

Modelling Fast Jet Infrared Countermeasures: Pseudo-Imaging Seekers with an Ultraviolet Guard Band

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ABSTRACT

In 2012, a study looking back 35 years, indicated that 90% of all aircraft losses in battle were caused by infrared (IR) guided missiles [1, p.295]. Man portable air defence systems (MANPADS) are a cheap and prolific resource to both state and non-state actors that enables the employment of IR guided missiles. As such, significant time is required to be invested in developing effective countermeasures to ensure a fast jet can attain and sustain air superiority in operations.

This article will provide a summary of the thesis by Glover [2] which aimed to develop a myriad of infrared based countermeasure techniques. Specifically, when a pseudo imaging, rosette scan IR seeker is employed against a fast jet with an ultraviolet (UV) guard band counter-countermeasure (CCM).

A series of seven trials were simulated using Chemring's CounterSim program to produce a spread of results based on the developed technique's effectiveness. Several of these trials produced outcomes with a probability of escaping hit (PEH) greater than 97% across a range of altitudes. The successful techniques involve an assortment of concepts including employment of spectral flares, aircraft manoeuvring, multi-flare patterns and the notion of masking.

Keywords: CounterSim, MANPADS, Infrared, IR, UV, Counter-countermeasures, Rosette, Flare

1. INTRODUCTION

In the modern military environment, the fast jet is the leading force to obtaining, and retaining air superiority. The force multiplier provided by tactically employing air superiority is second to none in conventional warfare. As such, opposing forces will expend significant time and energy in attempting to deny a safe operating environment for aircraft. One of the most common and relatively effective measures employed, is the use of Man portable air defence systems (MANPADS). These small, concealable systems have been highly proliferated throughout the world to both state and non-state actors to the point there is almost no control over their black-market sales. The United States government estimates approximately 500,000-750,000 MANPADS are stockpiled worldwide with the majority being infrared (IR) seeker systems [3].

MANPADS (dependant of generation) can be acquired on the black market for anywhere between \$500-\$30,000+ USD and requires only minutes of training for a user to become competent [4]. With an IR homing seeker, a user simply needs to visually acquire a target, uncage the seeker and pull the trigger for a fire and forget, automatic homing solution. It is for this reason a United States Secretary of State stated that “no threat is more serious to aviation” than MANPADS [5]. Furthermore, in 2012, a study looking back 35 years indicated that 90% of all aircraft losses in battle were caused by IR guided missiles [1, p.295].

The primary aim of this study was to provide an unclassified, ground up approach, to airborne IR countermeasure employment for fast jet aircraft. Specifically, where dual band IR/ultraviolet (UV), rosette scanning seeker systems are employed. The outcome is intended to determine the feasible parameters in which an IR countermeasure (CM) can be employed, to enable platform survivability against such a threat. There was also a primary focus on employing the least number of CMs as possible, given they are a vital and finite commodity.

Guided by open source data and assumptions of the author, the article does not claim to provide a real-world method to defeating such a system, but rather academically highlight fundamental concepts related to the topic at hand such as the UV guard band.

The guard band, as defined in the signal processing looks to ignore CMs by coupling IR and UV signatures. Figure 1 visually represents this phenomenon whereby segment 1 shows an aircraft signature in the IR and nothing in the UV (as expected). Segment 2 differs by the fact a UV signature is now present as the aircraft has released an Magnesium, Teflon, Viton (MTV) flare. To the seeker at this point there is no aircraft present only a CM. As the flare separates from the aircraft the seeker is able to differentiate the IR signatures. Then by coupling the IR and UV signatures it is able to determine which targets are CMs (given a coupled IR and UV signature) and which are aircraft (given the lack of a UV and IR coupled signature).

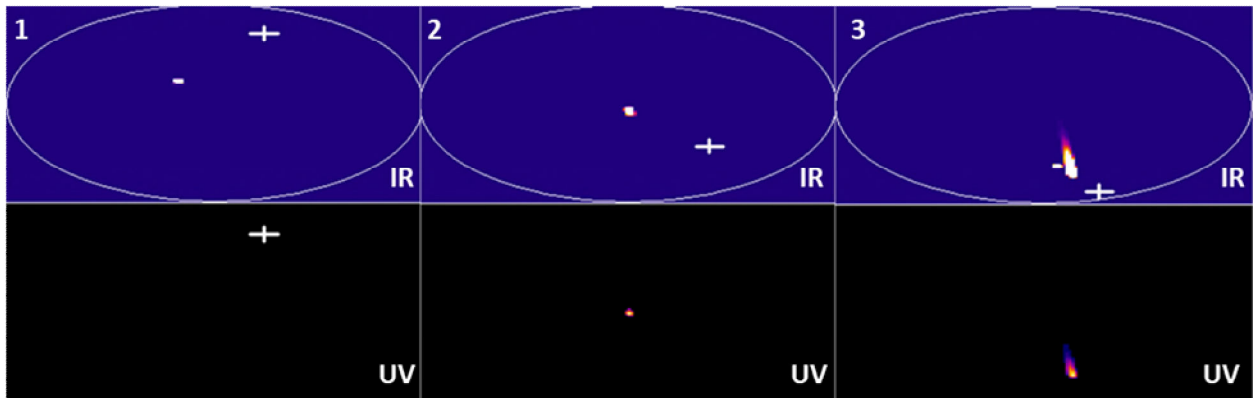


Figure 1 - UV Guard Band Masking Effect

2. LITERATURE REVIEW

It has been determined that there are numerous studies into the protection of fast jets from spin and conical scan (con-scan) IR seekers. Namely, Parkin [6], Clarke [7] and Jackman et al. [8] who considered various methods of defeating spin scan seekers and Parkin and Richardson et al. [9] who considered con-scan seekers. However, there is a lack of open source information into pseudo imaging seekers when concerned with the protection of fast jets.

