Science real and relevant conference 2010
Proceedings homepage://www.conference.csir.co.za/

CSIR optronic scene simulator finds real application in self-protection mechanisms of the South African Air Force

CJ Willers[1*], JP Delport[1], MS Willers[2]

[1] CSIR Defence Peace Safety and Security, PO Box 395, 0001 Pretoria, South Africa
[2] Denel Dynamics, PO Box 7412, 0046 Centurion, South Africa

*Corresponding author: Nelis Willers: nwillers@csir.co.za

Reference: DS18-PA-F

Abstract

The Optronic Scene Simulator (OSSIM) is a second-generation scene simulator that creates synthetic images of arbitrary complex scenes in the visual and infrared (IR) bands, covering the 0.2 to 20 μm spectral region. These images are radiometrically accurate and based on theoretical physics models. The image rendering is implemented in specialised algorithms and calculated in double precision floating point. The simulation system has been extensively used for near infrared and infrared simulations.

OSSIM is developed as a collaborative effort with Denel, following a strategy of joint development of shared core infrastructure capability, but private development of application modules at the user level in the CSIR and Denel. In this way the project leverages project needs to stimulate growth in the core shared library, which is then available to all users, current and future. In this manner the simulation becomes a knowledge management tool. OSSIM is under active development and is intended to be the simulation tool of choice for sensor, imaging algorithm and infrared system developers. This paper provides an overview of the application of OSSIM to the South African Air Force's (SAAF) needs for self-protection.

1. Introduction

Military and civilian aircraft are under real threat from non-state shoulder-launched surface-to-air missiles. Since 1996, 20 attacks worldwide were reported, and during 1999–2001 more than 150 illegal missiles were seized (Whitmire, 2006).

Simulation is being used increasingly to support military system development throughout all the product lifecycle phases, from concept analysis, system development to doctrine writing. The advent of imaging weapon systems presented the need for simulation to provide accurate image rendering in the optical spectral ranges (DIRSIG, 2010, RadthermIR, 2010). Physics-based infrared scene simulators are used in the development, evaluation and optimisation of electro-optical systems, such as infrared missile seekers and thermal imagers.

Image simulation is used extensively at the CSIR to support the SAAF in various self-protection applications. The CSIR optimises countermeasure deployment using the OSSIM simulation system together with accurate missile, aircraft and countermeasure flare models. These countermeasures are optimised using thousands of simulated missile launches, and each time the effectiveness of the deployment is evaluated. OSSIM is a second-generation scene simulation system, developed jointly in South Africa by the CSIR and Denel Dynamics (Willers, 2007a, 2007b, 2009). OSSIM, together with its predecessor, have a 20-year development legacy with an investment of more than 50 man-years of application-focused development. Current applications are mainly in defence, but OSSIM can also be applied in the civilian world.

Accurate and comprehensive models of all observed objects (targets) and sensors (cameras) implement the behaviour of the real object in minute detail. Images created by these sensor models of detail and target-rich scenes are often indistinguishable from images created by real cameras of real scenes.

These simulations are required to model the effect of diverse environmental conditions, such as adverse atmospheres, varying altitudes and different types of terrain scenes and backgrounds. It is particularly important to account for atmospheric effects on the operation of optical systems.

The key focus areas for the simulation modelling capabilities are (1) radiometric accuracy using physics-based, spectral radiometric floating point image calculation, (2) accurate target signatures, including self-emitted flux and reflected sunlight, ambient and sky radiance, (3) accurate atmospheric spectral transmittance and background modelling, (4) accurate weapon models (camera, signal processing, gimbals, missile aerodynamics and flight behaviour) and (5) a full three-dimensional world, where objects can move in all six degrees of freedom. Objects can move through space by the laws implemented in the model itself: sit stationary, crawl on the terrain or fly through space.

During the 1990s it became evident that the SAAF's extant Magnesium Teflon Viton (MTV) flares do not provide adequate protection against the then modern shoulder-launched missiles. The CSIR played a pivotal role in the design of a new type of flare, with lower emission in the shorter infrared wavelength band. This New Generation Flare (NGF) was demonstrated to be an effective countermeasure against the missiles at the time of its deployment in the SAAF. However, increased countermeasure sophistication leads to further sophistication in missile seekers – a never-ending cycle! In order to counter the more sophisticated modern missile seekers, the mere deployment of a single flare is not sufficient. It became necessary to deploy mixtures of different types of flares, in a carefully designed time-series sequence to decoy the more modern missiles.

This paper presents a brief non-technical description of the application of OSSIM in aircraft self-protection. Behind the overview presented here, lies a depth of physics, advanced computer science, environmental characterisation, infrared metrology and simulation modelling.

