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Optical signature modelling - Final report

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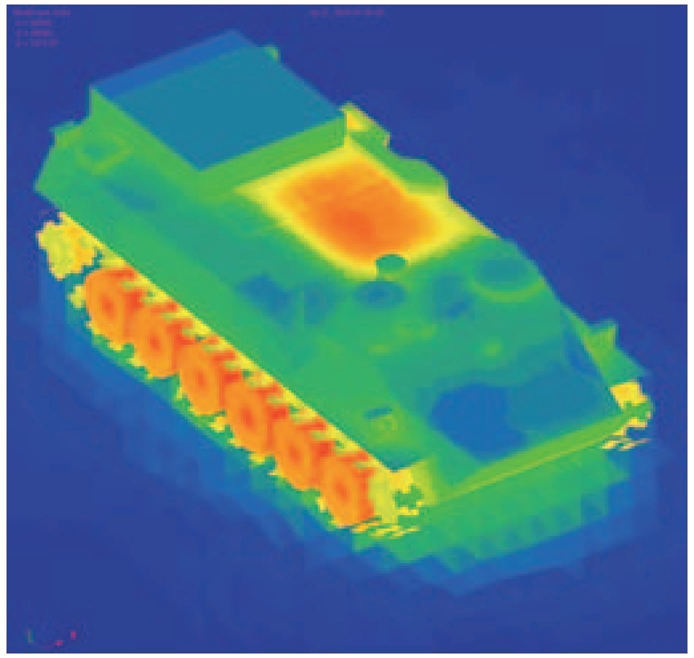

FOI-R-- 1812 --SE User report
ISSN 1650-1942 November 2005

Sensor Technology

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ISSN 1650-1942

Sensor Technology
User report

November 2005

Issuing organization FOI – Swedish Defence Research Agency Sensor Technology P.O. Box 1165 SE-581 11 Linköping	**Report number, ISRN** FOI-R--1812--SE **Report type** User report **Research area code** 6. Electronic Warfare and deceptive measures **Month year** November 2005 **Project no.** E3071 **Sub area code** 62 Low Obervables **Sub area code 2**
Author/s (editor/s) Claes Nelsson Göran Forssell Patrik Hermansson Sten Nyberg Andreas Persson Rolf Persson Stefan Sjökvist Thomas Winzell	**Project manager** Claes Nelsson **Approved by** Lena Klasén **Sponsoring agency** Armed forces **Scientifically and technically responsible** Claes Nelsson

Report title

Optical signature modelling
 - Final report

Abstract

The project has focussed on research issues regarding methods and models for a detailed prediction of optical signature of a target in background. Methods and a computational environment have been established for the needs of the armed forces. Different platform concepts can be studied in different environments and weather conditions. Both geometry and surface parameters can be optimized. Simulations can support the development of tactics. For the design and assessment of sensor systems predictions of target signatures are needed. Credible signature descriptions are also needed as input to duel simulations.

This document reports on the work that has been performed concerning the generation of input data, methods/programs for simulations and model validations. The primary programs used were RadThermIR and CAMEO-SIM. Two paths of development of validation methods are presented: 1. Methods for analysis and validation spatial image statistics; 2. Methods for quantifying the propagation of input data uncertainties to output parameters in computational predictions.

This report shows that relevant and qualified programs are available at FOI for optical signature predictions. The methods to use input data to obtain simulated targets in backgrounds have been clarified. Limitations have been shown and areas where improvements are necessary have been identified.

Keywords

CAMEO-SIM, IR, modellering, RadThermIR, signatur, vadidering

Further bibliographic information	**Language** English
ISSN 1650-1942	**Pages** 48 p.
	Price acc. to pricelist

Utgivare	**Rapportnummer, ISRN**	**Klassificering**
FOI - Totalförsvarets forskningsinstitut Sensorteknik Box 1165 581 11 Linköping	FOI-R--1812--SE	Användarrapport
	Forskningsområde 6. Telekrig och vilseledning	
	Månad, år November 2005	**Projektnummer** E3071
	Delområde 62 Signaturanpassning	
	Delområde 2	
Författare/redaktör Claes Nelsson, Stefan Sjökvist Göran Forssell, Thomas Winzell Patrik Hermansson Sten Nyberg Andreas Persson Rolf Persson	**Projektledare** Claes Nelsson	
	Godkänd av Lena Klasén	
	Uppdragsgivare/kundbeteckning Försvarsmakten	
	Tekniskt och/eller vetenskapligt ansvarig Claes Nelsson	

Rapportens titel

Optisk signaturmodellering - slutrapport

Sammanfattning

Projektet har fokuserat på forskningsfrågor om metoder och modellering för att kunna genomföra en detaljerad prediktion av optisk signatur hos ett mål i bakgrund. Metoder och beräkningsmiljö har byggts för försvarsmaktens behov av prediktion av optisk signatur. Olika koncept på plattformar kan studeras i olika miljöer och väderförhållanden. Optimering av parametrar kan göras, både med avseende på geometri och på ytmaterial. Genom att prediktera mål/bakgrundskontrasten för olika fall kan taktik utvecklas. Vid design och värdering av sensorsystem (inklusive signalbehandling) behövs signaturriktiga modeller av mål och bakgrund. För duellsimuleringar krävs signaturriktigt underlag.

Rapporten redovisar arbetet som bedrivits avseende generering av indata, metoder/program för simulering samt modellvalidering. De program som primärt har använts för signatursimuleringen är RadThermIR och CAMEO-SIM. I rapporten presenteras två olika typer av valideringsmetoder: 1. Analys och validering statistiska bildegenskaper; 2. Metoder för att kvantifiera fortplantningen av osäkerheter i indata till utresultatet från signaturberäkningarna.

Rapporten visar att relevanta och kvalificerade programvaror finns vid FOI för optiska signaturberäkningar. Metoderna för att gå från indata till simulerade mål i bakgrund har tydliggjorts. Begränsningar har belysts och områden där förbättringar bör ske har identifierats.

Nyckelord

CAMEO-SIM, IR, modelling, RadThermIR, signature, validation

Övriga bibliografiska uppgifter	**Språk** Engelska
ISSN 1650-1942	**Antal sidor:** 48 s.
Distribution enligt missiv	**Pris: Enligt prislista**

CONTENTS

1 INTRODUCTION

Computer programs for prediction of optical signatures of targets and backgrounds are valuable tools for signature assessment and signature management. Simulations make it possible to study optical signatures from targets and backgrounds under conditions where measured signatures are missing or incomplete. Several applications including studies may be identified:

Increase understanding: By modelling signature phenomena the understanding of the different processes can be increased.

Design and assessment of low signature concepts: Different concepts of platforms can be studied for different environments and weather conditions. Furthermore, studies of surface and geometry designs can be performed.

Assessment of tactics: By predicting the target/background contrast for different cases, rules for tactical behaviour can be developed. Modelling and simulation of optical signatures is also valuable when new environments are studied such as Battle group operations.

Design and assessment of sensor systems: Computer models with correct signature representation of targets and backgrounds are useful as design tools.