In contrast to fast jets, wide body aircraft studies considering pseudo-imaging seekers and ultraviolet (UV) counter-countermeasures (CCMs) have been conducted. Specifically, the protection of a C-130 Hercules via the use of spectral flares to defeat UV guard band CCMs. Skewes [10], Smith et al. [11] and Kumar et al. [12] focus on this same scenario but with varying alterations to their signal processing and atmospheric considerations. All three studies modelled their UV guard band in the 300-400 nm range and achieved a probability of escaping hit (PEH) above 90% in various scenarios. Furthermore, it is categorically concluded that standard MTV flares emitting in the UV spectrum will not provide adequate protection to a platform against a UV guard band CCM. Smith et al. expands this further to include smoke modelling (both when emitting in the UV and not) to conclude both the flare pellet and smoke need to not emit in the UV to be adequately effective.

3. CURRENT THREATS

While the threat modelled in this study is not representative of a specific in-service system, the following two platforms are examples of currently employed MANPADS. The Chinese FN-16 reportedly employs a dual band IR/UV pseudo-imaging (rosette scan) seeker, capable of cruising at speeds over 600 m/s [13]. With a maximum altitude of 4 km and maximum slanted range of 6 km, it reportedly can withstand greater than 18 Gs in lateral acceleration [13]. A FN-16 has a total weight of 18 kg, diameter of 72 mm and length of less than 1700 mm [13]. In addition to standard optical sights, the FN-16 is compatible with night sights and identification friend or foe (IFF) [14].

Appearing physically very similar to the FN-16, the Russian VERBA has been reported to employ a three band IR seeker which is said to have a CCM capability against pyrotechnic decoys [15]. It reportedly has a maximum range of 6 km and maximum altitude of 3.5 km [16]. The VERBA also has another larger variant called the GIBKA-S which incorporates 4 VERBA's into a single platform [17].

4. MODEL

The software chosen to model the fast jet engagement with a pseudo-imaging seeker is CounterSim, provided by Chemring Countermeasures Ltd. This software has been chosen in order to remain consistent with and build upon prior studies conducted. Specifically, the works of Skewes [10] on which the model discussed in this article was adapted from.

Figure 2 illustrates the model constructed in CounterSim and exhibits the parent/child relationships between components. The overarching parent is the engagement variable that defines the simulations run time variable. This feeds directly to its child the scene generator. The scene generator defines all the environmental factors and links platform models such as the missile and aircraft (F/A-18) in this case.

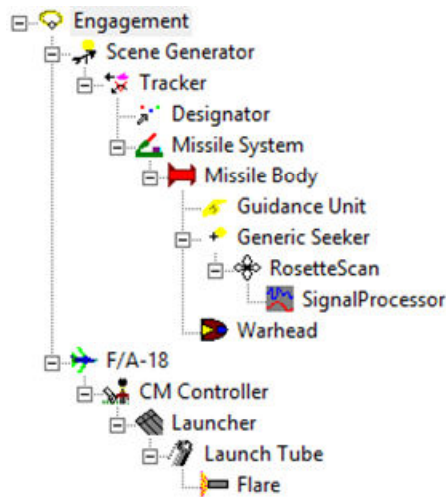


Figure 2 – CounterSim Model

4.1 Missile Parameters: The basic missile parameters set within the model can be found in Table 1. In terms of the development of the UV guard band, CounterSim’s user defined signal processor was utilised. The model for the signal processor was replicated from the work of Skewes [10].

Variable	Value	Variable	Value	Variable	Value
Diameter	72mm	Mass	11.8 kg	Sustain Thrust	600 N
Drag Co-efficient	0.4	Boost Thrust	1800 N	Sustain Thrust Time	6 s
Latex Limit	30 G	Boost Thrust Time	1.8 s	Launch Speed	35 m/s
Navigation Constant	3.5	Seeker Scan Rate	100 Hz	Field of Regard (FOR)	5°
Instantaneous FOR	0.2°	Rosette Freq 1	13 Hz	Rosette Freq 2	9 Hz
Resolution	150x150	IR Detector	3-5 μ m	UV Detector	0.3-0.4 μ m
Focal Length	46 mm	F/#	1.4	Optical Efficiency	80%

Table 1 – Modelled Missile Parameters

4.2 Aircraft Parameters: The aircraft modelled was an unclassified estimation of the F/A-18 Classic Hornet supplied with CounterSim. Its speed was constrained at a constant 200 m/s throughout all engagement scenarios. Figure 3 represents the IR (3-5 μ m) and UV (0.3-0.4 μ m) band signatures of the aircraft modelled, where the brighter shades represent higher temperatures.