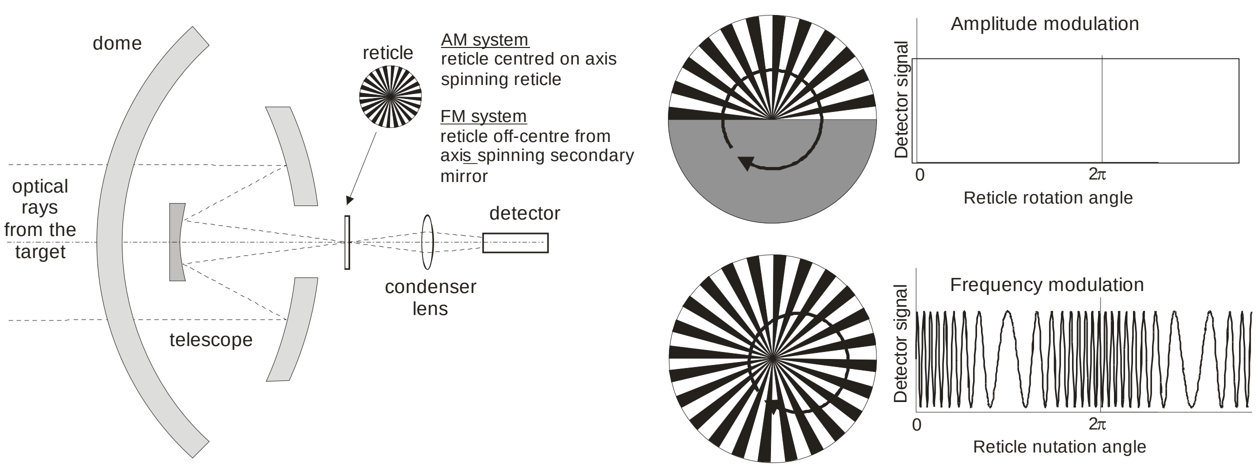


Figure 1: Amplitude and frequency modulation reticle operation

2. Missile threat

During peace-keeping operations SAAF aircraft experience a threat in the form of Man Portable Air Defence (ManPAD) missiles. These missiles employ amplitude modulation (spin-scan) reticles or frequency modulation (conical scan) reticle seekers, with single element detectors. As shown in Figure 1, an image of the aircraft is focused on the reticle. The reticle consists of regions with zero and unity transmittance, effectively ‘chopping’ the optical signal as the image moves across the reticle. The aircraft angular tracking error, decoded from the detector signal, is used to guide the missile towards the aircraft.

The objective of the aircraft’s self-protection system is to decoy or mislead the missile to miss the aircraft. The missile can be decoyed by creating a strong infrared source confusing the missile.

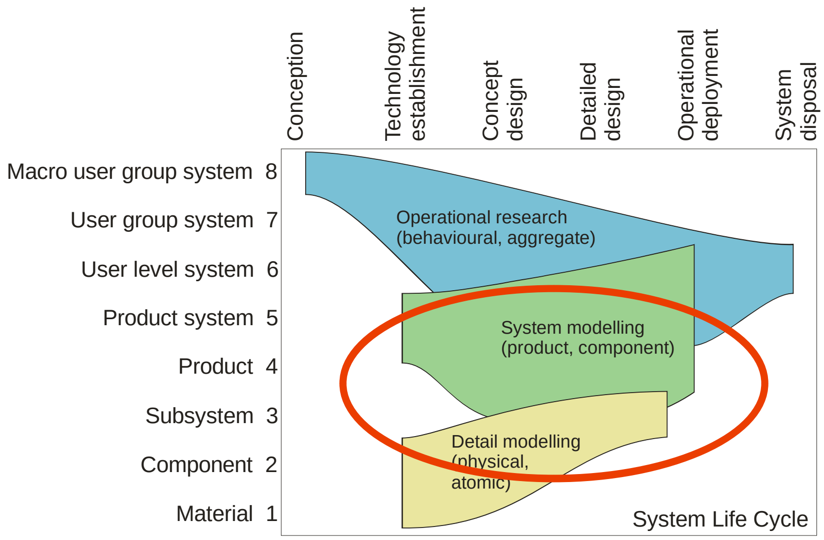


Figure 2: OSSIM positioning in the system hierarchy and lifecycle phases

3. Varying levels of detail in the simulation

In the SAAF self-protection application, OSSIM models system elements between levels 2 and 5 in the system hierarchy shown in Figure 2. Some elements are modelled at component level detail (e.g. infrared detectors, spinning reticle, aircraft fuselage and plume), while other elements in the same simulation are modelled at subsystem level (e.g. the guidance control system implemented in the frequency domain, using Laplace transforms) or even at a product or product system level (i.e. missile approach warning system). The power of OSSIM is that one simulation can house and execute models at all these different levels, in the same execution run.

