Simulating the DIRCM engagement: component and system level performance

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ABSTRACT

The proliferation of a diversity of capable ManPADS missiles poses a serious threat to civil and military aviation. Aircraft self protection against missiles requires increased sophistication as missile capabilities increase. Recent advances in self protection include the use of directed infrared countermeasures (DIRCM), employing high power lamps or lasers as sources of infrared energy. The larger aircraft self-protection scenario, comprising the missile, aircraft and DIRCM hardware is a complex system. In this system, each component presents major technological challenges in itself, but the interaction and aggregate behaviour of the systems also present design difficulties and performance constraints.

This paper presents a description of a simulation system, that provides the ability to model the individual components in detail, but also accurately models the interaction between the components, including the play out of the engagement scenario.

Objects such as aircraft, flares and missiles are modelled as a three-dimensional object with a physical body, radiometric signature properties and six-degrees-of-freedom kinematic behaviour. The object's physical body is modelled as a convex hull of polygons, each with radiometric properties. The radiometric properties cover the 0.4–14 μm spectral range (wider than required in current technology missiles) and include reflection of sunlight, sky radiance, atmospheric effects as well thermal self-emission. The signature modelling includes accurate temporal variation and spectral descriptions of the object's signature. The object's kinematic behaviour is modelled using finite difference equations. The objects in the scenario are placed and appropriately orientated in a three-dimensional world, and the engagement is allowed to play out.

Low-power countermeasure techniques against the missile seekers include jamming (decoying by injecting false signals) and dazzling (blinding the sensor). Both approaches require knowledge of the missile sensor and/or signal processing hardware. Simulation of jamming operation is achieved by implementing the missile-specific signal processing in the simulation (i.e. accurate white-box modelling of actual behaviour). Simulation of dazzling operation is more difficult and a parametric black-box modelling approach is taken. The design and calibration of the black-box dazzling behaviour is done by heuristic modelling based on experimental observations. The black-box behaviour can later be replaced with verified behaviour, as obtained by experimental laboratory and field work, using the specified missile hardware.

The task of simulating a DIRCM system is scoped, by considering the threats, operational requirements and detailed requirements of the respective models. A description is given of the object models in the simulation, including key performance parameters of the models and a brief description of how these are implemented. The paper closes with recommendations for future research and simulation investigations.

Keywords: infrared simulation, scene rendering, signature, DIRCM, directed infrared countermeasure, countermeasure, OSSIM

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1. INTRODUCTION

The proliferation of small Man Portable Air Defence Systems (ManPADS) missiles into the hands of non-government forces poses a serious threat to civilian[1] and military aviation. Many thousands of unaccounted for missiles are spread all over Africa, South America, and the Middle-East—and these missile can easily find their way into terrorist hands in traditionally stable countries. ManPADS missiles may be available for as little as USD10k, but are highly effective with kill and damage probabilities exceeding 70% of engaged aircraft.[1] The threat ranges from older missile systems (SA-7), to the very latest models such as the estimated 20 000 SA-24 missiles looted in Libia in 2011.[2] The United States distributed Stingers into Afghanistan, but attempts to reclaim the missiles met with varying success. With a total ManPADS production estimated at more than half a million missiles,[1] even just a small percentage of unaccounted for missiles poses a serious threat to aviation.

Aircraft self protection against missiles requires increased sophistication as missile capabilities increase. While it is feasible to develop a single countermeasure (CM) against a single missile, the complexity of aircraft self-protection rapidly increases if a countermeasure against diversely different missiles has to be found. In most scenarios, it becomes increasingly difficult to predict, with confidence, which missile threats are to be expected. Hence there is a need for a countermeasure solution with a broader and more generic coverage.

Various types of flares (Magnesium Teflon Viton (MTV), spectrally matched and pyrophoric materials) and mixed deployment of these flares in so called flare 'cocktails' sequences have varying success against the different types of missiles. An effective generic flare cocktail solution may be impossible to find. Recent advances in self protection include the use of directed infrared countermeasures (DIRCM), employing high power lamps or lasers as sources of infrared energy. The broader aircraft self-protection scenario, comprising the missile, aircraft and DIRCM hardware, is a complex system. In this system, each component presents major technological challenges in itself, but the interaction and aggregate behaviour of the systems also present design difficulties and performance constraints.

The design and optimisation of a countermeasure system, comprising traditional flares combined with a laser-based DIRCM system, is a difficult undertaking. The performance of the system depends critically on the interaction between the various components in the system. An iterative design process has been called for[3] to reach the optimal system level design. It is the notion of this paper that the iterative design process requires a comprehensive modelling and simulation environment. Few similar simulation systems have been reported.[4]

The paper presents a description of an image-based simulation system, the Optronic System Simulator (OSSIM). OSSIM provides the ability to model the individual components in detail, but also accurately models the interaction between the components, including the unfolding of the engagement scenario. The specific objective with this simulation is to provide an environment to support in-depth modelling of all aspects of the system, capable of supporting the subtle complexities in the missile-aircraft-DIRCM engagement. The simulation environment was used with great effectiveness to develop other weapon systems and flare countermeasures.[5,6]

This simulator can be used as a stand-alone experimental tool, using generic models and providing generic answers. It is however best used when tightly integrated with threat missile seeker hardware analysis and the development and optimisation of flare and DIRCM countermeasure systems. Initially, the simulator supports design decision making; later it supports laboratory, hardware-in-the-loop and field trial test and evaluation. The simulation infrastructure provided, supports any level of detail in the models: from high level generic models to end-to-end, finely detailed modelling of specific systems.

If detailed models of the seeker and missile airframe and guidance are available, the simulation can be used to develop specific jamming strategies—which must off course be validated using real hardware. If detailed models of the DIRCM are available, the interaction and time-line events can be studied in detail. If detailed models of the missile, aircraft and DIRCM are available, a detailed evaluation of the complete system is indeed possible. Considerable effort in modelling, and continual validation, is however required to reach this capability.

A description is given of the (1) respective object models in the simulation, including key performance parameters of the models and a brief description of how these are implemented, (2) the scenarios where the models are deployed and (3) results obtained from executing the simulations. The paper closes with recommendations for future research and simulation investigations.