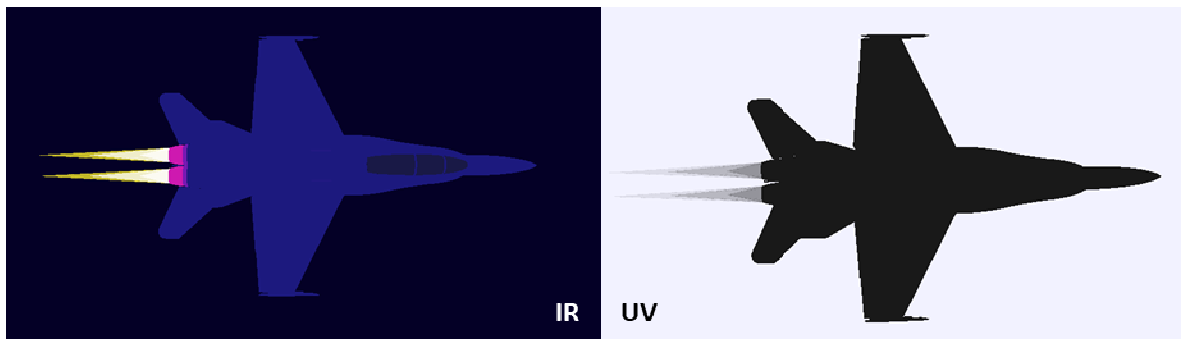


Figure 3 – Aircraft Signature in the IR (3-5 μm) and UV (0.3-0.4 μm) Bands

4.3 Flare Parameters: The basic flare parameters set within the model can be found in Table 2. Both MTV and spectral flares were simulated using CounterSim’s custom spectrum option. The Magnesium, Teflon, Viton (MTV) flares were modelled with 3-5 μm and 0.3-0.4 μm spectral components whereas the spectral flares only included the 3-5 μm band.

Variable	Value	Variable	Value	Variable	Value
Ejection Velocity	30 m/s	Length	148 mm	Diameter	36 mm
Temperature	1873.15 ⁰ C	Free Cooling Factor	3	Airspeed Cooling Factor	0.02
Expansion Velocity	2 m/s	Drag Factor	2 /s	Life	4 s

Table 2 – Modelled Flare Parameters

Beyond the basic variables of the flare item, some work arounds were required to accurately model an MTV flare when considering how it appears in the UV band. CounterSim models a flare where the pellet has the signature specified (via a .csv file) but the cooling tail plume adheres to Planck’s Law. The pellet retains its UV component, but the tail exhibits lower to no UV signature as it cools. At the point where the tail has a higher intensity when compared to the aircraft, CounterSim will allow the MTV flare to seduce the seeker.

This phenomenon can be observed in Figure 4 where a screen shot of the seeker’s view in CounterSim is pictured. The left segment represents the IR band and on the right the UV (both to the same scale). The smaller object viewed in the IR band is the aircraft as it has no partner UV signature. Note how the signature of the flare is not equivalent in the IR and UV bands but is expected to be. This flare is set to 3000 W/sr/m²/ μm and the seeker finds the tail plume a more seductive target than the aircraft. However, at 1000 W/sr/m²/ μm the tail signature is not sufficiently seductive, and the seeker can correctly employ the UV guard band.

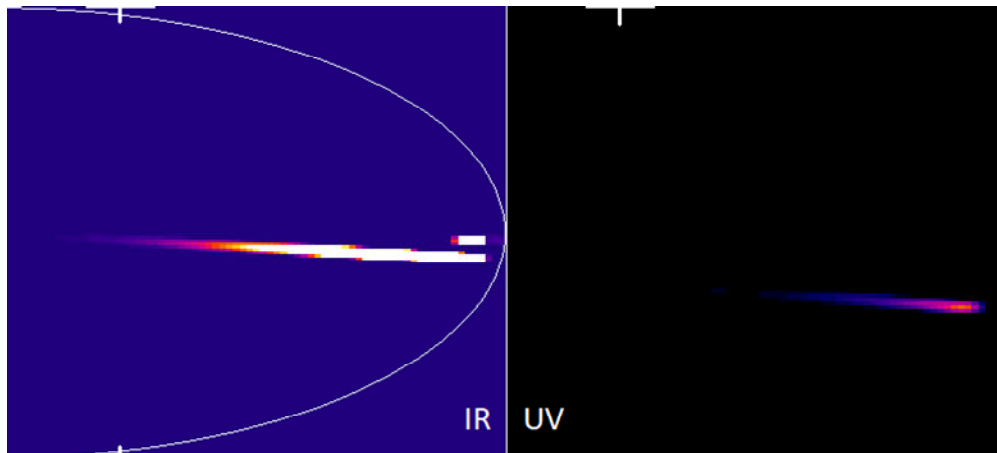


Figure 4 – Dual Band Seeker View (IR/UV) of Aircraft and MTV Flare

The results illustrated in Figure 4 are not realistic because it is the burning of by-products that causes the UV signature and not heat. Thus, as CounterSim does not model the UV spectrum of the tail realistically,

a low intensity flare was used. This allowed for the IR and UV signatures to remain comparably similar and not seduce the seeker erroneously. Moreover, if the seeker had no guard band, the pellet signature would be a viable CM, albeit not necessarily highly effective. But enough to determine whether the guard band being simulated is effective.

Another method to achieve a similar outcome would be to increase the free cooling factor of the flare significantly, such that it would then be modelled as a point source and not a pellet with a tail. Skewes [10, p.42] addressed this same issue by reducing the life of the flare pellet to 0.02 seconds, which ultimately also reduced the model to a point source. However, the point source methods eliminate many factors contributing to the masking effect that wish to be considered in this study.