4. Application of OSSIM in aircraft self-protection

OSSIM is developed in a consortium (CSIR and Denel Dynamics), where the two members have an interest in the joint development of shared code, but private development of their own application code. This requirement led to the definitions of ‘red code’ and ‘green code’, as indicated in Figure 3. The ‘green code’ is shared freely within the consortium, while the ‘red code’ is private to each consortium member.

The ‘green code’ (the shared library) covers general-purpose infrastructure elements such as radiometry, the scene graph, the atmosphere, rendering and rasterisation, time synchronising, and functionality to integrate all the ‘red code’ modules to work together. The functionality provided in the ‘green code’ is useable by any user and hence is not linked to any specific user requirement.

In the aircraft self-protection application, the ‘red code’ covers the application models, such as the aircraft and countermeasure flares (moving objects), sensors (observer objects) and background objects. These models describe the elements, with exacting specifications, present in the user's world. In the aircraft self-protection application, some elements of OSSIM have been imported into a Matlab simulation (indicated in blue in Figure 3), exploiting the strengths and benefits of both Matlab and OSSIM.

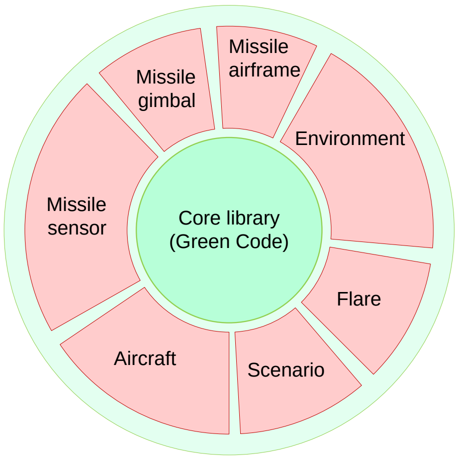


Figure 3: Aircraft self-protection as implemented using the OSSIM library

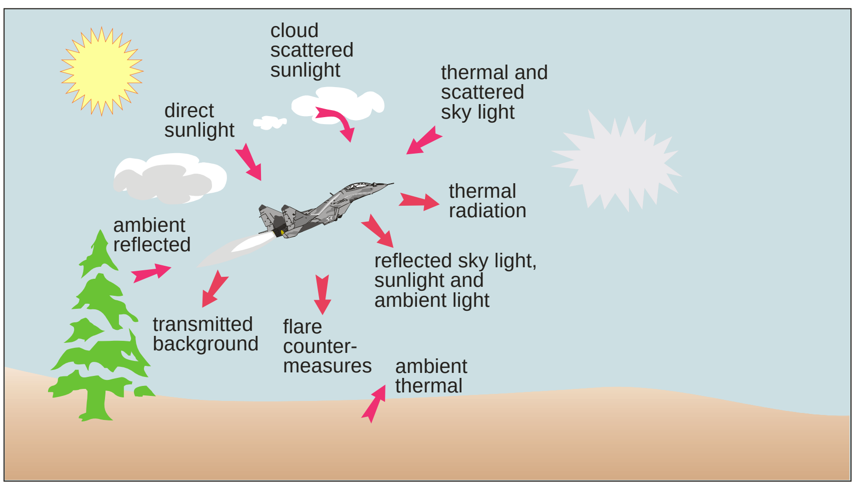


Figure 4: Sources of optical flux accounted for in aircraft self-protection

5. Physics-true modelling and image rendering

All objects in the simulated world, including the aircraft and attacking missile, are rendered in terms of emitted, reflected and transmitted energy (Figure 4). The emitted radiance of objects is determined by the object's inherent temperature and surface emissivity. The sun radiance, sky radiance and ambient background radiance are reflected from objects in the scene. Objects in the scene can be partially transparent (e.g. the aircraft exhaust plume) allowing the transmittance of background radiance. These radiance components are all attenuated by the atmosphere between the missile and the aircraft. The emitted atmospheric path radiance emanating between the missile and the aircraft is added to the total radiance. The image of the scene, as focused on the missile seeker reticle, is therefore quite complex – not just a simple picture of the aircraft fuselage outline.

