can easily be addressed), and we have:

$$d_r(m, a) = \left[ r_m^2 + r_a^2 - 2r_mr_acos(\phi_m - \phi_a) + h_a^2 \right]^{1/2}.$$  

(2)
We initially model the conditional hit probability as a function only of the straight-line distance \( d_r \) between a MANPADS and its target aircraft. In the next section, we modify this relationship to also include the effects of the vertical distance \( d_h \).

Beginning with the case where \( R_{\text{min}} \) is zero (in other words, there is no minimum range), we model the conditional hit probability as

\[
C_1(d_r) = P_{\text{max}} \exp\left\{ -\frac{d_r}{k_1} \right\}^{\gamma_1},
\]

(3)

where \( P_{\text{max}} \) is the maximum possible conditional hit probability, and \( \gamma_1 \) and \( k_1 \) are shape and scale parameters, respectively. We interpret \( R_{\text{max}} \) as the value of the straight-line distance \( d_r \) by which \( C_1(d_r) \) has decreased to 90% of \( P_{\text{max}} \). Given values for \( P_{\text{max}} \) and \( R_{\text{max}} \), this interpretation implies the following relationship between \( k_1 \) and \( \gamma_1 \):

\[
k_1 = R_{\text{max}} \left[ \log \left( \frac{1}{0.9} \right) \right]^{-1/\gamma_1}.
\]

(4)

Fig. 4a illustrates the conditional hit probability for three different sets of values for the shape and scale parameters (holding \( R_{\text{max}} \) constant at 4,200 meters).

We now include the effect of \( R_{\text{min}} \) to account for situations where the MANPADS is too close for its guidance system to be highly effective (or for missile detonation to occur). For some missiles, the chance of detonation approaches zero at distances substantially less than \( R_{\text{min}} \) because of user safety features. However, for greater generality, we allow for the possibility of nonzero hit probabilities even for distances substantially less than \( R_{\text{min}} \). In particular, we assume that as the distance from the target approaches zero, the probability of the MANPADS hitting its target approaches a fraction \( P_2 < 0.9 \) of the value from Equation (3).

To model the effect of \( R_{\text{min}} \) on the conditional hit probability, we multiply \( C_1(d_r) \) by a correction factor \( C_2(d_r) \) given by:

\[
C_2(d_r) = P_2 + (1 - P_2) \left( 1 - \exp\left\{ -\frac{d_r}{k_2} \right\}^{\gamma_2} \right),
\]

(5)

where \( \gamma_2 \) and \( k_2 \) are the shape and scale parameters, respectively. Here, we interpret \( R_{\text{min}} \) as the value of \( d_r \) at which the correction factor, \( C_2(d_r) \), is equal to 0.9. Given this interpretation of \( R_{\text{min}} \), the relationship between \( k_2 \) and \( \gamma_2 \) is given by:

\[
k_2 = R_{\text{min}} \left[ \log \left( \frac{1 - P_2}{0.1} \right) \right]^{-1/\gamma_2}.
\]

(6)

Taking both \( R_{\text{min}} \) and \( R_{\text{max}} \) into consideration, the conditional hit probability is now given by:

\[
P_C(d_r) = C_1(d_r)C_2(d_r)
= P_{\text{max}} \exp\left\{ -\frac{d_r}{k_1} \right\}^{\gamma_1}
\times \left[ P_2 + (1 - P_2) \left( 1 - \exp\left\{ -\frac{d_r}{k_2} \right\}^{\gamma_2} \right) \right].
\]

(7)
4.2.2. Conditional Hit Probability as a Function of \( d_r \) and \( d_h \)

We now account for the effect of vertical distance. As before, we do this using correction factors \( C_3 \) and \( C_4 \) to take into account \( H_{\text{max}} \) and \( H_{\text{min}} \), respectively. So, \( P_C(d_r, d_h) \) is now given by:

\[
P_C(d_r, d_h) = P_C(d_r)C_3(d_h)C_4(d_h),
\]

(8)

where \( C_3(d_h) = \exp\left\{-\left(d_h/k_3\right)\gamma_3\right\} \), \( C_4(d_h) = P_4 + (1 - P_4)(1 - \exp\left\{-\left(d_h/k_4\right)^{\gamma_4}\right\}) \), and \( \gamma_3, k_3, \gamma_4, k_4, \) and \( P_4 \) are defined similarly to the parameters in Equations (3) and (5). Fig. 5 shows the conditional hit probability as a function of both the straight-line distance \( d_r \) and the vertical distance \( d_h \). (Note that \( d_h \leq d_r \), by definition.)