4.4 The Dataset: The boundaries of the study's data include altitudes from 500-5500 m (in steps of 500 m), bearings from 0-180⁰ (in steps of 30⁰) and target ranges of 500-6000 m (in steps of 500 m). It is important to note that symmetry has been assumed in this study to limit the time taken to complete simulations. Full 360⁰ engagements were initially run and proved relative symmetry.

An example of a typical wheel plot can be observed in Figure 5, where the aircraft always begins the simulation at the origin and travels along the zero-degree axis. Each data point then represents the position of the MANPADS and the symbol signifies the result type. A hit is defined when the missile is less than 2 m from the aircraft, a near miss between 2 – 10 m and a miss greater than 10 m. When the seeker cannot lock onto the target signature this is defined as a did not fire (DNF) result.

5. TRIALS
5.1 Baseline Trial (1) Methodology: The aim of the Baseline Trial was to validate the developed CounterSim model for a fast jet environment. No countermeasures were deployed in order to determine the inherent survivability of a fast jet when faced with such a threat.

5.2 Trial 1 Results: Through this investigation, it was determined that the missile system modelled produced results comparable in magnitude to that of similar academic studies. A small variation of 4.98% was observed in PEH between this study (29.98%) and Jackman et al. [18] (25%) but considering the difference in simulated altitude range, this was considered more than acceptable.

Significant findings from this trial included the fact that at low altitudes (primarily 500 m) a fast jet is able to obscure its own IR signature on a 0⁰ bearing. This results in numerous DNF scenarios for the seeker as seen in Figure 5. Furthermore, the cruising velocity of a fast jet means that it has an advantage of outrunning the missile in tail chase scenarios (> 90⁰). However, this is counteracted by head on (< 90⁰) engagements where the aircraft becomes more susceptible to being hit as it flies towards to missile.

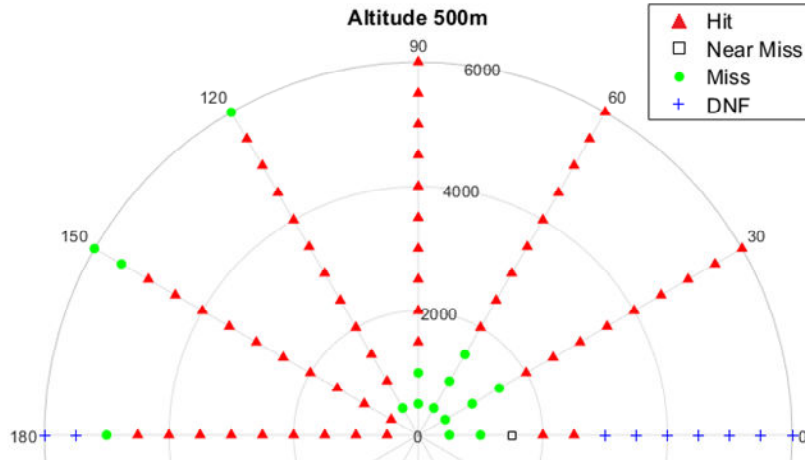


Figure 5 - Trial 1 Wheel Plot of 500m Altitude

Overall, the objectives of this trial were met through the comparison of similar studies results and via application of relevant theory. Hence, further trials were able to be undertaken to finalise the model's validation phase (Trial 2).

5.3 Guard Band Validation Trial (2) Methodology: The primary objective of Trial 2 was to verify the functionality of the UV guard band modelled in the missile system's signal processor. Secondly, it was envisaged to confirm the findings of numerous analogous studies that found MTV flares were highly ineffective CMs against UV guard band threats.

The simulated engagements were replicated from Trial 1, with the addition of a single MTV flare being deployed by the aircraft when the missile approach warning system (MAWS) was triggered.

5.4 Trial 2 Results: An unexpected and substantial increase in the PEH compared to Trial 1 (18.72%) resulted. From reviewing literature, little to no increase in the PEH from Trial 1 to 2 was expected, but ultimately this increase occurred due to the masking effect. A masking effect that was overstated in this study as a direct result of more realistic flare modelling compared to other academic sources. The overall PEH achieved via the use of a single MTV flare was 50%.

The term masking refers to the exploitation of the UV guard band CCM employed by the missile to the advantage of the defending platform [2]. This occurs when a platform releases a CM with a UV spectral component (such as an MTV flare) and due to limited initial spatial separation between the two objects, (from the seekers point of view) appear to produce a single combined signature. This combined signature now emitting in both the IR and UV bands means that the seeker will classify that target as a CM and loose track on the intended platform. If enough separation between the CM and platform occurs the seeker may be able to reacquire the target platform as it will no longer have a UV component in its signature. In this case, several CMs deployed in quick succession may be required to allow the platform to successfully escape the FOV.

The masking effect was found to be most effective at higher altitudes and shorter ranges (as observed by comparing Figures 6 and 7). Additionally, bearings of 90-150° yielded more effective masking compared to 30-60°. Directly forward and rearward bearings (0° & 180°) resulted in no masking effect occurring due to the viewing angle of the seeker.