The main contributors to the complex signature radiance are shown in the following simplified rendering equation (Willers, 2010) for *spectral* radiance, where the terms are defined in Table 1. The physics behind this equation and its implementation are extensively validated (Willers, 2007b).

$$
\begin{aligned}
L_\lambda \;=\; & \overbrace{L_p\mathcal{S}}^{\text{atmospheric path}} + \overbrace{L_{bb}(T_o)\epsilon_o\tau_a\mathcal{S}}^{\text{thermally emitted}} + \overbrace{L_{bb}(T_b)\tau_o\epsilon_b\tau_{abo}\tau_a\mathcal{S}}^{\text{transmitted background}} \\
& + \overbrace{L_{bb}(T_a)\rho_o\epsilon_a\tau_{ao}\tau_a\mathcal{S}}^{\text{reflected thermal ambient}} + \overbrace{\alpha_s\cos\theta_s L_{bb}(5900K)\rho_o\epsilon_s\tau_s\tau_a\mathcal{S}}^{\text{reflected sunshine}} + \overbrace{\cos\theta_a L_{\text{sky}}\rho_o\epsilon_h\tau_a\mathcal{S}}^{\text{reflected sky ambient}}
\end{aligned}
$$

Table 1: Radiometric signature elements

Symbol	Meaning
$\alpha_s L_{bb}(5900K)$	approximation of reflected solar radiance
ϵ_a	the ambient environment's spectral emissivity
ϵ_b	the background spectral emissivity
ϵ_h	sky radiance spectral emissivity
ϵ_o	object surface spectral emissivity
ϵ_s	solar surface's spectral emissivity
$L_{bb}(T_a)$	black body radiance, environment at temperature T_a
$L_{bb}(T_b)$	black body radiance, background at temperature T_b
$L_{bb}(T_o)$	black body radiance, object at temperature T_o
L_p	atmospheric path radiance: emitted plus scattered
L_{sky}	sky radiance: emitted plus scattered
ρ_o	object surface spectral reflectance
$\mathcal{S}$	camera spectral response
τ_a	object to sensor spectral atmospheric transmittance
τ_{abo}	background to object atmospheric transmittance
τ_{ao}	ambient to object spectral atmospheric transmittance
τ_o	object surface spectral transmittance
τ_{so}	sun to object spectral atmospheric transmittance
θ_a	angle between the surface normal and the vertical
θ_s	angle between the surface normal and solar incidence

The missile threat and aircraft self-protection application, operating in the 1–2.5 μm and 3–5 μm spectral bands, demonstrate the need for both reflected sunlight and thermal self-emission contributions to the signature, as demonstrated in Figure 5.

The signature of the aircraft exhaust plume is caused by hot CO_2 in the exhaust. The signature of the hot CO_2 is spectrally varying as shown in Figure 6. This spectral signature requires that calculations account for the spectral variations *within* a spectral band. It is very important that atmospheric transmittance be considered as a spectral variable within a band for such spectrally varying objects.

Atmospheric conditions have a significant effect on the radiometric representation of the aircraft signature, especially that of the plume as well as the spectral NGF flare. To allow for the subtleties and variability in atmospheric attenuation, the simulation employs the full scope of all the capabilities of the MODTRAN (MODTRAN, 2010) code. MODTRAN is a state-of-the-art computer code that calculates atmospheric transmittance and path radiance for frequencies from 0 to 50 000 cm^{-1} at moderate spectral resolution. The simulation sets up MODTRAN with information such as path geometry, aerosol conditions (fog, particulate matter), visibility, radiosonde profiles, and solar and lunar locations. After completion of the run, the simulation incorporates the MODTRAN results in its internal spectral radiometric calculations. Figure 7 shows a sample MODTRAN spectral atmospheric transmittance curve.