Duel simulations of EW: Computer models with correct signature representation of targets, countermeasures and backgrounds are needed, in many cases simplified to be able to treat a complex scenario.

Signature awareness: By knowing your signature in a tactical situation different kinds of actions, camouflage etc can be controlled. On-board models are needed to predict the signature.

The project covered in this report has focused on research issues concerning methods and modelling for performing a detailed prediction of the optical signature of a target in background. The project has been carried out during 2004–2005 and the aim has been to provide tools for the needs of the Swedish armed forces. At FOI (the Swedish Defence Research Agency), several commercial programs have been used for optical signature predictions, see Ref 9. Two of the commercial optical signature prediction programs available at FOI are CAMEO-SIM and RadThermIR. **CAMEO-SIM** (Camouflage Electro-Optic Simulation System) **(**Ref 20**)** is an advanced IR program aiming at producing high-fidelity physics-based images originally applied to camouflage assessments. **RadThermIR (**Ref 37**)** is a 3-D heat transfer program that uses Finite Difference Methods to first predict the temperature distribution for a target and then the IR radiance. RadThermIR is the commercial version of the Muses program. For applications in aircraft modelling the program **McCavity** (Ref *36* and Ref *38*) is used which includes capability to predict the signature of jet plumes. McCavity is not used in this project. The goals of the project have been:

- Assemble a database of necessary input data for signature predictions in Swedish and international environments. The database should consist of material properties, geometries, backgrounds and atmospheric properties.
- Study and increase the experience of different programs for optical signatures, mainly CAMEO-SIM and RadThermIR. Develop efficient routines for the modelling of different platforms in an environment.

- As a complement, develop algorithms and programs in areas were no commercial programs are available.
- Validation and assessment of simulation results and methods
- Develop international cooperation in the area of optical signature predictions for applications in international operations.

This report summarizes the activities in the project and the results obtained. Not all results from the project are presented here. Instead references are given to all documentation produced during the project period. The report is organized as a walk-through of all the necessary steps in creating and running a signature modelling case. As a start an overview of the process is given in section 2 that serves as an introduction to the following sections. The test case chosen is Pbv401 which is a tracked armoured vehicle which has been used previously at FOI for research purposes and therefore a lot of measurement data is available. The international name of the vehicle is MTLB. Two other vehicles have also been studied: T72 to get an example of a main battle tank and Tgb11 to get an example of a lighter wheeled vehicle. The development of the vehicle models has also been funded from the three FOI projects Advanced Target Seekers, Precision Weapons in Network Based Defence and Sensor node for surveillance and reconnaissance (SNOD). The models have played an important role in the development of target recognition algorithms.

One clarification of the report must be made: Even though the aim of the report structure is to provide something of a cookbook of optical signature modelling, the report to some extent stresses the parts that the project has focussed on. It might also be the case that some aspects of signature modelling are treated too briefly. The report ends with some conclusions and suggestions for future work.

2 OPTICAL SIGNATURE MODELLING – OVERVIEW

Modelling of optical signature fundamentally consists of two quantities to predict: 1. The temperature of a target and of the background due to their inherent properties and the present environmental conditions; 2. The amount of optical radiation that reaches a sensor from the target and the background due to self emission and reflected radiation. For the studies in the visible and near-IR regions only the second quantity is relevant. Temperature changes have no significant influence at shorter wavelengths.

An overview of the modelling process is shown in Figure 1. The starting point is to define the scene model including targets and background. Different kinds of data are necessary to set up the model. The procedures for this and the data needed are treated in sections 3, 4 and 5. The next step is to perform the actual simulation. For this, information about the scenario and the weather conditions have to be included as well as a sensor specification, see sections 67. In the work described in this report the simulation programs RadThermIR and CAMEO-SIM have been used which are further described in section 8. To achieve a simulated sensor-output a sensor model has to be included. This has not been a part of this project but is shortly commented in section 9. The completed simulations have to be validated for a number of cases to obtain credibility. Such activities have been performed in the project and they are described in section 10. A study has been performed concerning the modelling of polarization effects which is currently not included in the commercial programs used, see section 8.3.

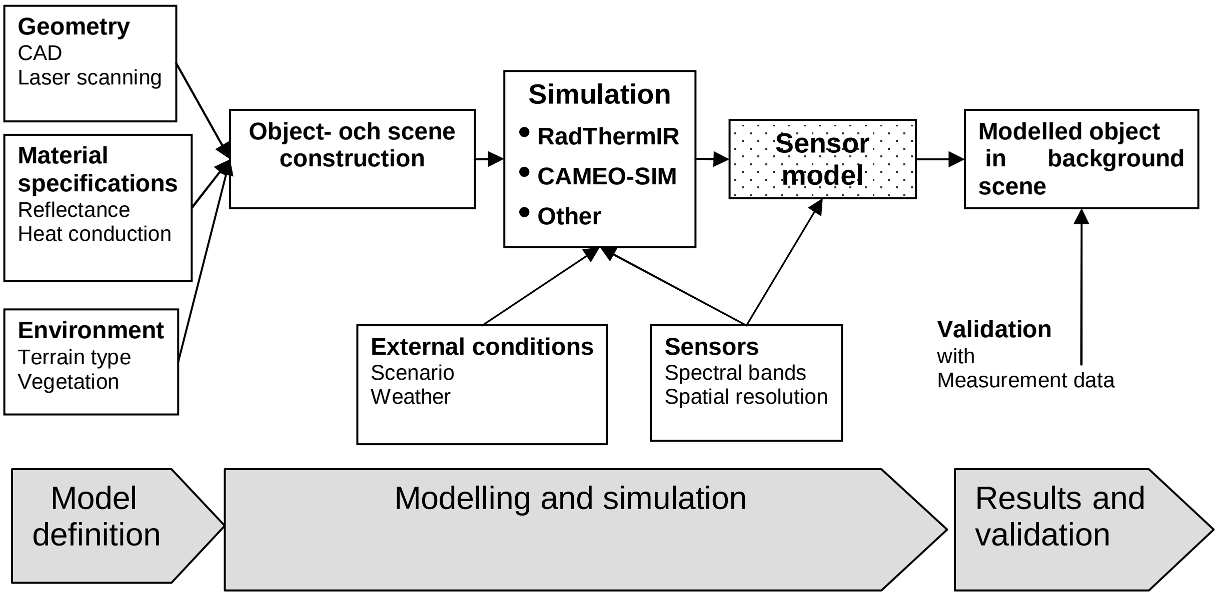

Figure 1. Schematic overview of the modelling process.

As always when it comes to modelling of physical phenomena certain assumptions and decisions have to be made regarding what phenomena to include in detail and what is possible to simplify. Concerning aspects of thermal environmental parameters used together with modelling tools, Table 1 is found in the literature. The table shows the individual thermal responses from different parameters. The table should be used with caution and only seen as a rule of thumb. When it comes to the modelling of optical signature the responses are slightly different for the parameters.

Table 1. Relative model responses to the variation of several input parameters, from Ref 26.