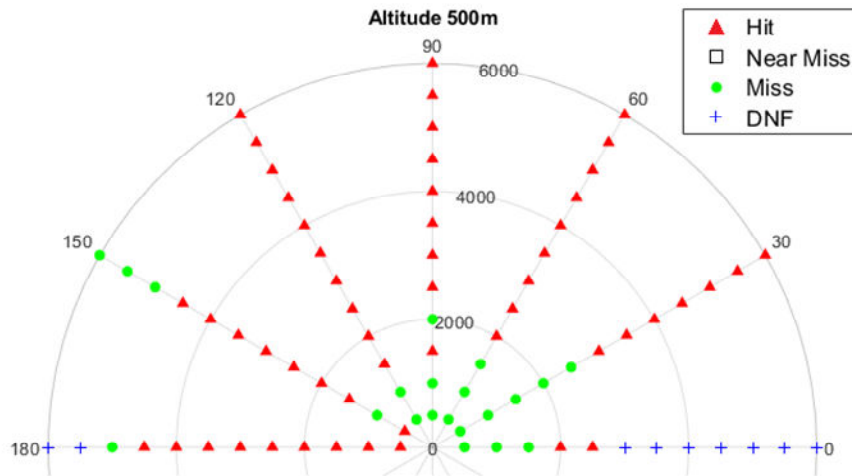


Figure 6 - Trial 2 Wheel Plot of 500m Altitude

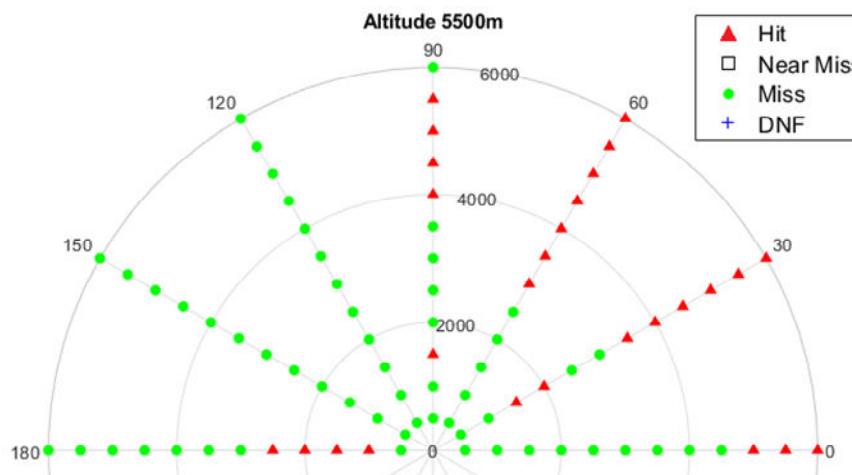


Figure 7 - Trial 2 Wheel Plot of 5500m Altitude

The results from Trial 2 were more successful than originally anticipated and verified the effectiveness of the UV guard band given the prevalence of masking occurring. Furthermore, it gave rise to further trials being conducted into developing a masking technique to defeat UV guard band threats (Trial 7).

5.5 Spectral Flare Trials (3) Methodology: Threats with a UV guard band are aimed at defeating traditional CMs such as the MTV flare. The concept of a spectral flare is to employ a CM that does not emit in the range of the guard band. Hence, the Trial 3 series were aimed at generating a technique utilising a single spectral flare to deceive the guard band CCM.

5.6 Trial 3 Results: Trial 3.1 was specifically aimed at employing a single low intensity flare ($3000 \text{ W/sr/m}^2/\mu\text{m}$). This underwhelmingly resulted in a PEH gain of 5.3% when compared to employing an MTV flare. Translating to an overall PEH of 55.3%. The primary shortfall was the limited effective life of the flare, as it was too short to allow the aircraft to escape the FOV.

As such, a higher intensity flare ($9000 \text{ W/sr/m}^2/\mu\text{m}$) was employed in Trial 3.2. The theory being that by increasing the intensity of the flare, the mass flow rate (MFR) would be altered to produce a longer

effective life. This hypothesis led to a PEH of 72.08%, which was a gain of 16.78% over the low intensity trial. Thus, confirming that increased flare life will produce beneficial gain to the PEH. Ultimately by causing it to be more effective at higher altitudes and longer ranges.

However, along the rearward (but particularly the 180⁰) bearing, it was found that even extended flare life was not an effective means of escaping hits. Given the similar seeker boresight and aircraft direction of travel, a means of causing separation between CM and aircraft was required. This leads into the conduct of Trial 5.

The initial results of the 3 series trials were lower than expected, and thus the concept of a single spectral flare defeating an incoming threat was found to be unrealistic. However, the trial did affirm that the use of a single spectral flare against a UV guard band CCM is far more effective than a single MTV flare.

5.7 Altered MAWS Sensitivity Trial (4) Methodology: The purpose of Trial 4 was to take an alternate approach to increasing CM effectiveness without directly altering the spectral flare characteristics. The MAWS sensitivity was reduced such that its effective range was altered from 6 km down to 3 km. The notion being that by delaying the release of a single CM, its effective life need not be higher.

5.8 Trial 4 Results: At first look, the results were superlative with a 96.97% PEH being achieved. However, it was later found that these results were misleading given the manner in which CounterSim modelled the MAWS' capability. The expected blind range that would have been present by reducing the MAWS sensitivity was not being modelled. As such the results were over-inflated when compared to a more realistic scenario.