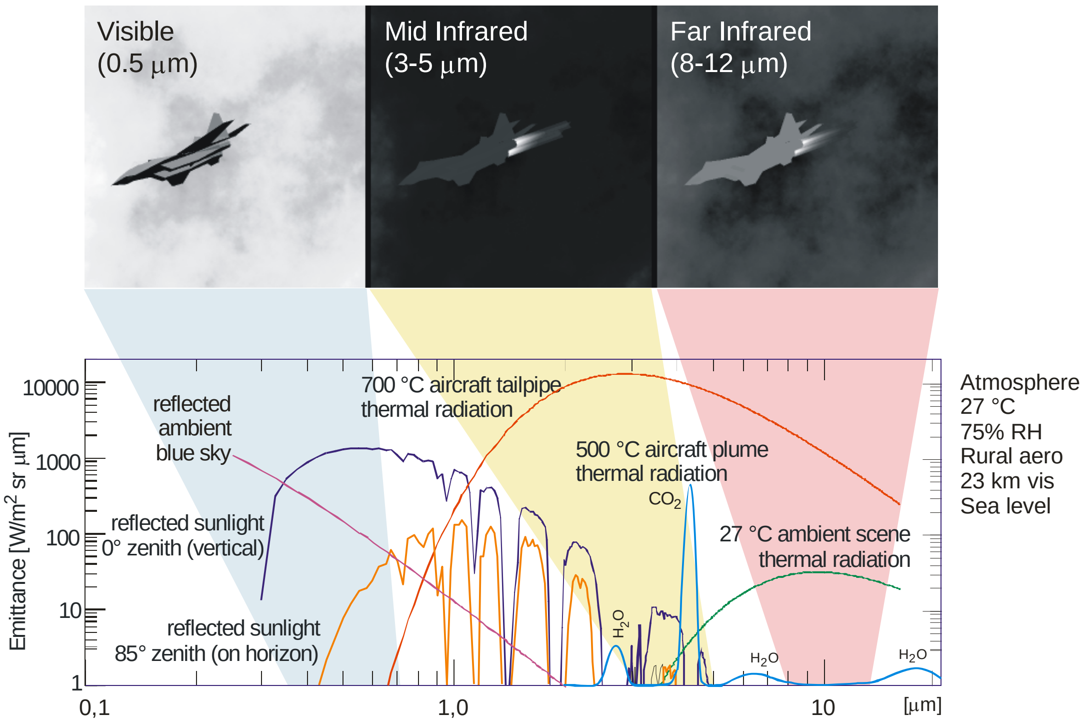


Figure 5: Reflected sunlight and self-emitted thermal signature components

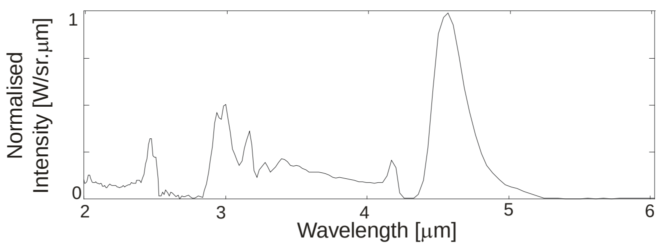


Figure 6: Normalised spectral radiant intensity of a gaseous radiator

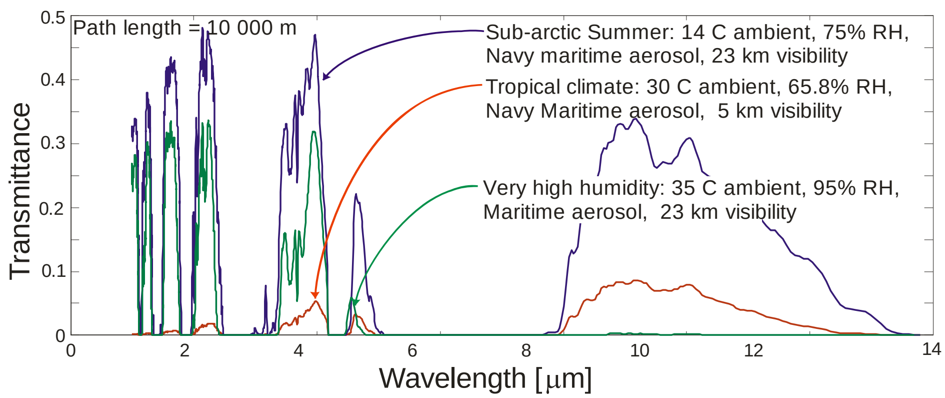


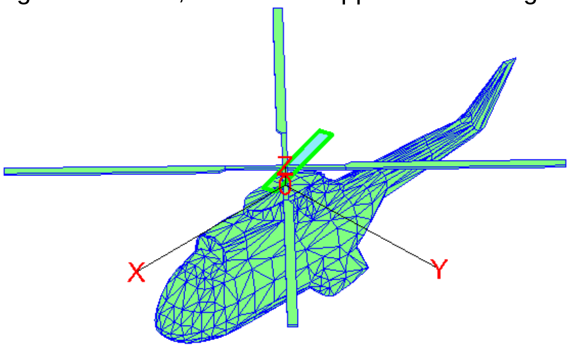
Figure 7: Atmospheric transmittance for different atmospheric conditions

6. Aircraft model

The aircraft geometrical shape (Figure 8(b)) is modelled as a three-dimensional complex hull, comprising a large number of flat convex polygons (Figure 8(a)). Each polygon is assigned radiometric properties for the different wavelength regions in the simulation. These properties include material type, emissivity, reflectance, transmittance, temperature, specular reflectance parameters, thermal properties and more.