Very Sensitive	Moderate Sensitive	Very Insensitive
Air temperature	Relative humidity	Air Pressure
Solar irradiance	Target height	Cloud cover (high level clouds)
Solar absorption coefficient	Wind speed	Time Step
Thermal emission coefficient	LWIR sky irradiance	Thermal diffusivity
Top layer heat conductivity on ground	Thermal conductivity	Mesh Size
Cloud cover (middle layer clouds)	Bottom heat flux (if the model is deep enough)	
Cloud type		Diurnal repetitions
Initial conditions		
Vegetation		

RadThermIR and CAMEO-SIM that are treated in this report have a different focus when it comes to emphasizing different physical phenomena. RadThermIR has its strength in thermal predictions and CAMEO-SIM in radiometry. The ongoing linking of those programs is probably a very fruitful way to go. The programs are further described in section 8.

3 GEOMETRY

Geometrical models are a necessity in simulation of optical signatures. They can of course be quite simple, e.g. a four cornered panel (Ref 9), and quite complicated such as a terrain background. Still, a description of the object at hand has to exist, and this can be carried out in a number of ways, usually dependent on the application. For example, the thermal modelling program RadThermIR has quite strict requirements on how a satisfactory geometry (mesh) has to be, while the synthetic optical scene generator CAMEO-SIM does not. The differences between these two types of geometrical requirements lie in the differences between these two simulation programs. For RadThermIR it is important that a complete 3-dimensional geometry exist, as the program models heat transfer in all directions. CAMEO-SIM has only a 1-dimensional heat transfer and only requires a 'shell' description of say a vehicle. In CAMEO-SIM heat transfer only occur perpendicular to the surfaces, while in RadThermIR heat transfer also occur laterally. In the next two subsections geometrical set-up will be discussed first for targets such as vehicles, secondly for backgrounds.

3.1 TARGETS

Generating a mesh for thermal analysis is a complicated task requiring expertise and advanced tools. This step in the thermal analysis chain is essential for good quality thermal analysis later on and can also be the most time-consuming. The initial geometry sometimes has a lot of issues that has to be straightened out before the meshing process can be initiated (sometimes referred to as geometry preparation). Depending on the original CAD-geometry, the geometry preparation can be really cumbersome – in our test case, the Pbv 401, it really was.

The three objects, Pbv 401, T72 and Tgb11, were created in 3D-Studio Max with a geometry obtained with a laser scanner as template. The laser scanned version of the geometry itself was impossible to use as geometry in RadThermIR as it was not close to fulfil the demands for proper thermal analysis. The method of using laser scanned versions as template was successful though any blueprint probably (at least for the well-known T72) could have been used as template with equal but faster result.

The Pbv 401 was possible to render with good results visually but for good thermal analysis the demands can be quite different, for example it is of vital importance that the interior structure corresponds with reality. The interior parts which from a thermal point have influence (engine, exhaust, engine compartment walls) must be constructed, though perhaps in a simplified manner.
All edges must have contact to allow conductance though in some cases conductance may not be present i.e. a glass window or hatch is isolated from the hull by a rubber gasket.
A lot of work can be saved if the geometry is created from the beginning with these things in consideration.

3.1.1 Creating a mesh

The final Pbv 401 was constructed with 51 different parts defined by differences in material, thickness or surface optical properties (paints). All mesh elements have full conductance between the part limits, see Figure 2 and Figure 3 for the Pbv 401 and T72 respectively. The original number of elements for the Pbv 401 was approximately 110 000 elements (including the inner elements) which is fairly much. The large amount of elements is partly the result of the "low-quality" original CAD-geometry which forced the use of patch independent meshing in ICEM CFD (Ref 18).

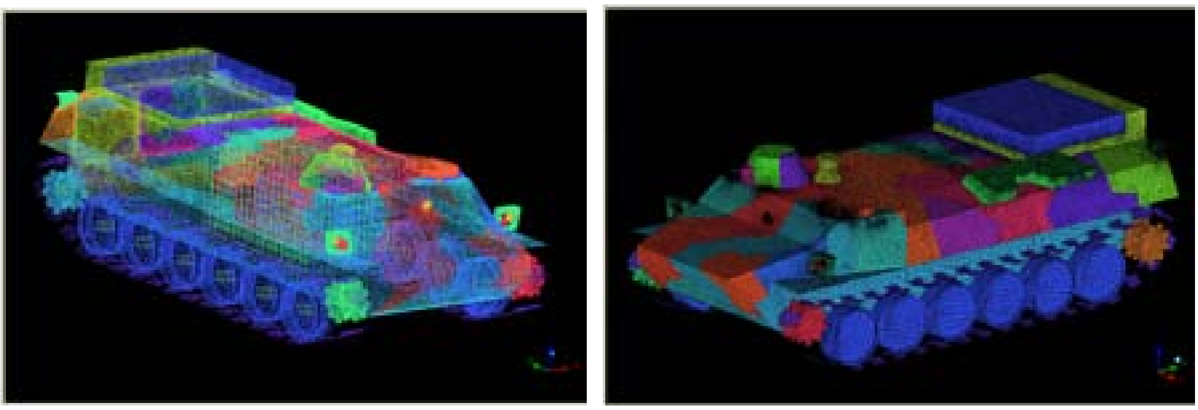

Figure 2. The meshgrid of the Pbv 401 shown in ICEM CFD. Left, semi-transparent mode. Right, surface mode.

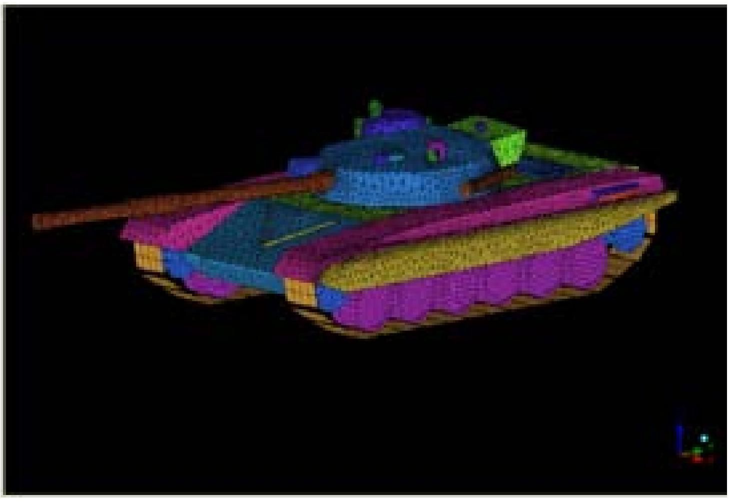

Figure 3. The meshgrid of the T72 shown in ICEM CFD, surface mode.

The general steps to create a proper thermal mesh can be summarized in:

- All thermal elements have to be arranged to capture important heat transfer features. To account for accurate calculation of the exposure to solar load, convection, and radiation exchange the geometry must be correct. Heat transfer linkages must be modelled accurately. The conduction paths between internal heat sources and sinks to the outer surface facets must be included in the model at the appropriate areas.
- The facets and parts must define the boundaries of changing material type, surface optical properties (paints), thickness and thermal boundary conditions.
- The mesh must be of sufficient resolution to model the roundness of surfaces.
- Adjacent facets must share common vertices. This constraint can create the need for staggered arrays of triangular elements between high and low-resolution regions.
- Internal heat sources, such as engine and drive-train components should be included in the thermal model. Depending on the model and the application requirements, the heat sources can be modelled as an engine with different status – idling – full throttle – cooling down after exercise, or as a heat generating geometry with a set temperature or an imposed amount of energy.
- When minimizing time spent on computation, the mesh should contain as large facets as possible, given all of the above factors and constraints. These large facets should encompass high conductance, high thermal mass, uniform thermal property surfaces

that are insulated from heat transfer drivers and hence tend to have a low temperature gradients across their surfaces.