However, these results did demonstrate how effectively a fast jet could escape incoming missiles given a smart or integrated MAWS. By integrating other aircraft systems such as laser range finders, visual band optics or even machine learning capabilities, a new generation of MAWS could be developed. If this were to occur, the results obtained in this study may be considered valid.

Ultimately, Trial 4 was unsuccessful as it failed to accurately simulate the intended scenario. However, it provided valuable learning points and an avenue for extensive future works.

5.9 Aircraft Manoeuvring Trials (5) Methodology: The aim of the trial five series was to increase the PEH by having the aircraft manoeuvre such that it will escape the FOR in all engagement scenarios faster than simply straight and level flight. The pitching up manoeuvre was chosen given it provided a singular solution to the full range of 360⁰ engagements without bias to bearing or altitude.

5.10 Trial 5 Results: The initially investigated manoeuvre, being a 500 m climb in altitude, at a pitch angle of 45⁰, produced effective results (91.67% PEH) when combined with a single spectral flare being employed. Theory then led to the pitch angle to be reduced to 30⁰, in hopes to further increase the PEH however, this was not the case in practise and a loss of 3.22% PEH resulted. Although, after further analysis of the 30⁰ pitch manoeuvre results, it was found that a gain in missile avoidance occurred at bearings of 30-60⁰ but to a significant detriment at bearings of 90-180⁰ (see Figure 8). Additionally, there were cases of the aircraft being reacquired by the seeker post flare burnout and manoeuvre completion. The climb height was subsequently increased to 750 m to avoid these occurrences.

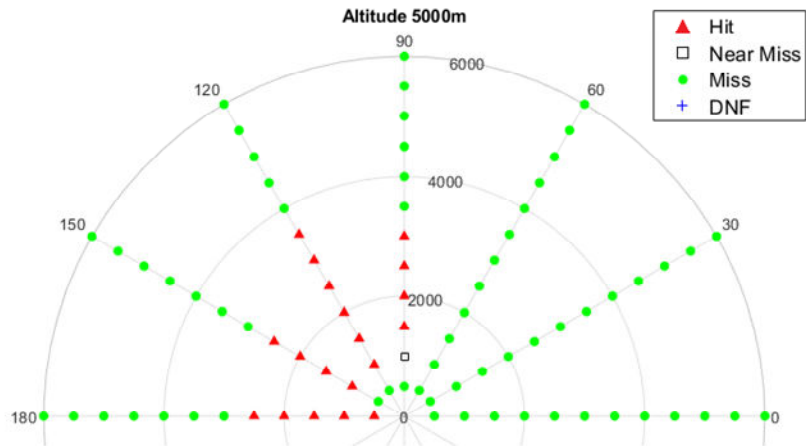


Figure 8 - Trial 5.2 (30⁰ Pitch up Manoeuvre) Wheel Plot of 5000m Altitude

Ultimately, altitude gain was found to be the most effective means to increase the PEH. As such, the pitch angle was altered to 60⁰ to favour altitude gain and a PEH of 97.4% was achieved (5.73% gain over the 45⁰ manoeuvre).

In all, the results of the aircraft manoeuvring trials exhibit a simple and very feasible technique of evading a pseudo imaging seeker with UV guard band. The inclusion of the 60⁰ pitch up manoeuvre resulted in a PEH gain of 25.32% over mere use of a spectral flare and therefore, clearly met the intended objectives of the trial.

5.11 Multi-Flare Patten Trials (6) Methodology: The objective of Trial 6 was to determine if the use of multiple flares was a worthwhile technique given its increased use of valuable and finite resources. The primary concept being that by implementing a collective MFR from a CM pattern, the effective life could be increased when compared to a single flare and thus the PEH would also rise.

5.12 Trial 6 Results: Initial simulations of a CM pattern utilising two spectral flares, one with a standard MFR and one with an inversed MFR, increased the effective life from four seconds to five (as seen in Figure 9). This resulted in a 84.63% PEH (without aircraft manoeuvres), which was an increase from Trial 3.2 (the single flare equivalent) of 12.55%.