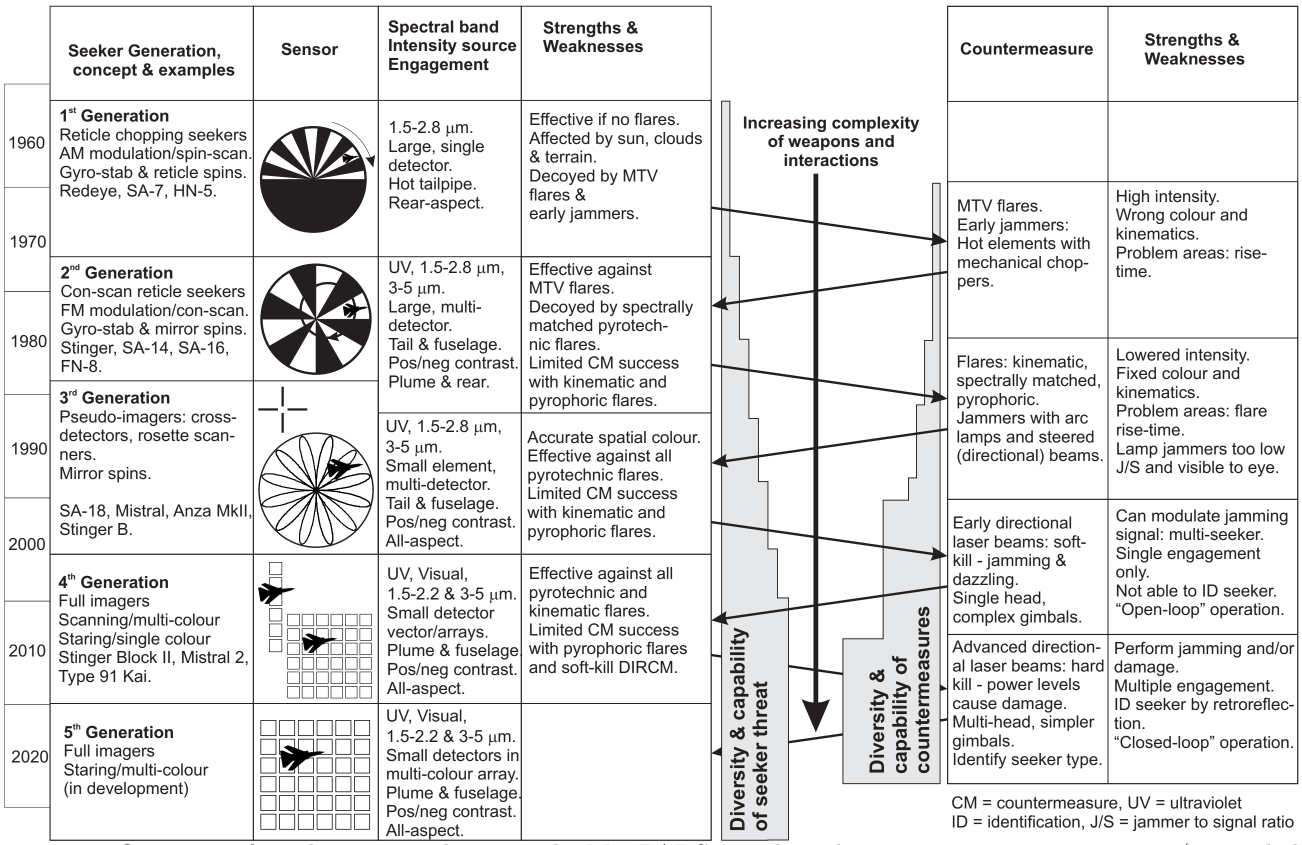

Figure 1: Overview of escalating complexity in the ManPADS missile and countermeasures interaction (expanded from[7–10]).

2. DIRCM ENGAGEMENT SCENARIO

2.1 Overview

Figure 1 provides a brief summary of the development of ManPADS missile seekers and countermeasures. The diagram is not meant to be a concise historical treatment, but rather to demonstrate the growth in diversity and complexity on the part of the seekers and the countermeasures and by implication, the interaction between these elements. While ManPADS deployment poses a threat to civilian and military aviation, the situation is complicated by the uncertainty of which missiles are present. ManPADS missiles can be transported quickly and easily; furthermore, a mix of missiles from various origins may well be expected in conflict hot-spots. An aircraft self-protection system must therefore be able to counter any one of a number of different missile types.

DIRCM presentations glibly mention missile identification and closed loop jamming, but mostly fail to mention the technical difficulty and increasing complexity of making this work in an operational system. Furthermore, while these concepts are feasible in principle, the risk of actually making it work in an operational context rises. The very high costs of such systems can naturally be justified against the value of the pilot and aircraft and in the case of civilian aircraft, the business case of safe air travel. Keep in mind also, that for the later generation ManPADS missiles (generations 4 and 5), the missile cost increases and the general missile availability should be low.

3. DIRCM SYSTEM MODEL

3.1 Basic operation

The objective with the DIRCM is to inject a signal into the missile seeker to defeat the missile mission, and to do this as quickly as possible. A simple block diagram of a DIRCM system is shown in Figure 2. The typical

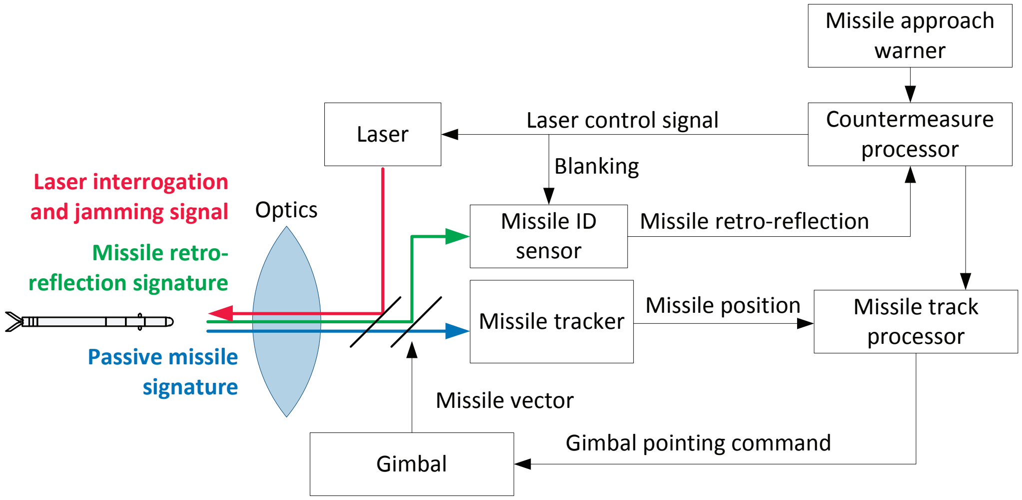

Figure 2: High level block diagram of a closed loop DIRCM, adapted from.[11]

action sequence during a defeat cycle of the DIRCM operation is:[1,12–14]

1. Wait for a missile approach warner (MAW) alarm and a designation vector to the threat.
2. Slew the missile tracker sensor gimbal to point along the designation vector, towards the missile.
3. Activate the missile tracker to search for and locate the missile in the tracker sensor image.
4. Activate the tracking loop to track the missile location.
5. Start the jamming procedure, with one of two approaches:
   (a) Traditional DIRCM system: Select a jam code from a library of generic and specific jam codes, one at a time, until the selected code shows effect. This could take some time, since the codes are tested sequentially. It may not be possible to determine if a particular code had effect.
   (b) Closed loop DIRCM system:
      i. Enable the laser in interrogation mode, to illuminate the missile seeker for interrogation.
      ii. Command the missile tracker to search for the laser glint retro-reflection from the seeker optics.
      iii. Command the tracking loop to track the laser retro-reflection. Tracking the reflected laser signal provides for more accurate tracking, hence allowing a smaller laser beam divergence.
      iv. Analyse the temporal variation in the signal reflected from the missile seeker (seeker retro-reflection signature), identify the seeker type and select appropriate disruption strategy. Appropriate action in this context is the activation of the optimal jamming code and frequency, at the most appropriate wavelength, at the required power level setting.
      v. Activate the jamming strategy. Since the optimal code is selected early, the response time and effectiveness of closed loop DIRCM systems are improved over traditional DIRCM systems.
6. Assess the success of the jamming, using the missile track history and/or the quality of the seeker retro-reflection signal.