If the original CAD-structure always came from commonly used software, for example Pro/E (http://www.ptc.com/), there are plug-ins (for meshing) to interface directly to RadThermIR/MuSES, thus eliminating the need for a separate mesher. With varying sources and quality of geometry, instead a general mesher was chosen that can be used for any kind of geometry – ICEM CFD/A*I Environment. This program is a combined surface and volume mesher with excellent geometry preparation possibilities. Due to the quality of the geometry there are two ways to mesh, either using patch based or using patch independent. The meshing process for the Pbv 401 used patch independent. The mesh was quadrilateral, though ICEM internally first creates a tetra volume mesh where only the trilateral surface mesh is retained and which then is transformed to a quadrilateral mesh.

It is often much more difficult to generate a low-resolution thermal model than a high-resolution one because every element in a low-resolution mesh is critically important. When using the patch independent method in ICEM CFD it is extra difficult to do a low-resolution mesh, with low-resolution the mesh no longer sticks to the geometry and a tedious manual work has to be done.

3.2 BACKGROUNDS

The modelling of backgrounds can be conducted in many ways. For modelling and simulation it may in some cases be enough to use photographs as backgrounds and then scale targets from either pictures or simulations and put them onto the photograph. In other cases, where optical signature prediction is necessary this is not sufficient and a complete model with case based input has to be set up. As mentioned previously the modelling reported here is from a fundamental physical base. This of course sets high requirements on the targets as seen in section 3.1, but also on the background geometry. Naturally the application limits the geometrical resolution, e.g. modelling a scene through a sensor where each pixel is 10 m wide does not require a cm resolved terrain CAD model. On the other hand, one tends to create a library of both backgrounds and targets where these should be fit for more or less any application. Therefore, it is necessary to create also the background with the highest possible resolution.

In e.g. CAMEO-SIM, backgrounds have to be created as CAD models, i.e. be created using polygons. The making of a terrain background in a CAD program is a very difficult task, but there are shortcuts to be made. At FOI several pieces of terrain, both rural as well as urban, have been laser scanned and thereby a highly geometrically resolved elevation map can be created. From this elevation map a CAD model or rather a polygonised geometry can be created. The laser scan sets the geometrical model resolution, but there is one other important thing that has to be created at this stage, and that is the material classification. Scanning a piece of land, e.g. a meadow with a dirt hill, some trees, a river, a dry ditch, might give you a very high resolution polygon model, but there exist no information in this model to what is the river, the ditch, the dirt hill etc. Therefore, whenever a piece of geometry (this of course also holds for targets as discussed in the previous section) this geometry has to be regionally divided, e.g. into the parts first mentioned, the meadow, the dirt hill, etc. There is also a possibility to create terrain geometry from terrain elevation images within CAMEO-SIM.

Buildings are often a direct part of a background, where again they are materially separated from the rest of the background. This also holds for trees. In a ray-tracing program such as

CAMEO-SIM (see section 8.2) it is not enough to put picture textures of a tree onto a square polygon, which from a perpendicular aspect would still look exactly like a tree. The reason is that when studying the optical signature of this tree, light scattering e.g. sunlight will not be reflected in a physical truthful manner, and hence, the optical signature will not be correct. Still, this way of treating certain background constituents such as trees is very common, but nevertheless very wrong when it comes to estimating optical signatures from basic physics. Instead, trees should also be created as 3-dimensional objects, i.e. with a tree trunk, branches, leaves, needles, etc, and each of these identified components should be separated with respect to material classification, i.e. the leaves from the branches, and from the tree trunk etc.

From laser scans of terrain backgrounds it is often possible to define the position of trees, and also measure the heights, and widths of trees. Furthermore, from intelligent sorting algorithms it is also possible to classify a certain tree as a birch instead of a pine. In the autumn, different tree species can be separated from the change in colour. In this way, a terrain very close to reality can be created, where a certain tree has its size and co-ordinates very close to the real-life terrain. Together with the target geometry developed in the previous section, a target-background scene can be created for e.g. first model validation, and secondly new estimates, e.g. at different times of day, different seasons, different weather, etc.

4 THERMAL PARAMETERS

When carrying out physically based thermal modelling and simulation a lot of parameters are collected and put together in conjunction with physical rules and equations. The thermal parameters are of vital importance in physically based modelling and simulation of optical signatures. In the modelling tools used for prediction of optical signatures it is essential that correct values of thermal parameters are used in simulations. Some of the physical processes that should be accounted for in thermal modelling of background environments are illustrated in Figure 4.

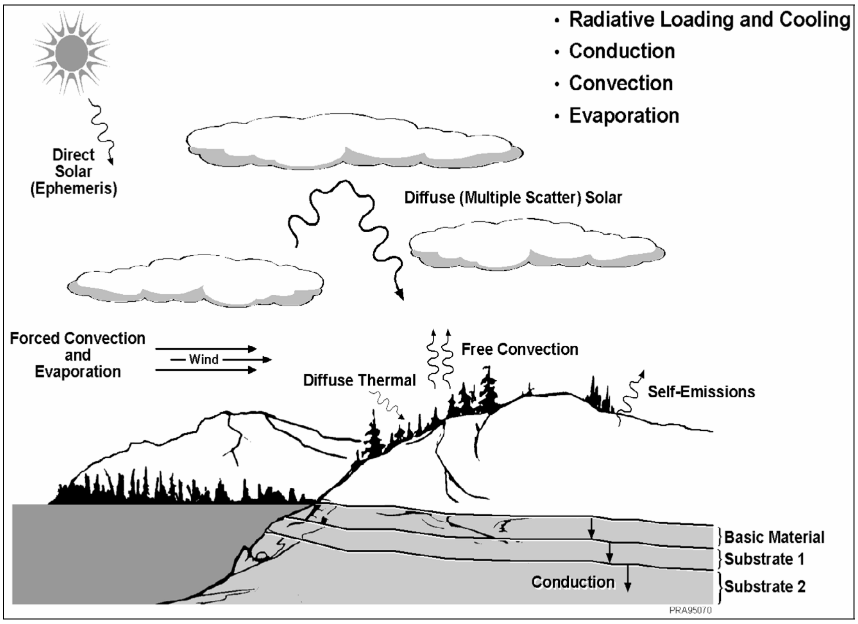

Figure 4 Some of the environmental quantities which needs to be taken into consideration when performing thermal signature modelling of backgrounds (natural environments). Figure from http://www.photon.com, "Sensorvision," 1995.