We interpret \( H_{\text{max}} \) as the value of \( d_h \) at which the correction factor \( C_3 \) is equal to 0.9. This interpretation of \( H_{\text{max}} \) gives the following relationship between \( k_3 \) and \( \gamma_3 \):

\[
k_3 = H_{\text{max}} \left[\log\left(\frac{1}{0.9}\right)\right]^{-1/\gamma_3}.
\]

(9)

Similarly, we interpret \( H_{\text{min}} \) as the value of \( d_h \) at which the correction factor \( C_4 \) is equal to 0.9, yielding:

\[
k_4 = H_{\text{min}} \left[\log\left(\frac{1 - P_4}{0.1}\right)\right]^{-1/\gamma_4}.
\]

(10)

Fig. 5 shows a representation of \( P_C(d_r, d_h) \).

4.2.3. Aircraft with Onboard Countermeasures

Countermeasures are intended to prevent weapons (in this case, MANPADS) from acquiring and/or destroying their targets.\(^{(11)}\) Several types of MANPADS countermeasures exist. All of them exhibit some delay from when a weapon is first detected to when the countermeasure is highly effective. This delay is referred to as countermeasure latency. The distance corresponding to this delay time can be estimated by multiplying the delay time by the (average) speed of the approaching missile, and will be referred to as delay distance.

We now introduce another correction factor to adjust the conditional hit probability, \( P_C(d_r, d_h) \), to account for countermeasure effectiveness. This correction factor is given by:

\[
C_{\text{cm}}(d_r) = P_{\text{cm}} + (1 - P_{\text{cm}})\exp\left\{-\left(d_r/k_{\text{cm}}\right)^{\gamma_{\text{cm}}}\right\},
\]

(11)

where \( P_{\text{cm}} \) is the reduction in the conditional hit probability when the countermeasure is maximally effective, and \( k_{\text{cm}} \) and \( \gamma_{\text{cm}} \) are scale and shape parameters, respectively, describing how the effectiveness of the countermeasure varies with distance. Fig. 6 illustrates the behavior of the correction factor \( C_{\text{cm}} \) for a hypothetical countermeasure that is 80% effective (i.e., reduces the conditional hit probability of a missile to roughly 20% of its original value), provided that the missile is fired sufficiently far from the target aircraft (roughly 2,500 meters, in this case).

We define the delay distance \( D \) as the value of \( d_r \) such that \( C_{\text{cm}}(d_r) = P_{\text{cm}} + 0.1(1 - P_{\text{cm}}) \); i.e., the point at which the countermeasure is at 90% of its
maximum effectiveness. Also, note that countermeasure effectiveness is assumed to be a function of only $d_r$, not $d_h$. The above definition of $D$ implies the following relationship between $k_{cm}$ and $\gamma_{cm}$:

$$k_{cm}(D) = D \left[ \log \left( \frac{1}{0.1} \right) \right]^{-1/\gamma_{cm}}. \quad (12)$$

Considering the effect of a countermeasure with delay distance $D$ on $P_C(d_r, d_h)$, we obtain:

$$P_C(d_r, d_h, D) = P_C(d_r, d_h)C_{cm} = P_C(d_r, d_h)[P_{cm} + (1 - P_{cm}) \times \exp\{- (d_r/k_{cm}(D))^{\gamma_{cm}} \}]. \quad (13)$$

Fig. 7b illustrates the conditional hit probability for this case, $P_C(d_r, d_h, D)$, and Fig. 7a gives a two-dimensional plot for the case where $d_h = 2,000$ meters. Here, one can clearly see that the MANPADS is only nominally effective (with a conditional hit probability of roughly $P_{cm}$) over much of its range. It is highly effective only within a small window where the aircraft is far enough from the missile launcher for the guidance system of the MANPADS to be highly effective, but too close for the countermeasure to be highly effective.