3.2 DIRCM effects on the missile seeker

Depending on the laser power, the DIRCM can achieve jamming, dazzling or damage of the seeker. Figure 3 provides a summary of these effects. Note that the boundary between jamming and dazzling is not well defined; there is a transitional boundary where both effects could occur at the same time. It is evident that no single solution works perfectly for all missiles, perhaps except out-of-band-damage, which does not require any seeker knowledge.

	Jamming	Dazzling	In-band damage	Out-of-band damage
P	0.5 W to 10 W. Matched to modulation.	2 W to 10 W. Continuous or high pulse rates.	10 W to 200 W, >0.1J/pulse. Continuous or high pulse rates.	1 kW and higher.
Operational effect	Jamming interferes with the seeker by injecting false signals via the optical sensor, within design limits of radiometry and geometry. Mixes with target signal and creates false target signal. Requires only relatively low jammer/signal ratios. The jam signal must be reasonably close to the seeker internal signal to have significant effect. At the higher power settings the effect changes from jam to dazzle.	Dazzling denies normal sensor operation by injecting signals beyond design limits of radio-metry & geometry. Influence sensor control /operating status. High jam/signal ratios. Affects the sensor automatic gain control (AGC) or saturate (a part of) the detector. Scattering in optics produces ghost images. Could reinforce target signal, i.e. centroid tracker remain locked on to laser signal. Effects depend on actual hardware build.	In-band damage uses seeker optics to focus laser in small spot, damaging components in the focal plane. Sufficient flux must pass through optics and atmosphere. Damage is localised, only where and when laser spot falls on the sensitive device. In scanning systems, damage only if the pulsed laser spot scans on detector; but if damaged the effect is 'global' over the image.	Damage by melting, vapourising or shattering components. Out-of band damage requires a high power density/concentration, thereby effecting damage over several seconds of heating. Requires a small laser beam divergence and precise tracking of a single spot on the target. Damage is more easily afflicted to thin missile casing on the side, than to the thick dome.
Applications	Effective against first and second generation reticle seekers, much less so against third generation and not effective against later generations.	Effective against first and second generation reticle seekers, less so against third generation. Depending on sensor, could be effective against later generations.	Damage less effective against reticle seekers. Damaging more effective against pulse position & imaging sensors.	Effective against any missile, no dependency on seeker specifics.

Figure 3: DIRCM effects: jamming, dazzling and damage, adapted from.[3,10,12,14]

3.3 Elements of the DIRCM system model

Figure 4 provides a conceptual framework for a modern closed loop DIRCM system. The diagram is somewhat simplified but still serves to indicate (1) the various components in the system and (2) the interaction and dependencies between the components. The diagram emphasises the DIRCM elements, but this does not mean that the other elements are less important or complex.

In the real-world engagement each element is a physical component; in the simulation the same structure is followed with the same components, but now in simulation code and data. A key principle in the DIRCM simulator is that the network of hardware components must map to the network of software components; in presence and in networked context.

4. SIMULATION FRAMEWORK

4.1 DIRCM simulator functional requirements

Figure 5 provides a simplified overview of the functional elements in a real-world DIRCM system. The centre of the diagram shows a high level engagement time-line, with primary interactions between the DIRCM and the missile. The left hand side and right hand side panels show the functionality required in the simulator. Simulation of these hardware systems requires an in-depth knowledge of the hardware, which is required to build high fidelity models. Such in-depth knowledge requires analysis of the hardware systems under laboratory and operational field conditions.

4.2 Simulation overview

The DIRCM simulator is built on top of the strong infrared rendering and system simulation support infrastructure in the engineering development tool, OSSIM.[15] The OSSIM core library is designed as a high-fidelity physics-true simulation. OSSIM has demonstrated its capability to support missile development[5] in several missile development programmes (imaging and reticle).

OSSIM has a modular approach with a standard core — radiometry calculation, image renderers, time management and similar functions — with well-defined interfaces to support a variety of specialist user subsystem

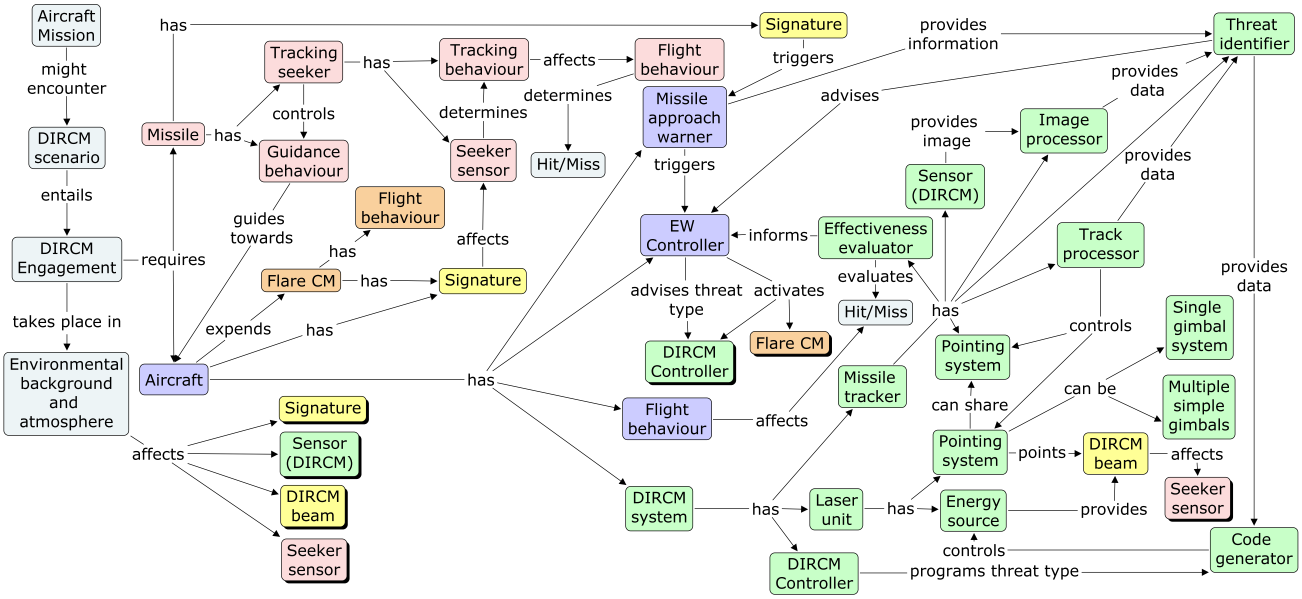

Figure 4: Missile-aircraft-DIRCM engagement, emphasising DIRCM concepts and interactions.

models. These user modules mimic the real-world hardware in operation, degradation and performance. The simulation is written in the C++ object oriented language, resulting in a modular and extendable software code base. The architecture provides a strong decoupling between 'user code' and simulation core library code. User modules typically describe various weapon subsystems, e.g. the sensor sub-assembly, image processing, mechanical gimbals, missile dynamics and kinematics.