The basic thermal material parameters are *density* (kg/m^3), *conductivity* (W/m K) and *specific heat* (J/kg K). The parameters could be derived from experiments or from literature such as handbooks. The parameters are based on data prepared by statistical or physical approaches. Some of the parameters are also temperature dependent.

Heat transfer is defined as the movement of energy due to a difference in temperature. The following three mechanisms define the nature of heat transfer.

Conduction. Heat conduction takes place through different mechanisms in different media. Typical for heat conduction is that the heat flux is proportional to the temperature gradient.

Convection. Heat convection takes place through the net displacement of a fluid, which translates the heat content in a fluid through the fluid's own velocity.

Radiation. Heat transfer by radiation takes place through the transport of photons, which solid surfaces can absorb or reflect.

The state of the actual material could be solid, liquid or gas. In reality some materials are combinations of all these states, for example soils. In this case a bulk approach needs to be applied for a practical decision of the thermal properties of the material. Besides conduction, convection and radiation we sometimes also have to include phase transitions in materials, such as melting, evaporation, condensation and solidification, in thermal modelling. The heat fluxes associated with evaporation and condensation of water is in heat transfer usually referred to as latent heat. Evaporation is a cooling process and condensation is a heating process.

When using a modelling tool the thermal parameters normally are set by the use of a data file that describes the properties for each material. In addition, some geometrical input needs to complement the thermal properties e.g. the thickness of a material or paint. The solution of the thermal behaviour of an object is normally presented as stationary or time dependent.

The used software in this project also handles materials which are constructed in several layers e.g. composites but also for the ground and soil. To solve this multilayer problem some sub-calculations needs to pre-calculate new effective “bulk” parameters for all elements before the main solution calculates.

5 OPTICAL PARAMETERS

Calculation of the amount of radiation that reaches a certain point in space from a certain direction, so called radiometric modelling, is of fundamental importance in physically based modelling and simulation of optical signatures. Included in the radiometric calculations are often components from emitted and reflected radiation with atmospheric effects accounted for. In Figure 5 we schematically illustrate some of the components included in radiometric calculations. The radiometric modelling is needed for prediction of the object and background temperature as well as directly for the radiance.

Figure 5 Schematic illustration of some important components included in radiometric calculations.

The radiometric modelling performed in the simulation software requires different types of optical material data. Examples of optical material data used in radiometric modelling are spectral reflectance, BRDF (Bidirectional Reflectance Distribution Function), DHR (Directional Hemispherical Reflectance) and sometimes also transmittance. Definitions of these optical quantities can be found in for instance Ref 8. Here we just mention that BRDF describes the relation between the reflected radiance in a certain angle and the incident irradiance from a certain angle and therefore it roughly can be viewed as a quantity for "angle resolved reflectance". For modelling of polarization effects the reflectance data also has to be resolved in different polarization states.

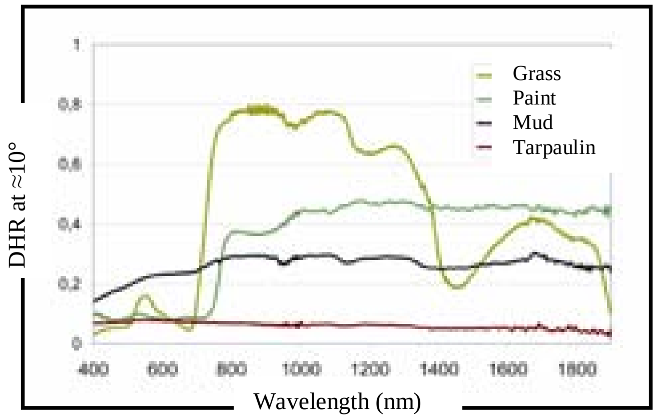

Figure 6 Measured DHR at (about) 10°angle of incidence, also sometimes called diffuse reflectance.

Some of the thermal and radiometric input quantities are related to each other. For instance, solar absorptivity can be calculated from spectral reflectance and solar irradiance and the DHR can be calculated from the BRDF by integrating over angles. In practice, a measured DHR are in many cases used to normalize a measured BRDF to improve the accuracy. Some optical quantities can in principle also be calculated from more fundamental physical principles.

Some of the optical input parameters are specifically measured for the modelling work whereas other can be found in the literature. FOI has an increasing interest in optical signature modelling and therefore the amount of measurement data that is obtained as a support for the modelling has increased. As a result, a need to efficiently list all the data for optical modelling at FOI has arisen. Most of the data available is reflectance data that cover the spectral region from the visual to the thermal infrared (0.4–14 µm). During the spring of 2004, work to list data in a database at FOI begun. The structure of the database has been reported in Ref 8.

6 WEATHER

Information about the weather conditions are essential in optical signature modelling and influence the phenomena in several aspects:

a. Temperature of target and background
b. Reflected radiance off target and background
c. Atmospheric transmission and radiance in the path between the target/background and the sensor.

Therefore the modelling of signature requires different kinds of meteorological data. Table 1 lists the several meteorological parameters and their importance for thermal modelling. As discussed in section 2 the radiometric part of the modelling show a slightly different response to different weather parameters. Weather data can be obtained in different ways; from measured data (manual observations or acquired from an automatic weather station, from statistics e.g. mean, min and max values for a certain period of time), adapted weather statistics packaged into a computer program or meteorological forecast models, which are used on the national weather centres, e.g. the Swedish SMHI.

Two distinctive cases for the use of weather data can be identified: Validation exercises where the actual weather at the measurement situation is needed; Predictions of signatures for specified cases. In the following sections different ways of getting the weather information is presented, both for Sweden and for the international arena, the later being more important in the future. An overview of the different needs of inputs for low-signature work in international operations has been compiled in the project and is presented in Ref 14.

6.1 WEATHER DATA AND STATISTICS

If the modelling work is to be performed for locations in Sweden there is access to collected data and statistics from synoptic stations from quite many places. It is also possible to set up a weather station to get hold of data for supplementary or environmental data during a field campaign. By placing temperature loggers on vehicles it’s possible to get information about warming and cooling due to daily variations or heating by e.g. the vehicles engine. Temperature loggers can also easily be placed in the terrain, e.g. with the purpose of measuring the ground surface temperature. Temperature and humidity data for altitudes from ground to some kilometres can be measured with radio sounding (weather sounds carried with balloons or small rockets).

But before international operations it can be more difficult to get relevant weather data for a certain location, better than monthly mean, minimum, and maximum values. Especially it is hard to get access to data with high time resolution. On the Internet there are a number of sites with weather information, e.g. on Weather Underground (Ref 40) there is access to newly updated observations from stations world wide. There are also data histories with e.g. one hour resolution and statistics for temperature, dew point, humidity, sea level pressure, visibility, wind direction, wind speed, gust speed, precipitation, events and conditions.

In the Earlinet project where FOI participated (Ref 2) (partly financed by the EC) three years of Lidar measurements started in 2000, the purpose was to collect values of the backscatter coefficient from ground to about 10 kilometres. The acquired data from about 20 places in Europe, measured at the same time, three times a week, have built up a database over aerosol concentration with resolution in time and space. From this database statistical values of extinction coefficients can be brought for locations in Europe.