The plume polygons are rendered with a CO_2 spectral emissivity and a spatial texture map to model spatial variations in the plume. The texture data are extracted from measured infrared images. These plume polygons are also partially transparent, allowing the background to be partially visible.

The aircraft dynamic behaviour is implemented in algorithms in C++ code. These algorithms control the flight behaviour, the missile approach warning and the decision when to dispense countermeasure flares.



(a)

(b)

Figure 8: Aircraft modelled by polygons, and a real-world flare dispensing

7. Countermeasure flare models

The countermeasure flare is modelled by a series of textured surfaces and, very importantly, a spectral emissivity, with illustrative values shown in Figure 9 (security constraints prohibit publication of the true spectrum). Figure 9 shows that the spectral intensity of the old technology MTV flare is very different from the spectral intensity of the aircraft plume and the new technology NGF flare. This difference is exploited in the more modern missiles, which are programmed to detect the difference in signatures by measuring in two spectral bands, as shown in Figure 9, and hence ignoring the MTV flare.

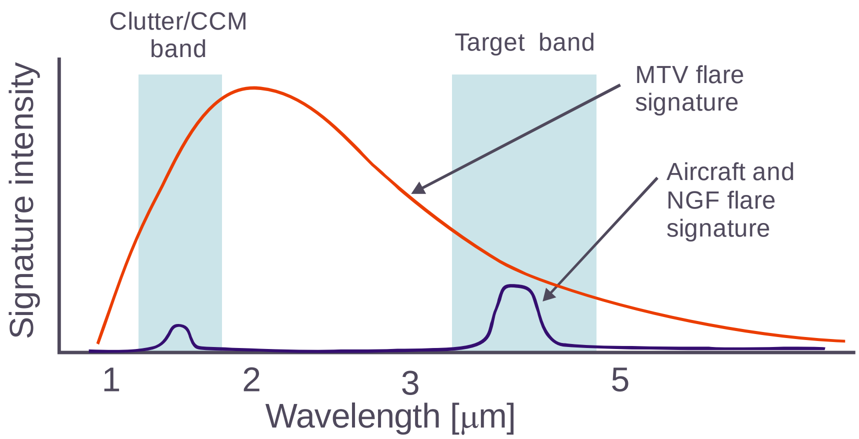


Figure 9: Countermeasure flare model spectral intensity (illustrative values)

8. Threat missile models

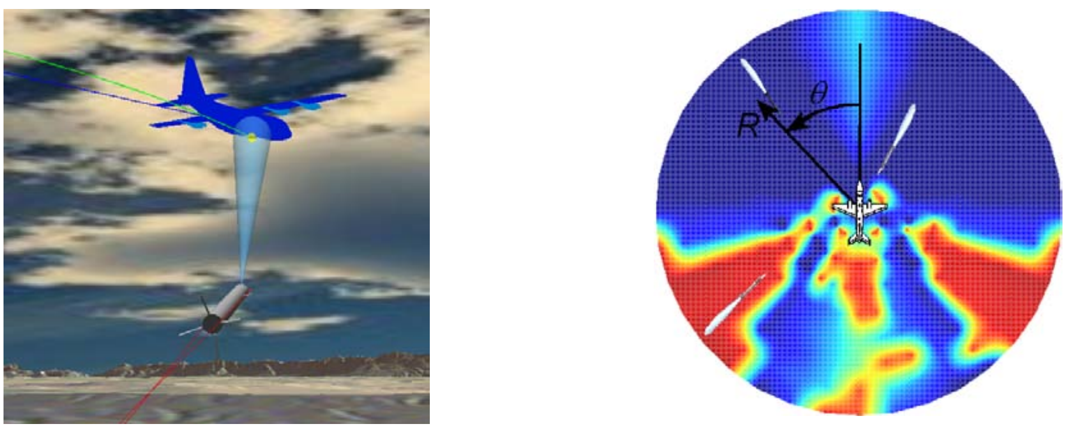
The missile models implement algorithms that calculate the image on the reticle, then rotate or nutate the image across the reticle pattern (see Figure 1), calculating the instantaneous detector current. The detector signal is processed according to the missile signal processing, and the missile is guided towards the aircraft. These models are implemented in varying levels of detail, as necessitated by the need for accuracy and the amount of information at hand. The image formation and optical sensor are modelled in some detail, while the tracking and guidance control loops are modelled at a much higher level.

9. Countermeasure flare optimisation

Since missiles can be launched at an aircraft from any position on the ground, it is necessary to optimise the flare-dispensing direction relative to the approach of the attacking missile. If the flare is ejected at a sub-optimal angle, it may even assist the missile instead of decoying the missile!