### 5. ATTACKER LOCATION STRATEGIES

Here, we explore various possible strategies an attacker may use in choosing a location from which to fire a MANPADS. The position, $m$, of the attacker in the region $I$ can be described by three parameters: $r_m$ (the attacker’s radial distance from the airport); $\phi_m$ (the angular distance of the attacker from the trajectory $c - w$); and $h_m$ (the attacker’s elevation). The defender’s beliefs about the attacker’s strategy can be modeled by choosing an appropriate joint distribution over $r_m, \phi_m, \text{and } h_m$. For simplicity, we assume a flat terrain for region $I$, so that $h_m = 0$.

#### 5.1. Case 1: Uniform

In this case, the attacker is assumed to randomly place the MANPADS within the region of interest $I$, but outside the secure region $S$. Fig. 8a shows some randomly chosen attacker locations based on this strategy. The aircraft trajectory is indicated by the dark line in the figure.

#### 5.2. Case 2: Near Center

In this case, the attacker is assumed to randomly place the MANPADS $M$ within $I$ but outside $S$ (in other words, we assume the probability of being in the secure region is zero), with a greater likelihood of being close to the secure region $S$. The rationale for this strategy is the supposition that the attacker may attempt to increase the odds of hitting the aircraft $A$ by trying to get as close as possible to $S$. Here, $\phi_m$ is assumed to be uniformly distributed on $[0, 2\pi]$, and $r_m$ is assumed to have a normal distribution with mean at the center of $I$ and standard deviation $\sigma_2$ (but with all points within the secure region...
excluded). Fig. 8b shows some randomly chosen attacker locations based on this strategy for the case where the standard deviation $\sigma_2$ equals $0.2r_I$.

5.3. Case 3: Normal Across Flight Path

In this case, the attacker is assumed to know the flight path, $c - w$, of the aircraft, and to randomly place the weapon near the flight path. Here, the weapon’s location is assumed to be uniformly distributed along $c - w$ at distances between $r_S$ and $r_I$ from $c$, but with a perpendicular offset from the line $c - w$ that is normally distributed with mean zero and standard deviation $\sigma_3$. In other words, the expected attacker location would be along the line $c - w$, at a distance $(r_I + r_S)/2$ from $c$. Fig. 8c shows some randomly chosen attacker locations based on this strategy for the case where the standard deviation $\sigma_3$ equals $0.2R_{\text{max}}$.

6. SIMULATION

MATLAB was used to compute the expected maximum hit probability for the attacker location strategies discussed above, and to explore the sensitivity of the expected maximum hit probability to the parameters of the model. For the weapon characteristics, we chose parameters representative of the SA-7B, and for the aircraft $A$ we used parameters roughly representative of the Boeing 747.

a. Simulation Technique. Let $f_M(m)$ be the probability density function of the attacker’s location. Consider the aircraft’s trajectory, $c - w$, and let the aircraft’s position, $a$ vary along $c - w$. Then the maximum hit probability, $P(m)$, achievable if an attacker shoots when the aircraft is at a location such that the conditional hit probability is maximum, is given by $\hat{P}(m) = \max_a \{P_c(d_c(m, a))\}$. The expected maximum hit probability taking into account the location of the attacker is given by:

$$E[\hat{P}(m)] = \int m \hat{P}(m) f_M(m) \, dm. \quad (14)$$

Note that the value of the above integral is computed using a discrete approximation in our simulation; see Table III for details. Table II specifies the base-case values and ranges of some parameters of our model.

b. Simulation Algorithm and Sensitivity Analysis. The algorithm shown in Table III incorporates: (1) the simulation approach to obtaining the expected maximum hit probability by randomly sampling the attacker’s location as dictated by the strategies outlined in Section 5; and (2) the sensitivity analysis.

7. SIMULATION RESULTS

We now discuss the results of our simulations by considering two broad sets of parameters in turn: those under the control of the attacker (attacker-controlled); and those under the control of the defender (defender-controlled). Although every parameter in our model can be classified as either attacker-controlled or defender-controlled,
some parameters are not discussed here because they have relatively little effect on the expected maximum hit probability.

### 7.1. Without Countermeasures

This section presents the results of our simulation for the case of an aircraft without onboard countermeasures. Figs. 9 and 10 illustrate the effect of the attacker-controlled and defender-controlled parameters, respectively, on the expected maximum hit probability.