The value of weather satellites has increased continuously. Since the sixties satellite images has come to be the most important tool in a meteorologists work. Satellite data are also used as input data to numeric forecast models. The most important satellites for SMHI and the Swedish Armed Forces weather service (FM METOCC) are the NOAA and Meteosat satellites.

At the UN contribution in Congo 2003-2004 when Sweden served with an airport unit (FK01) in Kindu, the Swedish unit had its own options to perform weather observations at the airport with both personal and equipment. To secure the access to meteorological data in international contributions the FM METOCC recently has purchased a mobile automatic weather station TAMOS with relevant sensors. The station gives values for in situ data but is also logging data for future analyses.

The need for high resolved information – sensor values stored down to 1 minute level – about the environment and wave propagation in foreign surroundings has lately been brought up. It has been pointed out in certain studies that it can be difficult getting hold of highly resolved environmental, weather and wave propagation data.

During 2003 a weather data acquisition system with sensors for about ten parameters was installed onboard the Swedish naval ship HMS Carlskrona. It was used at the voyage to South America to collect data with the purpose of test and evaluate the possibility to collect the desirable weather data from a ship. During 2004 an equivalent system was installed onboard the Swedish corvette HMS Sundsvall to acquire weather data during the TREVA trial in the Mediterranean Sea.

6.2 ADAPTED WEATHER DATA STATISTICS IN COMPUTER PROGRAMS

The American computer climatology module CLIMAT that is a part of the Electro-Optical Systems Atmospheric Effects Library (EOSAEL) (Ref *34*) provides a database that lets the user select appropriate atmospheric parameters for a variety of surface locations around the world, see Figure 7. The climatologic data include averages and standard deviations or percentages of occurrence of 11 meteorological surface parameters in each of 22 weather classes. Statistics are given for four seasons of the year and for four times during the day.

Figure 7. The parts of the world that is covered by CLIMAT are marked in black. (from Ref 19*).*

6.3 FORECAST AND TRANSMISSION MODELS

The international HIRLAM (High Resolution Limited Aera Model) project (Ref 32) is a cooperation of a number of European meteorological institutes. The aim of the project is to develop and maintain a numerical short-range weather forecasting system for operational use by the participating institutes. Examples of outputs are shown in Figure 8. Forecast calculations can be performed for Europe and adjacent areas. The model can in principle be run for the whole world but this is not done regularly.

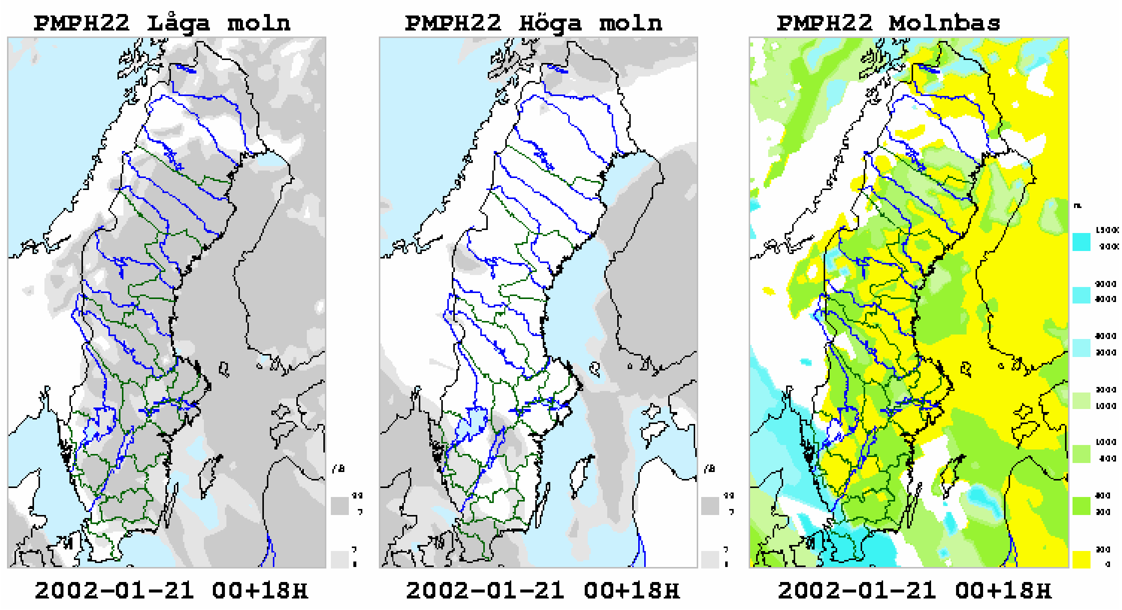

Figure 8. Example of HIRLAM -22.products. The maps show low clouds high clouds and cloud base (left to right).

At Air Force Geophysics Laboratory (AFGL) a model for computing atmospheric transmission and radiance at medium spectral resolution with name MODTRAN has been developed (Ref 27). It predicts atmospheric effects at optical wavelengths such as: atmospheric transmission, background radiance, single and multiple scattered sun radiance, atmospheric path radiance and direct sun irradiance. The spectral resolution in the range of 0 – 50000 cm^{-1} (from LWIR to Ultraviolet) is 2 cm^{-1}. Measurements at FOI (former FOA) has resulted in a new aerosol attenuation model NORAM (Ref 6), which is better suited to Nordic environments than the models included in MODTRAN. MODTRAN is used as an integrated part of CAMEO-SIM via a graphical user interface (GUI).

EOSTAR (Ref 28) which is a model for prediction of the performance of electro-optical sensors contains a ray tracing model for marine environments. A micro-meteorological bulk model, which calculates profiles of the temperature and other parameters including the refractive index, is included. Input parameters are: air- and water temperatures, relative humidity and wind velocity.

7 SCENARIO

Another part of the set-up of a simulation case is the definition of the actual scenario to simulate. The aim of the current signature study is the most important input to the scenario set-up. The term scenario could be defined to include the following aspects:

- State of targets (engines on/off, driving history, camouflage, etc)
- Positions of targets in relation to the background elements (inside/outside forest, ground type at target, etc)
- Weather
- Time of day and year
- Movements of targets and sensors

Some other aspects that are relevant when it comes to setting up a simulation activity are more related to the type of study being performed:

- Application / validation: For a validation the actual measurement conditions are modelled. For an application the desired conditions are modelled.
- Parameter studies: What parameters to vary? In what interval?

8 SIMULATIONS

At FOI several commercial programs have been used for optical signature predictions. Due to the great complexity involved in modelling IR signatures the models used in (commercial) signature prediction programs are usually adapted to the main area of application of the program. **CAMEO-SIM** is an advanced IR scene simulation program aiming at producing high fidelity physics based images, originally applied to camouflage assessments. **RadThermIR** is a 3-dimensional (with some restrictions) heat transfer program that originally was developed for thermal and IR signature predictions of targets (such as vehicles). A link between CAMEO-SIM and RadThermIR is also available which makes it possible to combine the advantages of the two programs.