Simulation steps are sequenced to perform a 'closed-loop' simulation in an endless loop, like a dog chasing its tail. The system starts by calculating an image as seen by the sensor. The sensor and signal processing calculate a response and change some aspect of the missile (e.g. position and direction), then requesting a new image. By activating all the relevant modules sequentially in a repetitive sequence, a time-sequential, closed-loop simulation is executed. The missile, in effect, flies through space, towards the aircraft, reacting to all events in its field of view.

The effect of flare spectral signature, ejection direction and flare sequence timings are evaluated using thousands of simulated missile firings. The proposed deployment procedures are evaluated by launching missiles from different aspect angles (θ) and ranges (R) at the aircraft. It is sometimes difficult to interpret the results, and hence the missile flight is reviewed using the CSIR's Sentience3D tool (Duvenhage, 2010). See Figure 10(a).



(a) (b)

Figure 10: Aircraft vulnerability results – visualisation and typical results

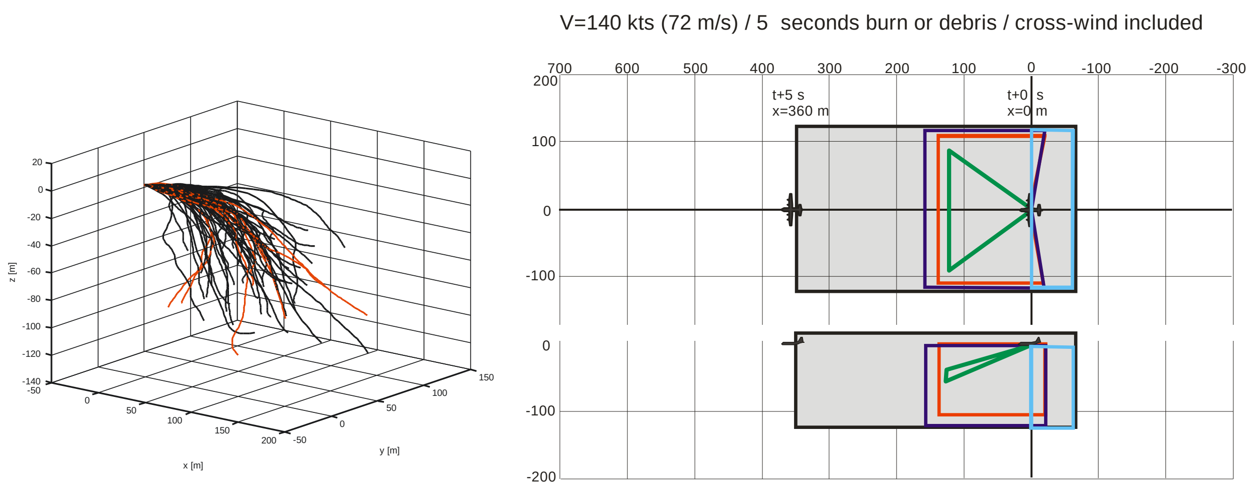
An example vulnerability result is shown in Figure 10(b). Each spot in the graph represents a missile launch from that location (indicated by the small missiles in the picture). If the countermeasure is effective in decoying the missile away from the aircraft, the miss distance is large (indicated by blue) and if the missile passes close to the aircraft, the aircraft is vulnerable (indicated by red). Different flare deployment strategies are evaluated with respect to the indicated vulnerability and the strategy is rejected or revised for improvement. The objective is to maximise the blue zones and minimise the red zones.

Once the strategy is optimised in simulation, it must be tested for validity in the real world (Figure 8(b)). Using the vulnerability graphs, a limited number of field trial test points are defined. These test points are typically selected on boundaries and in the high-vulnerability zones of the graphs. Once defined, the SAAF executes a real-world field trial to verify the validity of the simulation results.

Invariably, some test point results will be at variance with the simulation results, requiring further model improvements and redesign of the procedures. After a number of such cycles, the procedures are then accepted as part of the SAAF standard operating procedures.

10.Flare safety footprint

Flares ejected from aircraft pose a threat to other aircraft flying in close formation or located nearby the ejecting aircraft on the ground. The SAAF approached the CSIR to provide information on the flare trajectory during flight, with the aim of defining a safety footprint around each aircraft.



(a) (b)

Figure 11: Flare footprint modelling – (a) flare trajectory under turbulence (b) safety footprint

For this purpose the flare free-flight trajectory model in OSSIM was used to predict flare trajectories under static, ground-based and flight conditions. Previously recorded flight test data were used to construct a model for flare trajectories under turbulent air flow conditions. Figure 11(a) shows predicted flare trajectories under turbulent conditions. From these predictions the flare footprint was determined for the different aircraft and ejection angles, an example of which is shown in Figure 11(b).