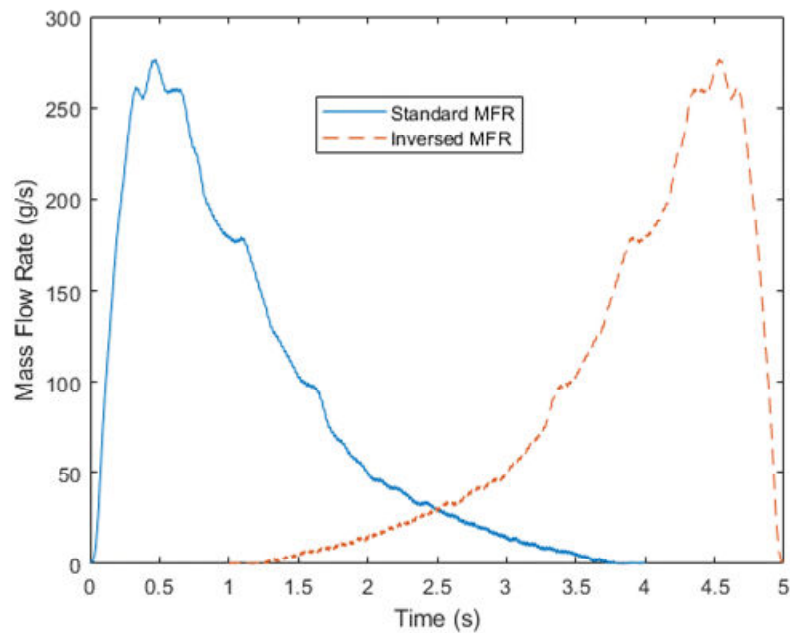


Figure 9 - Trial 6 Initial Collective Mass Flow Rate

Interestingly however, a phenomenon coined in this study as the *follow effect*, was observed to be occurring due to the delayed launch of the two flares in the pattern (one second apart). The follow effect was named to describe the effect whereby the seeker follows the aircraft when multiple flares are deployed inside the FOR [2]. As a seeker's primary target will always be the brightest signature, when the aircraft deploys newer flares they are centralised in the FOR as the primary target. Therefore, as the newest flare is also the closest to the aircraft the distance between flare and jet is equal to the distance between the FOR centre and jet. Hence, while the aircraft continues to release flares inside the FOR it cannot escape.

In order to eliminate this effect a second pattern using two standard MFR spectral flares was simulated. The primary difference being in this case that both flares were launched simultaneously with one flare having a 3 second delayed ignition time. This pattern had an effective life of seven seconds (as observed in Figure 10) and resulted in a PEH of 98.16%.

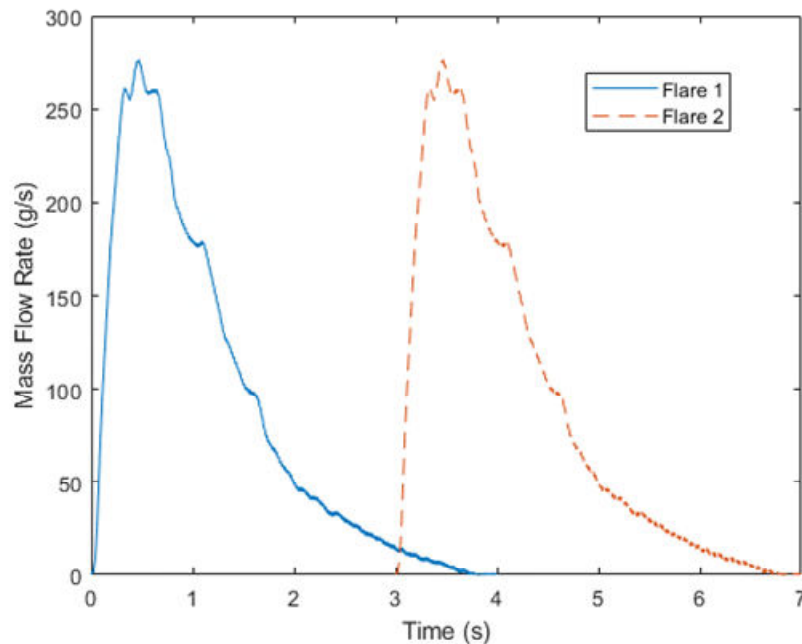


Figure 10 - Trial 6 Modified Collective Mass Flow Rate

But this second pattern alone was unable to protect the aircraft along the 180° bearing at low altitudes. Thus, from lessons learnt in Trial 3.2 and the 5 series, an aircraft manoeuvre was incorporated (60° pitch up). The manoeuvre allowed for successful evasion of the low altitude 180° engagements however, secondarily proved to make the aircraft now vulnerable at high altitude and close range. This was as a result of the seeker reacquiring the aircraft post manoeuvre completion within the half second re-acquisition time of the simulation. While not exhaustively tested, increasing the climb height from 750 m to 1000 m had the potential to increase the techniques PEH to 100%.

Therefore, it was found that multi-flare patterns have the potential to out-perform single flare techniques. Although, the maximum increase found (assuming a true 100% PEH from Trial 6.3) was only 2.6% theoretically and as practically shown in this study 1.51% (comparing Trial 5.3 and 6.3). Thus, it is hard to say whether the 100% increase in resources needed to produce a CM pattern is a worthwhile trade off, as it would depend heavily on the platform and operation in question.

5.13 Masking Trials (7) Methodology: Trial 7 aimed to investigate the survivability of a fast jet when only fitted with MTV flares (as opposed to spectral), given the effectiveness of masking observed in Trial 2.

5.14 Trial 7 Results: As Trial 2 achieved a PEH of 50% with a single MTV flare, the first pattern tested was 3 MTV flares being launched at intervals of 0.3 seconds. This pattern achieved a PEH of 87.88% and reinforced many of the findings in Trial 2.

A second pattern consisting of five MTV flares also being launched at 0.3 second intervals was simulated and resulted in a PEH of 97.19%. The vast majority of cases where the pattern failed to protect the aircraft occurred along the 180° bearing and at altitudes below 3000 m. Interestingly however, contrary to previous trials, the extended masking time proved to allow for successful masking and evasion to occur along the 0° bearing which ultimately increased the PEH significantly over other trials.

The results of Trial 7 produced overwhelmingly positive results, given how categorically negative current literature frames the use of MTV flares against missiles with UV guard bands. While certainly not an elegant solution to the problem and completely disregarding initial intents to reduce the amount of flares being employed per threat, it is a solution none the less.