The simulation creates a virtual 3-D world containing all the elements of a real world scenario. The objects in the scenario are placed and appropriately orientated in the three-dimensional (3-D) world, and the engagement is allowed to unfold. Objects in the scene all fit in a class hierarchy of increasingly more specialised objects. The base class is *World Objects* which represent all objects in the world. Some objects have the additional property of movement (*Moving Objects*), while some objects have more specialised properties of observation (*Observer Objects*). This hierarchy ensures that all objects are visible in the world, and hence, that all observer objects can observe any and all other objects in the world. The simulation supports an arbitrary number of moving objects and observer objects. For example, an optical missile warning sensor and an approaching missile can observe each other throughout the engagement.

Static and/or dynamic moving objects, various background scenarios, and realistic modelling of atmospheric conditions are included in the simulation. A high premium is placed on accuracy at a detailed level in areas of radiometry, atmospheric modelling, object kinematics and signal processing.

Physics true radiometry is achieved by the rendering of reflected sunlight and thermal self-emittance signatures; thereby ensuring accuracy over the different spectral bands (see Figure 6). To allow for the subtleties and full scope of variability in atmospheric attenuation, the simulation employs all capabilities of the Modtran[16] computer code. The user sets up the appropriate atmospheric conditions, whereafter the simulation sets up the path geometry as required and executes Modtran. After completion of the Modtran run, the simulation incorporates the spectral transmittance and path radiance results in its internal spectral radiometric calculations.

Objects in the world, such as aircraft, flares and missiles are described in terms of a 3-D complex hull, consisting of a set of flat, convex polygons (see Figure 6). Each polygon is assigned spectral radiometric properties, supporting the modelling of spectrally selective radiators, such as aircraft and missile plumes. Polygons are rendered with texture, enabling the modelling of spatial variation on the object's surface. Polygons can also be partially transparent to represent gas clouds. The temperature of a polygon is calculated by a heat balance equation that includes modelling of all heat sources, including diurnal solar influx, thermodynamics, internal

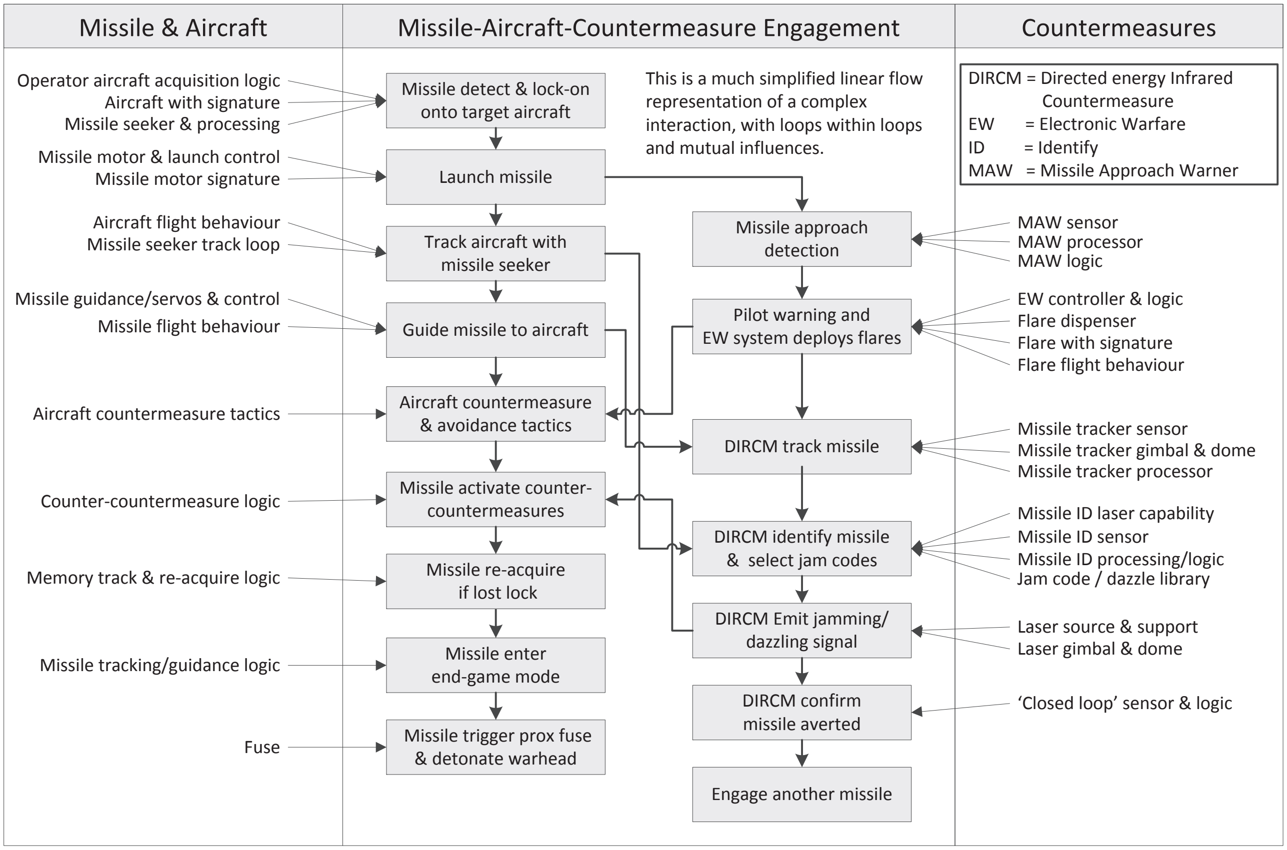

Figure 5: DIRCM engagement, emphasising functionalities present/required in missile, aircraft and DIRCM.

heat sources, and aerodynamic heating. The signature modelling also includes temporal behaviour of the object's signature.

Figure 6: Helicopter 3-D complex hull polygon model and OSSIM rendered images in the shortwave and medium-wave infrared spectral bands.

The image renderer extracts the 3-D scene data from the database and renders two-dimensional ideal 'high resolution' images simultaneously in multiple spectral bands, covering the 0.4–14 μm spectral range (wider than required for ManPADS missiles). These images are computed at a higher resolution than the sensor image resolution, for subsequent sensor image calculation at a lower resolution.

Specialist user application sensor sub-assembly modules process the rendered 'high resolution' image into a time varying digital signal or image, The sensor module typically accounts for the field of view, optical vignetting and point spread function (PSF), mechanical image scanning, detector type, detector noise and focal plane processing, electronics signal transfer functions, as well as processing time delays. The objective is to calculate an image in the simulation that will look exactly like the real-world sensor image. The quality of the modelling is limited by the effort expended in the modelling process, not by the software.