11. OSSIM as a knowledge management tool

OSSIM is an environment in which tacit knowledge is captured in the form of model behaviour. The SAAF aircraft, missile threats and flare models are constantly revised and improved towards greater fidelity. Likewise, the core library is continually upgraded and expanded (Figure 12). The end-effect of this process is an ever-growing tool, ready for research and operational use – even outside the scope of the current activity (Willers, 2009, Willers, 2010b).

12. Conclusion

The application of the OSSIM image simulation system in the protection of SAAF aircraft has been shown to be an effective means to decrease the vulnerability of our aircraft. The long-term view taken in this work ensures continuous growth in capability and understanding of the field, preparing the CSIR and the SAAF to meet the challenges of future threats.

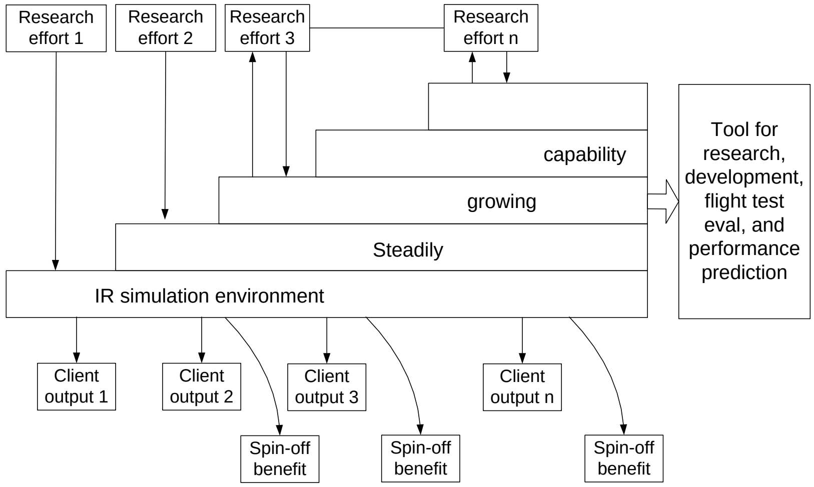


Figure 12: OSSIM as a knowledge management repository

13. References

DIRSIG, 2010, Digital Imaging and Remote Sensing Image Generation (DIRSIG), http://www.dirsig.org Accessed on 17 June 2010.

Duvenhage, B., Delport, J.P. 2010 Using 3D and Information Visualisation to Improve Perception and Facilitate Situation Awareness. Paper DS11-PO-F, Science Real and Relevant conference 2010, www.conference.csir.co.za

MODTRAN. 2010. http://www.modtran.org/ Accessed on 16 June 2010.

RadthermIR. 2010. http://www.thermoanalytics.com/products/radthermir/index.html Accessed on 17 June 2010.

ShipIR. 2010. http://www.wrdavis.com/NTCS_intro.html Accessed on 30 June 2010.

Whitmire, J.C. 2006. Shoulder-launched missiles (a.k.a. ManPADs): The Ominous Threat to Commercial Aviation, Counterproliferation Papers, Future Warfare Series No. 37, USAF Counterproliferation Center, December 2006.

Willers, C.J. 2010a. The Technique of Radiometry: Analysis & Modelling, book in draft form for publication.

Willers, C.J., Wheeler, M.S. 2007a. Application of Image Simulation in Weapon System Development, Proceedings: IX SIGE Electronic Warfare Conference, CTA São José Dos Campos, São Paulo, Brazil, 2007.

Willers, C.J., Wheeler, M.S. 2007b. The validation of models in an imaging infrared simulation, IEEE International Microwave and Optoelectronics Conference (IMOC 2007), ISBN 978-1-4244-0661-6, Salvador, Brazil.

Willers, C.J., Willers, M.S. 2010b. OSSIM: Optronics Scene Simulator, CSIR White Paper 6700-PG-103400-01.

Willers, M.S., van den Bergh, J.S.H. 2009. Application of Optronics Scene Simulation in Infrared System Development. *Sensors, MEMS and Electro-Optical Systems (SMEOS 2009)*, ISBN 978-0-620-45648-7, Skukuza, South Africa, 2009.

14. Endnote

The application of OSSIM in support of the SAAF is funded by Armscor technology funds. The aircraft self-protection work is done in close liaison with the SAAF. Denel Dynamics is acknowledged as an equal partner in the creation of the core OSSIM library. The CSIR's contribution towards the OSSIM library is funded by CSIR Parliamentary Grant allocations.