From Fig. 9, we see that the expected maximum hit probability is relatively sensitive to the maximum effective range of the weapon, \( R_{\text{max}} \), and the standard deviation of the attacker location in the Near Center strategy, \( \sigma_2 \), and less sensitive to the maximum effective height, \( H_{\text{max}} \), and the standard deviation of the attacker location in the Normal Across Flight Path strategy, \( \sigma_3 \). Thus, as expected, attackers with long-range weapons or those able to get close
Fig. 9. Sensitivity analysis for attacker-controlled parameters.

to the airport have a relatively high probability of success.

From Fig. 10, we observe that the expected maximum hit probability is sensitive to the radius, \( r_S \), of the secure region \( S \). Note, however, that the expected maximum hit probability does not become small, say less than 20%, until \( r_S \) is about six kilometers, which translates to an area much larger than the area that can be realistically secured at most airports. Unfortunately, the expected maximum hit probability is less sensitive to the other defender-controlled parameters. Thus, attacker-controlled parameters such as weapon choice and location strategy seem to have more impact on the success probability of an attack than defender-controlled parameters, suggesting that defenders may not be able to achieve desirable levels of security without onboard countermeasures.

For aircraft without onboard countermeasures, the worst strategy for the attacker is the Uniform strategy, and the Near Center strategy is the best overall strategy, except when the aircraft’s altitude is low (because of a low cruising altitude or a large value of \( \gamma_A \)), the radius of the secure region is large, or the maximum effective range of the attacker’s MANPADS is small. In these cases, the Normal Across Flight Path strategy is better. This is because when the aircraft is flying at low altitudes, being close to the airport confers less of an advantage than being near the flight path. Also, when the MANPADS’ effective range is small relative to the radius of the secure region, the Near Center strategy will tend to be ineffective because the radius of the secure region will be greater than the range of the weapon.
### 7.2. With Countermeasures

This section presents the results of our simulations for the case of an aircraft with onboard countermeasures. As before, Figs. 11 and 12 illustrate the effects of the attacker-controlled and defender-controlled parameters, respectively.

From Figs. 11 and 12, we see that the sensitivity of the expected maximum hit probability is similar to that discussed in Section 7.1. The expected maximum hit probability is still more sensitive to $R_{\text{max}}$ and $\sigma_2$ than to $H_{\text{max}}$ and $\sigma_3$. Similarly, increasing $r_S$ greatly reduces the expected maximum hit probability, hence substantially improving security (see Fig. 12b). Fig. 12 also considers two additional parameters not included in Fig. 10: the shape parameter $\gamma_{\text{cm}}$ of the countermeasure effectiveness; and the delay distance $D$, representing the countermeasure latency. Small values of both $D$ and $\gamma_{\text{cm}}$ are helpful to the defender.

Overall, for aircraft with onboard countermeasures, the *Near Center* strategy is still the best for the attacker. However, for low-altitude flight paths, large secure regions, or a small MANPADS effective range, the *Normal Across Flight Path* strategy becomes better. The reasons for this are similar to those outlined in Section 7.1. The worst overall strategy is again the *Uniform* strategy. Note also that even with onboard countermeasures, the success probability of an attack is not in general reduced to desirably small values (e.g., less than 10%), except when the attacker is constrained to the *Uniform* strategy.

### 8. OBSERVATIONS AND CONCLUSIONS

Subject to the assumptions made in our analysis, our results suggest that without onboard countermeasures, the best strategy for reducing the expected maximum hit probability of a MANPADS attack is to increase the radius of the secure region around an
airport. Unfortunately, securing a region of several kilometers around an airport would be extremely costly, and probably infeasible at most airports. This is especially problematic given recent development patterns of locating warehouses, hotels, and other businesses in the vicinity of airports, even airports that are relatively remote from the metropolitan areas they serve.