The simulation structure allows the end-user to easily integrate signal/image processing algorithms into the simulation environment. The image processor module processes the detector signal or image to determine the error signal for the purpose of target designation and tracking. Typical processing includes detection algorithms, automatic target recognition algorithms, auto-tracking algorithms, counter-countermeasure algorithms and control algorithms.

Very sophisticated movement kinematics and aerodynamics (e.g. missile control systems, flight dynamics and kinematic movement) are easily implemented in the built-in, user extendable, finite difference equation library. The error signals calculated by target tracking algorithms are consequently input to the gimbal and missile simulator modules. The mechanical gimbal stabilises the sensor sight-line against vibration and base motion. The gimbal module describes the gimbal mechanical properties, inertial and mechanical angular sensors, sensor platform dynamics and kinematics and the stabilisation and tracking control systems. The tracking system keeps the target in the centre of the sensor field of view and provides the target sight-line rate as output. The missile module uses the target sight-line rate to determine a guidance command and adjust the missile location and attitude in the world accordingly. The module comprises models for the missile aerodynamics, flight control servos, the auto-pilot, guidance and navigation.

A typical OSSIM simulation run includes both discrete events (missile launch, laser pulses) and continuous time[17] elements (gimbal motion, flight motion). The 'world' contains many independent objects, all of which must be time-synchronised with each other. OSSIM employs a flexible time management system where objects manage their own discrete event actions, while continuous time simulation is optimised to match the rate of change of the specific subsystem. Each subsystem registers a touch or update interval with the time manager. Subsystems with higher bandwidth requirements update at shorter touch intervals, while slower systems touch at longer intervals (see Figure 7). This approach optimises computational loading by differentiated execution updates.

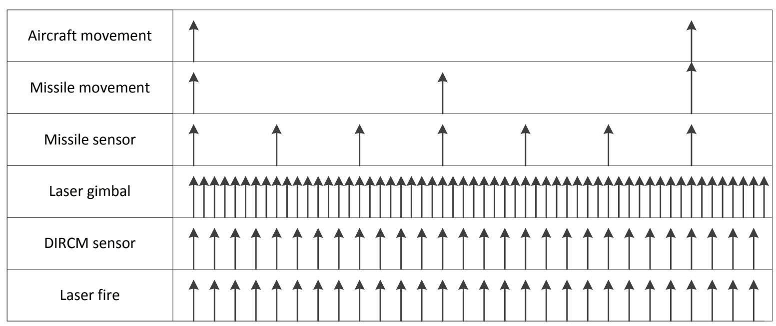

Figure 7: OSSIM timing touch concept: high bandwidth systems are sampled more frequently.

Model behaviour is hard-coded in C++ code, but all parameter input to the model is provided in a number of XML data files (separate files for different subsystems). The user can readily set up a simulation scenario with the User Guide and a regular text editor, or the OSSIM graphical user interface (GUI) scenario editor. Since practically all simulation and subsystem parameters are numerated in the XML files, the simulator is highly configurable. In the event that an existing model does not provide the required capability, a new model is constructed in C++ code, according to the need.

5. DIRCM SIMULATOR

5.1 DIRCM simulator block diagram

The modular DIRCM simulation model follows the OSSIM concept of object encapsulation. The four primary objects are the missile, the aircraft, countermeasure flares and the environmental background. In Figure 8, sensors are indicated with blue eyes, while radiating sources are indicated with red stars. Optical signatures are all-aspect signatures, as the object would appear from any view in the real world. Objects (missile and aircraft with DIRCM) have position and attitude in the world, supporting movement in six degrees of freedom (6-dof). The sensors of the observers form images of whatever is visible in the field of view at any moment in time.

The simulation can implement any potential DIRCM concept. Two possible concepts are (1) the traditional DIRCM with a steerable sensor and laser, and (2) a set of fixed sensors and steerable lasers. The steerable sensor and laser configuration requires a gimbal to point the sensor towards the missile. The same gimbal can also steer the laser through a shared aperture with the sensor, or alternatively, a second gimbal can be used to steer the laser.

Currently, the sensor and laser are co-axially steered, through a single three-axis gimbal system. The alternative configuration requires a number of sensors statically mounted to the airframe, but each with a steerable laser. Such a system may have up to four or five optical assemblies, each comprising a fixed sensor and a gimballed laser. The simulator block diagram for such a system is shown in Figure 8.

Accurate and high fidelity modelling of the individual components requires insight in the detailed functionality of the respective systems. Characterisation and modelling of own-forces equipment are relatively easy, while characterisation and modelling of adversary force equipment are much harder, since access to such equipment and the design authorities is limited and often nearly impossible. The only way to obtain such information is by counter-intelligence and by characterisation of captured equipment, sometimes referred to as missile exploitation. In the absence of adversary missile information, generic models are often used, but the results so obtained do not really represent a specific missile threat. Missile exploitation is an arduous task and the resultant information is not commonly shared or available. Interestingly, the interest in safety from commercial aviation[14] may lead to more open dissemination of ManPADS information. Surrogate seekers and seeker simulators[18, 19] can provide a good starting point for hardware and simulator experimentation to grow experience and insight in missile counter-countermeasures.

In keeping with the OSSIM philosophy, the DIRCM simulator is build and improved incrementally, starting from a basic working framework. As more insight in missile operation and countermeasure strategies are gained, the respective models are upgraded.

5.2 Missile

The missile model comprises a seeker model (sensor, counter-countermeasure processor, stabilised gimballed platform with tracking control loop), a missile airframe model with flight behaviour and guidance system, a 3-D wire-frame missile body model with an observable signature, and a detailed and accurate aerodynamics model. Each of the components can support different user selectable variations, as indicated below.

5.2.1 Sensor

The current seeker model in the DIRCM simulator is an imaging seeker. The generic staring array sensor model requires the user to specify parameters governing the detector, optics and proximity electronic processing. Simulated sensor images can be created simultaneously in any number of spectral bands. Each detector is described by the number of detector elements, pitch, noise equivalent irradiance (NEE), non-uniformities, offsets, responsivity, optical fill factor, spectral response and thermal response time (if required). The focal length, F-number, optical PSF and spectral transmittance describe the sensor optical system. Other sensor parameters include the frame time, the flux integration time interval and number of bits in the digital sampling. Temperature and emissivity values for the seeker mechanics, dome and optics are used to calculate the flux contribution in the detector from these seeker components. Some parameters allow a statistical spread in value. The user also specifies the anti-aliasing super-sampling[20] image size for accurate rendering of small or distant targets.

The current seeker model provides accurate image formation, but does not yet provide a retro-reflective seeker signature. In a physical sensor the retro-reflection signature results from reflection from reflective surfaces on or near the focal plane,[21] which must be near-perpendicular to the optical axis. Modelling such a reflective signature is certainly feasible, but it requires missile hardware characterisation support for accurate modelling of both the optical cross section and the temporal response of the reflected signal (frequency spectrum, amplitude variation, etc.).