8.1 RADTHERMIR

8.1.1 General

RadThermIR is a thermal-analysis program for simulating multimode heat transfer (multi-bounce radiation, conduction, and convection) and one-dimensional fluid flow for heat management design and analysis. It is developed by ThermoAnalytics Inc. in USA. Originally, RadThermIR was used as an IR signature prediction tool for designing ground vehicles but now it has found use in several other areas including ships, UAV, UGV, helicopters. Support for aircraft will be included in the next program release.

RadThermIR can solve thermal models of virtually any size. The model size is limited only by available computational resources. Radiation, conduction and convection are solved simultaneously by utilizing a time-averaging Crank-Nicholson implicit finite difference scheme to discretize the governing equations. A basis for the radiative transfer calculations is the generation of view factors which is made by a voxel-based ray tracer. The view factor calculation settings are adjustable which determines the speed and accuracy of the view factor calculation. RadThermIR also allows the elements to be subdivided for improved accuracy.

An overview of the modelling process is found in Figure 9. For general use all settings are given inside the Graphical user interface (GUI). For certain applications other modes of operations are used such as batch mode, transient restart and the TDF IO library.

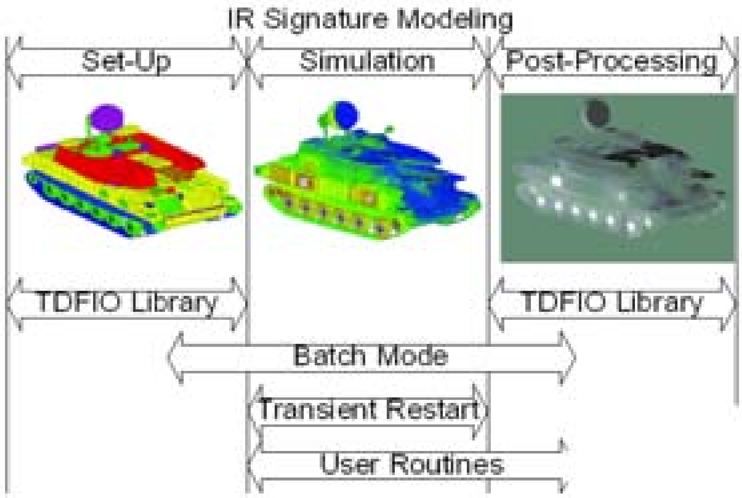

Figure 9. A general overview of an advanced modelling process with RadThermI . (Image © ThermoAnalytics Inc.)

RadThermIR is the infrared signature prediction version of the ThermoAnalytics product RadTherm but it is also the limited export version of MuSES (Multi-Service Electro-Optic Signature) which is developed for the US Army. The main differences between MuSES and RadThermIR are the support for plume radiation calculations, hyperspectral functionality, support for anisotropic BRDF, and inclusion of a sensor model to account for sensor effects.

Three ground vehicles have been modelled with RadThermIR: Pbv 401, T72 and Tgb11. The main purpose has been to gain knowledge and experience. Pbv 401 has been modelled as the prime object. A focus has been on geometry and meshing (see section 3.1) but partly also simulating inner heat generation from the engine as well as heat generated from friction in the wheel (-bearings) and on tracks. Modelling it in different environments (Kabul, Baghdad and Stockholm with the local weather of each city on the 21 July 2005) has been made as a case study and is reported in section 11.

There are different levels of ambition on how to model a vehicle, ranging from a simple steady state simulation to highly advanced simulations with engine and drive trains including transient cases (driving – idling –cooling). The degree of detail in the geometry limits the possibilities to model different features. We have modelled the Pbv 401 with a very high quality exterior geometry and mesh but with a simple inner geometry (engine and engine walls). With reference to Figure 9, the Pbv 401 modelling has included set-up, simulation, post-processing, batch mode and transient restart.

8.1.2 Model setup

In the set-up procedure all the input parameters discussed in all the previous sections are fed into RadThermIR. How this is made for the Pbv401 is described below.

To start with the vehicle geometry with proper mesh is imported to RadThermIR. Then all material parameters have to be set such as bulk and surface properties including number of layers, material thickness etc. For the surface a paint reflectance curve is given which also may include BRDF information according to the Sanford-Robertson model. For the Pbv401 reflectance measurements made at the Kvarn trial have been used, see section 10.1.2. Thickness of the different chassis parts were measured and used in the model setup. Other necessary inputs include convection set-up where several models could be used. For improved accuracy, results can be imported from a CFD (computational fluid dynamics) solver such as Fluent. Fluid advection links are used to connect the programs.

Currently the Pbv 401 has a very simple engine with engine walls that has been set up with a fixed temperature resembling idling, se Figure 10. Further development of the engine modelling is scheduled to take place at FOI next year using the supplied engine model in RadThermIR. The functionality of the model will improve in the next version of RadThermIR.

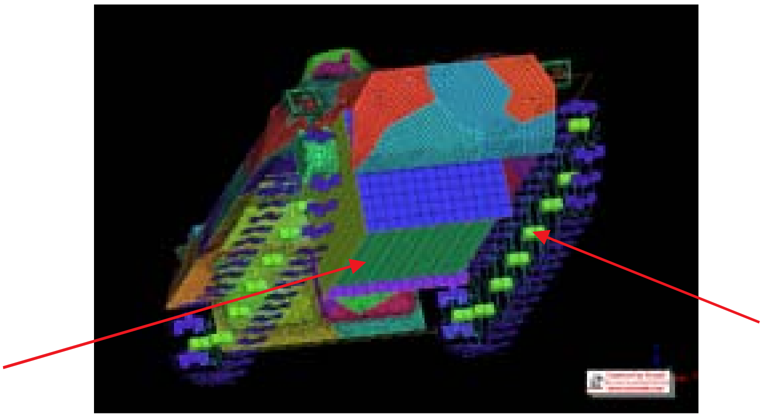

Figure 10. A simplified engine representation is used for the Pbv401. Heat sources are also placed at the wheel bearings.

Terrains are modelled according to first principles, including core temperature, moisture content, foliage type etc. The Pbv 401 was modelled on a laser scanned part of a broken ground. Individual blades of grass and bushes are not simulated in RadThermIR.

The vehicle geo-location is set for correct solar azimuth and zenith angles. Imposed heat loads etc could be given. Vehicles can be modelled with different speeds and directions either by values or curves. The Pbv 401 has only been modelled in four different directions north, east, south and west. A GPS-logging of direction and speed on a real course can be used as input for modelling as well.

The weather input for the simulation is given in a certain file. This weather file often originates from a field measurement (as in the case of Pbv 401) where a weather station is logging all parameters. This enables simulations for validation purposes where simulation results are compared to results from signature measurements.

Depending on the demand of accuracy, different settings for number of rays are set for the viewfactor calculations. Element subdivision can be selected as well. The viewfactor calculation for the Pbv 401 has been performed with the lowest settings on number of rays cast and no subdivision of element – the resulting vfs-file was still very large, approximately 380Mbyte.

Different wavebands can be selected to simulate a threat sensor. The Pbv 401 has been solved with the wavebands 3-5µm, 8-12µm and 8-9µm which reflect different sensor types.

The number and size of the time increments is given and information on what time steps to save to file. For the Pbv401, 24h runs for a number of different days and nights have been made, with 5 to 20 minutes increments.