Installation of onboard countermeasures does significantly reduce the success probability of attacks. However, if terrorists are able to choose attack locations sufficiently near airports or aircraft flight paths, installation of onboard countermeasures by itself is not sufficient to bring the success probability of an attack down to desirable levels (e.g., less than 10%). This is because the reaction times for most countermeasures make them relatively ineffective when the attacker is close to the aircraft. This points out a key difference between the use of countermeasures in the military context (in which an aircraft would typically take off and land at a relatively secure location, such as an aircraft carrier, a military base, or an airport in a friendly country) versus in commercial aviation (where airports must be accessible to the general public, and often attract extensive commercial activity). Thus, the effectiveness of onboard countermeasures in ensuring the security of commercial aviation may depend critically on whether attackers are deterred by success probabilities on the order of 20% or 30% per shot. If installing countermeasures deters terrorists from attacks on commercial aircraft, then they may be worthwhile, although such a conclusion would require a detailed consideration of countermeasure costs,\(^{(8, 12)}\) as well as the risk

Fig. 11. Sensitivity analysis for attacker-controlled parameters with onboard countermeasures.
Expected Max. Hit Prob. vs Cruising Altitude of Aircraft
(Weapon Type: SA-7B MANPADS; Countermeasure: Yes)

Expected Max. Hit Prob. vs Radius of Secure Region
(Weapon Type: SA-7B MANPADS; Countermeasure: Yes)

Expected Max. Hit Prob. vs Scale Parameter of Aircraft Trajectory
(Weapon Type: SA-7B MANPADS; Countermeasure: Yes)

Expected Max. Hit Prob. vs Shape Parameter of Aircraft Trajectory
(Weapon Type: SA-7B MANPADS; Countermeasure: Yes)

Expected Max. Hit Prob. vs Shape Parameter of Countermeasure Correction Factor
(Weapon Type: SA-7B MANPADS; Countermeasure: Yes)

Expected Max. Hit Prob. vs Delay distance due to Countermeasure Latency
(Weapon Type: SA-7B MANPADS; Countermeasure: Yes)

(a) $C_A$

(b) $r_S$

(c) $k_A$

(d) $\gamma_A$

(e) $\gamma_{cm}$

(f) $D$

Fig. 12. Sensitivity analysis for defender-controlled parameters.
of terrorists shifting to other weapon types if MANPADS attacks become infeasible. By contrast, if attackers are willing to undertake multiple attacks in the hope of even a single spectacular success, then countermeasures may make things more costly and difficult for potential terrorists without actually making aviation substantially more secure.

Our results also suggest that in order to be maximally effective, onboard countermeasures should have short reaction times, and should ideally be viewed as one part of an overall package of security measures. Other desirable measures might include: (1) enhanced security in the vicinity of airports (e.g., surveillance for suspicious activity at long-term parking lots, warehouses, hotels, and other businesses around airports); and (2) steeper aircraft flight paths (possibly including spiral ascent and descent in high-threat situations), to ensure that aircraft are already at reasonably high altitudes by the time they leave the regions of enhanced security around airports.

It is also important to bear in mind that attackers may change strategies in response to the installation of onboard countermeasures on aircraft. For example, attackers may switch to weapons that do not utilize a guidance system (such as high-powered rifles). Such weapons would typically have lower probabilities of successfully hitting their targets, but would not be affected by the types of countermeasures that interfere with the guidance systems of MANPADS. This might limit the extent of security that can be obtained through onboard countermeasures, if attackers merely change weapon types rather than refrain from attacking.

9. CURRENT LIMITATIONS AND FUTURE DIRECTION

One limitation of this work is the lack of data, both in quantity and quality, of actual MANPADS performance. Though we were able to obtain kill probabilities for some SAMs, battlefield performance data of SAMs would have been more helpful in the development of the conditional hit probabilities. A second limitation is that we made simplifications to some aspects of the geometric modeling. For example, the airport, the secure region inside the airport, and the region of interest surrounding the airport were all assumed to be circular. Also, the airplane was assumed to be a point mass. We do not know how these simplifications may affect the conclusions we have made.

Future work may consider other distributions other than the Weibull distribution, e.g., the Lévy skew alpha-stable distribution, and compare the results generated from different distributions. To give more insight into the sensitivity of the expected maximum hit probability to various parameters, more parameters may be introduced into the model; for example, the probability of entering the secure region (assumed to be zero in this work) may be varied between zero and one. Also, a broader range of scenarios may be considered, e.g., more attacker location strategies, more MANPADS, and different types of airport geometries (rectangles, squares, triangles, polygons, etc.). Another aspect of the work that can be expanded on is the reaction of the attacker to the introduction (by the defender) of onboard countermeasures. Given that the attacker is aware of this modification, how does the attacker enhance the attack strategy? Future work may use game theory to explore possible answers to this question. The cost and potential benefit of installing, operating, and maintaining onboard countermeasures can be further investigated in a future study.

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