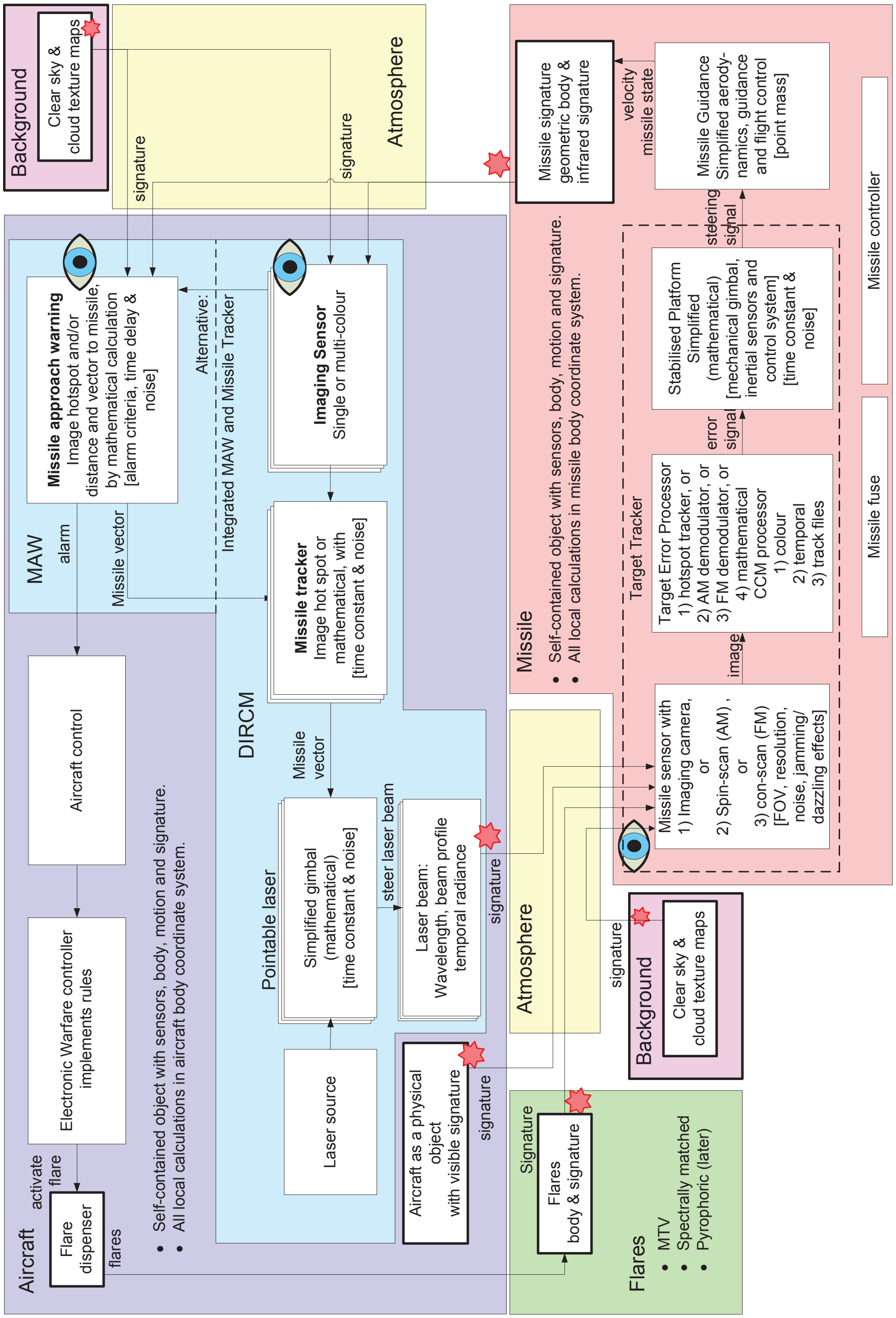

Figure 8: DIRCM simulator block diagram; configuration with wide-angle fixed sensors.

5.2.2 Counter-countermeasure processor

Development and evaluation of counter-countermeasures require an intimate knowledge of the missile signal processing and countermeasure algorithms. Basic target extraction and signal/image processing for the various types of seekers are documented,[22–24] but development of countermeasures against a specific missile requires details of the missile. Variations between different block builds of the same missile can have significant effect on countermeasure operation.

Modelling low-power jamming and dazzling require intimate knowledge of the missile sensor and/or signal processing hardware. Simulation of jamming operation is achieved by implementing the missile-specific signal processing in the simulation, i.e. accurate white-box modelling (understanding the inside details) of actual behaviour. Simulation of dazzling operation is more difficult. Dazzling is affected by, often unintended and unwanted, parasitic hardware characteristics (e.g. optical diffraction and aberrations, scattering stray light[4] flare, electronics saturation, carrier diffusion effects, gain control weaknesses and image processing weaknesses).[25] Simulated dazzling is initially modelled with a parametric generic black-box model (absence of insight in hardware details), despite the obvious inadequacies of this approach. The design and calibration of the heuristic black-box dazzling behaviour is based on experimental laboratory observations and published information.[19,25] The heuristic models are built on observation of events and outcomes, rather than first principles physics modelling. The black-box behaviour will later be replaced with behaviour as verified in hardware, as obtained by laboratory and field experimental work, using the specified missile hardware. Hardware-in-the-loop simulation (HILS) can perform the white-box modelling behaviour by using real missile hardware as the 'simulation model' in the HILS simulation loop. HILS laboratory work plays an important role in transitioning the black-box models into white-box models by means of data gathering for, and validation of, the dazzle models.

5.2.3 Tracking, guidance and aerodynamics

Modelling of the missile tracking loop and guidance loop is more amenable to white box modelling, provided that key characteristics of the two control loops are available. Low modelling fidelity in the track and guidance loops has less severe impact than low fidelity modelling of the sensor, signal processing and countermeasure logic. A generic three-axis gimbal model is implemented using the finite difference equation library. This model takes as input the signal processing pitch and yaw errors as well as the missile base motion from the missile body dynamics model. The model includes the calculation of the missile pitch and yaw command from the signal processing yaw and pitch errors, the pitch and yaw stabilisation loops with rate feedback, the calculation of applied torque in pitch and yaw, the gimbal roll control with roll stabilisation rate feedback, calculation of pitch, yaw and roll disturbance torque, and the calculation of pitch, yaw and roll applied torque to angle. The missile aerodynamics model is an important element, determining the missile flight behaviour under guided as well as decoyed scenarios. The aerodynamics modelling process requires access to a wind tunnel and aerodynamics expertise.

5.2.4 Signature

The missile has an optical signature. For the purpose of this paper, a considerably simplified head-on signature is based on a disk with area of 0.27 m^2, an average disk temperature of 1200 K (adapted from[26,27]) and a carbon rich spectral emissivity shown in Figure 9. This model agrees roughly at 500 m with values in,[7] stating that the missile motor infrared signature is 100 W/sr in the boost phase and 10 W/sr in the sustain phase (assumed head-on). Post burn-out, the signature is 0.1 W/sr attributable to aerodynamic heating. The *more advanced missile model currently in the simulation* supports a full 3-D plume and airframe model, allowing the investigation of laser beam width and parallax effects attributable to the spatial displacement of the seeker (to be illuminated) and the plume (being tracked), an issue raised by.[28] This problem does not arise in seeker sensor retro-reflection trackers.