6. CONCLUSIONS

This research stems from the adverse threat that MANPADS pose to fast jets and their ability to attain and sustain air superiority. The circular design process between guided missile and countermeasure engineers will be forever ongoing, but it is research such as this that is vital to protecting the lives of aircrew and their platforms.

The works of this study has aimed to provide a ground up approach to developing successful IR countermeasure techniques for fast jet aircraft. Specifically, when faced by pseudo-imaging seekers that employ a UV guard band CCM. This was achieved through the introduction of basic electro-optics theory, coupled with discussion of military applications and strategy. Furthermore, the CounterSim model was developed on a basis of previous and newly attained knowledge to investigate the effectiveness of various countermeasures and their employment techniques.

The techniques were developed over the course of seven trials, ranging from model validation to the employment of MTV, spectral, varied MFR and delayed ignition flares; coupled throughout with various aircraft manoeuvres. Several of which these techniques successfully achieved a PEH of over 97% in their last iterations, as seen in Table 3.

Trial	Technique	PEH
TRIAL 1	Nil employed CMs or manoeuvres	29.98%
TRIAL 2	Single MTV flare	50.00%
TRIAL 3	Single spectral flare	72.08%
TRIAL 4	3km MAWS Range (invalid trial and results)	96.97%
TRIAL 5	Single spectral flare and 60 ⁰ pitch up manoeuvre	97.40%
TRIAL 6	Spectral flare, delayed ignition (3 sec) spectral flare, and 60 ⁰ pitch up manoeuvre	98.91%
TRIAL 7	5 MTV flares fired 0.3 seconds apart	97.19%

Table 3 - Summarised Trial Results

Of particular note is the effectiveness of employing MTV flares against a threat with a UV guard band as observed in Trials 2 and 7. Previous research had strongly suggested that masking was highly ineffective in such scenarios however, the results obtained here drastically contradict this. In terms of resources required though, the use of spectral over MTV flares has proven to be the better option, given their specific design to defeat such threats. Furthermore, the use of simple aircraft manoeuvring has shown significant improvements to the PEH when coupled with spectral flare use specifically.

Interestingly using multiple spectral flares can induce phenomena such as the follow effect. Such an effect which results in significant detriment to the aircrafts PEH, rather than the intuitive gain.

While the model posed in this study does not necessarily represent a true and realistic scenario, it certainly does provide a basis for considerable adjustments, should true parameters be known. The CounterSim program gives a substantially intuitive environment to work from and has the potential to facilitate a vast variety of electro-optic countermeasure studies. The obvious next step for these studies would be to validate them against real-world trials to further enhance the model's ability to accurately simulate missile engagements.

7. FUTURE WORK

As has always been intended in this study, there are a multitude of further works than can be conducted surrounding even the basic most trial. Significant alterations to even small parameters such as the data point resolutions could provide noteworthy further insight. By reducing the altitude, range and/or bearing step size, more precise engagement characteristics could be modelled. Furthermore, conducting full 360⁰ simulations potentially could also produce results varying to that of what is found herein.

In order to develop the research further, rather than revalidating the current works the introduction of atmospheric, noise and weather modelling could be considered. All these factors have shown to significantly alter the effectiveness of a missile system in other academic studies. This could potentially lead to variations of CM techniques needing to be developed.

Other model variations could merely include alterations of the aircraft signature or other parameter such as speed. By adapting the model to suit a specific aircraft result could easily differ once again. This goes equally for the missile system and altering any of the parameters such as thrust, physical size, scanning method or hit radius could see different results.

Another viable concept to consider would be to increase the number of missiles being fired at the aircraft. In many cases, the aircraft will be faced with scenarios where multiple incoming missiles are present. The developed techniques of this study could be tested against multiple threats in order to determine if they are still viable.

The most significant area for future works is to investigate a more accurate model of MTV flares in the UV band. Concessions were made in this study by reducing the flare intensity to mimic a realistic scenario however, this is far from ideal. Ultimately, the inclusion of a UV signature even when combustive materials cool needs to be incorporated. Furthermore, addition of smoke from combustion is a likely next step to being added into the model. It is likely that these changes could result in an even more effective outcome for the masking phenomenon.

The future research opportunities of the masking trials would have great potential when considering pre-emptive CM techniques. Given the vast number of flares required to achieve suitable PEHs, it is only logical to employ the technique in an environment where a large number of flares must already be deployed. Specific high-risk manoeuvres such as bombing runs, that can be refined into a threat window would be a rational scenario to explore further.

As an alternative or in addition to aircraft manoeuvring, kinematic flares could be investigated. Pitching up an aircraft is suitable when the only concern is to escape the incoming threat. But when the intent is to remain on a constant flight path, the use of kinematic flares could be feasible alternative. This could be called for in a bombing run scenario where pitching up would cause the run to be aborted. By remaining on the original flight path and utilising kinematic flares the aircraft may be able to avoid a threat and still

achieve its mission objective. Hence, a whole range of new techniques could be available given the potential of kinematic or aerodynamic flares.

However, the manoeuvring (and proposed kinematic) techniques rely heavily on the fact that the missile does not have kinematic CCMs. As such, it would be relevant to study the incorporation of such a CCM and the effect it has on the techniques developed in this study.

Finally, research into the feasibility of integrating MAWS systems with visual band optics, laser range finders or other established aircraft systems could be considered. The results of Trial 4 did show promising PEHs if such a smart MAWS/CMDs could be developed.

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