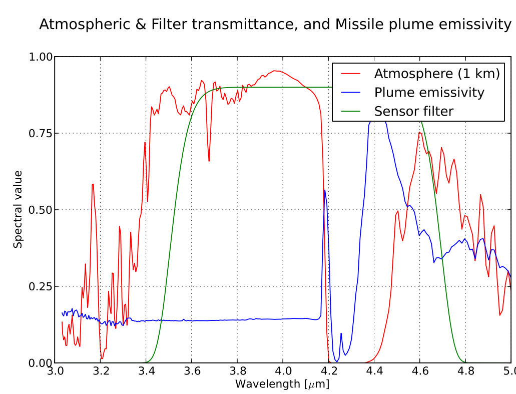

Figure 9: Missile plume emissivity, atmospheric transmittance and missile tracking filter.

5.3 Aircraft

The aircraft is equipped with the imaging DIRCM sensor, hence it is an observer object in the OSSIM context. The aircraft comprises a body with flight behaviour, an electronic warfare controller, a MAW and the DIRCM components. The aircraft body has a 3-D fuselage and plume with accurate radiometric signature properties. The radiometry characteristics include temperature and emissivity for opaque fuselage polygons, as well as in-band spectral emissivity for carbon dioxide radiance in the plume. Hence, the aircraft will be rendered accurately in missile sensor images from any view aspect angle.

5.3.1 Missile approach warner

The MAW is normally not part of the DIRCM hardware, but could be integrated with a wide-angle missile tracking sensor, if available. The MAW is modelled in different levels of detail and hardware fidelity. At the simplest level the MAW is modelled as a sector-warning sensor with time-to-go or detection range triggers. At the more comprehensive level, and if required, can the MAW be modelled as a single or two-colour electro-optical sensor with associated processing. This option is open to the designer, even though the MAW is not a primary focus area of the simulator.

5.3.2 DIRCM steerable sensor

The DIRCM steerable sensor is modelled using the OSSIM models described in Sections 5.2.1 and 5.2.3. The model allows for customisable multi-colour operation in the shortwave, mediumwave and longwave spectral bands. The 3–5 μm sensor has a field of view of $4^\circ \times 4^\circ$, with a 512×512 detector with elements at 15 μm pitch and a fill factor of 0.8. The focal length of the F/4 sensor is 110 mm. The pixel field of view is 0.02 μsr. At a 100 Hz full-frame operation at maximum integration time, with detector D^* of 1×10^{10} cm$\sqrt{\text{Hz}}$/W and NEE of 5 nW/m^2. The signal to noise ratio of the missile when observed with this sensor is very high.

5.3.3 DIRCM fixed sensor

The DIRCM concept considered here has a number of 'heads' each with a fixed wide field of view sensor and a gimballed laser. Four heads cover all around the aircraft, plus one looking down. Each head has an imaging sensor, a track processor and a gimballed laser director. A single laser source feeds each of the heads by fibre.

Each head covers a wide field of view ($90^\circ \times 60^\circ$), assembled from two sensors, each ($45^\circ \times 60^\circ$), each with its own lens and detector (eight focal plane array detectors to cover 2π). Each 3–5 μm sensor has a 1024×768 detector with elements at 15 μm pitch and a fill factor of 0.8. The focal length of the F/4 sensor is 15 mm. The pixel field of view is 1 μsr. At a 100 Hz full-frame operation at maximum integration time, with detector D^* of 1×10^{10} cm$\sqrt{\text{Hz}}$/W, the noise equivalent irradiance (NEE) is 0.37 μW/m^2. Given the missile signature defined before, and this sensor definition, the signal to noise ratio is given in Figure 10. This configuration is technically feasible and mechanically simple, but expensive. Fortunately, it is quite inexpensive in simulation!

The sensor operating at 100 Hz is too slow to analyse the retro-reflection signature. Once the missile is detected, the laser reflection signature can be sampled at a higher frequency (4 kHz was investigated in[14]) in a sub-window. Sub-window imaging at higher frequencies is readily achieved in the simulation. Also, in the simulation it is a simple matter to implement a two-colour detector. Hardware implementation would be more challenging.

A weakness of this sensor is the hand-over from missile motor boost phase to sustain phase, when the signature drops ten-fold. At a closing distance of 2 km to 2.5 km the sensor will pick up the sustain motor again. Careful review and optimisation of missile signatures and the sensor design can be done very conveniently in the simulation.

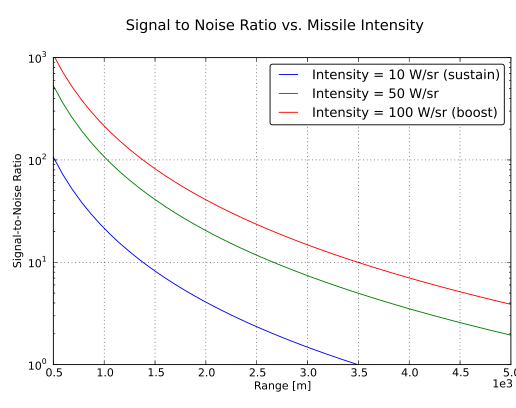

Figure 10: Head-on missile plume signal to noise ratio .

Image distortion can be corrected by lens calibration.[29] This sensor provides a designation vector with spatial resolution of 1 mrad near the center of the field of view, increasing slightly at larger field angles. Sub-pixel tracking will complicate the signal processing, but provides finer resolution than the optical image pixel resolution.

5.3.4 DIRCM laser

Modelling the laser in the DIRCM simulation is restricted to modelling the in-band effects on the sensor, rather than modelling the laser physics. The simulation implements the laser as a special polygon with directional and temporal behaviour. The laser model parameters are closely matched to the measured physical performance. Parameters include wavelength, spatial beam shape and divergence, and temporal radiance (intensity). The laser parameters can be readily varied to investigate various design options and trade-offs.

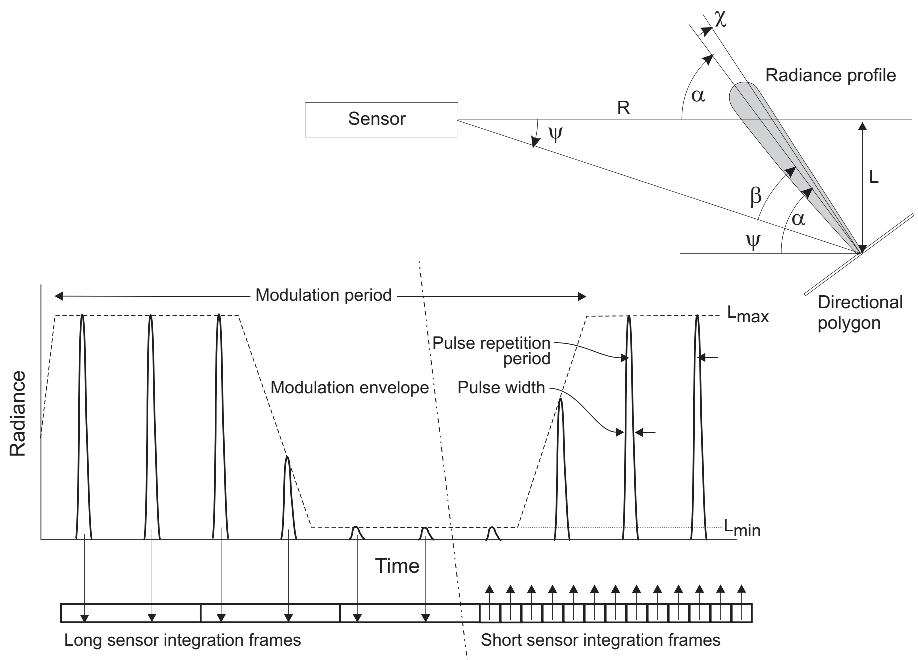

Figure 11: Laser model directional polygon and timing design.

5.4 Countermeasure Flares

Flares are physical objects with a body, a radiometric signature and flight behaviour. The gaseous nature requires radiance modelling by semi-transparent texture maps. All flares have in-band spectral emissivity properties. Temperature, area and texture changes temporally,[20] *for each colour separately*, to allow for different variations between the different spectral bands. Flare trajectories are calculated with a model of temporally decreasing mass and area.

5.5 Environmental aspects

All functionality of the Modtran atmospheric radiative transfer code is available in the simulator. Conversely, only the Modtran functionality is currently available. Turbulence effects[4] such as beam spreading, scintillation and spatial modulation transfer function (MTF) image degradation are not currently modelled. It is envisaged that such functionality will be added at a later stage.

The sky radiance (calculated with Modtran) presents the backdrop against which all other objects are painted. OSSIM also provides the functionality of background texture in the image, which can model terrain and sky/cloud clutter radiance and statistics (Figure 6).

5.6 System integration aspects

The greater DIRCM engagement system has a number of different axes, normally assumed to be ideally aligned (inertial measurement unit, MAW, missile tracker, laser pointer, multiple laser beams, etc.). In practice, these axes have non-zero alignment errors with statistical spread and drift. Likewise, can there be dynamic errors (offsets and noise) and angular leads or lags during tracking of moving objects. The end-to-end OSSIM DIRCM simulation can readily implement these effects in its object encapsulated modelling approach.

During tracking, the combined relative tracking error (lag and jitter/noise) between the carriage aircraft and missile plays a significant role in the performance of the respective systems. The required behaviour arises by its own nature, since the individual components in the system are accurately modelled. Of course, this requires accurate modelling of the subsystems.

The encapsulated nature of all the OSSIM models requires that each object (e.g. missile, aircraft or DIRCM) implements its behaviour in a built-in ‘controller’. All system mode or state control, logic or decision thresholds are implemented in the controller. Since each object acts in accordance with its internal controller, the interaction between objects is representative of the interaction expected in the real world systems.

6. PRELIMINARY RESULTS AND FUTURE WORK

6.1 Current model status

The underlying OSSIM library is well established and used in several other projects. Various aircraft and missile generic models are available, with infrared properties in the near infrared to longwave infrared, but not yet in the visible or ultraviolet. Given a project requirement, the data files for shorter wavelength models can be compiled.

The current missile model is a large air-to-air missile, while a ManPADS missile model is being ported from Matlab Simulink to the built-in OSSIM format. The imaging sensor model is a generic sensor model, allowing for different fields of view, detector configurations, multi-colour spectral band definition and other parameters. A centroid tracker is used to detect and track the aircraft.

The wide field of view, fixed sensor DIRCM configuration is designed but not yet fully implemented in simulation. The current two-colour 4° sensor model is suitable for modelling a steerable, narrow field of view sensor DIRCM configuration. The DIRCM tracker uses a centroid tracker to detect and track the missile.

The laser model, implemented as a polygon with special radiance properties is implemented and demonstrated on 'static' polygons. The behaviour includes spatial beam shape/divergence and temporal laser radiance pulses.

A number of scenarios were evaluated with the steerable sensor DIRCM configuration and an imaging missile sensor. The scenarios include scenarios with no countermeasures, with flares only, with DIRCM only and with flare and DIRCM.

6.2 Preliminary results

The simulation implementation successfully implements the two systems observing and tracking each other. The missile tracks and guides towards the aircraft, while the aircraft tracks the approaching missile. The flare countermeasure is fully operational and effective, while the laser countermeasure provides basic functionality. The basic laser functionality is effective in providing an interference signal. Jamming codes as required for reticle seekers are not yet implemented, since the reticle seeker models are still under development.

Experimental scenarios demonstrated the simulation's capability for each object to operate completely independently from each other, reacting to each other as would real-world objects. The only points of interaction between the missile and DIRCM are the two respective sensors. This capability is critical for modelling the complexities of the missile-DIRCM interaction.

One observation very early in the investigation confirmed the principle that low power jamming is not effective against imaging seekers; in fact, the centroid of the laser pulse aids in providing a stronger signal! From this observation it would seem that in-band damage could be at least one essential element in a countermeasure strategy. The fact that damage could be localised in the focal plane (i.e. only some detector elements) might be insufficient in itself, additional countermeasure means are still required.

6.3 Future work

The list of completed tasks is considerable, but the list of tasks requiring completion and future work is also considerable. The short term objective is to complete a ManPADS missile with AM (spin-scan) and FM (con-scan) seekers, with appropriate colour and sector suppression countermeasures. Also in the short term is the finalisation of the narrow field of view steerable sensor DIRCM laser. The laser polygon coordinates, which is currently static with respect to the fuselage, must be made steerable to follow the gimbal. At the completion of this work, the simulator should provide the infrastructure for the development of jamming codes against first and second generation missiles. In the longer time term, the wide-angle static sensor DIRCM will be developed, together with a number of pseudo-imager sensors.

7. CONCLUSION

The spiral of ever escalating complexity in the missile threat versus aircraft self-protection measures, together with the diversity of missiles, results in considerable challenges to the developers of aircraft self-protection systems.

An advanced DIRCM system hold some promise in this battle, by virtue of its high optical power levels (jamming or damaging), jamming signal programmability and more advanced interaction with the missile. The more advanced features in these systems require more sophisticated development environments, of which an accurate simulation is a critical element. The simulation provides a means to investigate the interaction between the missile, aircraft and DIRCM. However, in order to be of value, the simulation must be accurate and validated—both requiring considerable effort.

The present project indicated the feasibility of using the OSSIM simulation core to implement simulators for two different DIRCM configurations: a gimbal steerable sensor/laser configuration and a fixed sensor, steerable laser configuration. Both configurations are physically realistic and could be implemented. Initial experiments demonstrated that the approach taken in this research holds the promise to model the complex interactions in the missile-aircraft-DIRCM engagement.

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