The number of iterations needed is given by a convergence criterion in the simulations which can be set using two different methods, tolerance and tolerance slope (combined with a maximum number of iterations). Both these are defined as the maximum change in any node temperature between two iterations. For very large high-resolution models RadThermIR can restart transient solutions to continue a run further in time. The Pbv 401 has been modelled with transient solutions to limit the size of the result file (TDF). Files exceeding 2 Gbyte can not be written. The tolerance has usually been set to 0.05°C.

When there is a need for parameter studies the different RadThermIR models can be set up using TDF IO library functions and run in batch mode. One example is studies of the influence of different weather environments or paints. The TDF IO library can also be used for post-processing such as BRDF renderings from different angles. A number of simulation parameter may be changed from the command line, weather file, solution start and end time, latitude, longitude and time zone, sea surface temperature, vehicle heading and speed as well as wave bands.

8.1.3 Calculations

First the viewfactor calculation is performed and the results saved as separate vfs-file. This is in contrast to all other data which is saved in the tdf-file. Reusing the viewfactors from a previously run calculation can significantly improve run time and thus allow for increased efficiency in the simulations.

In the next step the thermal solution is invoked. The energy balance equation is solved simultaneously for convection, conduction and radiation. The computation of conduction is done between elements and through the thickness of elements. The thickness is independent of the model geometry as RadThermIR requires only a surface mesh.

The last step is the radiance solution which is solved for each specified waveband separately at the end.

8.1.4 Model output and post-processing

There is a built-in post-processor for viewing, animating, plotting and exporting results. The front and back surface in-band apparent and physical temperature or in-band radiance can be viewed through the computed time interval as well as solar radiation and heat flux for all the layers of each element. Examples of image results are shown in Figure 11. In this simulation engine, exhaust, tracks, wheels and wheel bearings have been assigned a temperature (resembling idling after heavy driving) or imposed heat. Even though no proper validation is made here the results can be compared to the measurement results shown in Figure 22 and Figure 23. Please note that the simulation did not use the weather parameters measured at this trial. Validations by using the data described in section 10.1.4 are planned for the future.

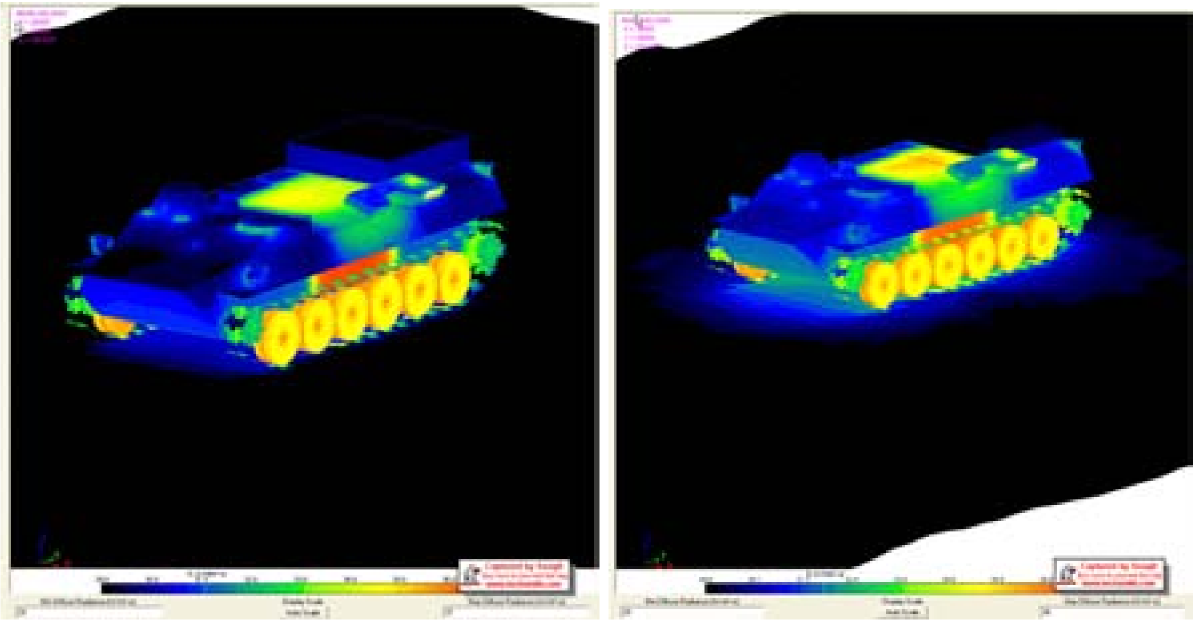

Figure 11. Model predictions of the radiance in LWIR for Pbv 401 after a harsh terrain drive. At 00:00 (left) and at 22.00 (right).

BRDF renderings can be done from any direction as well as in batch mode with specified azimuth and zenith angles. The built-in BRDF representation is based on Sandford-Robertson empirical model with multi-bounce. Earlier modelling work on ships at FOI has used the BRDF rendering function but for the Pbv 401 this was not done. Future version of RadThermIR/MuSES will support multi-bounce and user defined BRDF representations. Inclusion of BRDF rendering functions increases the demand on fine mesh or mesh subdivision to avoid overestimations, especially in cavities with a large number of reflections.

All different parameters for the elements can also be retrieved by using the TDF I/O library to export selected data in any customized format for use in other programs. Data from Pbv 401 (in passive state only) simulations have already been successfully retrieved using the TDF IO library for further use in the development of target recognition algorithms within projects Advanced Target Seekers and Precision Weapons in Network Based Defence.

8.2 CAMEO-SIM

8.2.1 General

The synthetic image generating tool, Camouflage Electro Optic Simulation (CAMEO-SIM) has been developed by Insys Ltd in the UK, see Ref 20, Ref 24 and Ref 30. CAMEO-SIM is a commercially available program for generating synthetic scene images in the optical domain 0.4 μm to 14 μm. It is based upon solving the radiation transport equations that influences the scene, i.e. radiatively, atmospherically and thermally. Physically based models for weather (via MODTRAN, see section 6.3), thermodynamics for physical surface temperature calculations, and powerful rendering algorithms for modelling the scattering, transmission, reflectance, and absorption of light are the cornerstones in CAMEO-SIM. This makes the CAMEO-SIM program package quite extensive, but it is quite user friendly through a GUI. FOI has been running CAMEO-SIM since 2003, and has ongoing support from the manufacturer as well as DSTL, who first initiated the development of CAMEO-SIM. It is beyond the scope of this report to go through the intrinsic physic models that CAMEO-SIM is based upon. Instead a brief discussion will be given on how CAMEO-SIM works, what requirements on input it has, and what output it produces.

8.2.2 Model setup

Modelling a vehicle in a background, at a certain time and for certain weather conditions, from a fundamental physical basis requires quite a lot of input data. Besides full 3D geometrical descriptions of all components in the scene as discussed in section 3, CAMEO-SIM has to be fed with information on material properties such as spectral reflectance, light scattering parameters (e.g. BRDF), thermal parameters, and weather data to complete the scene's energy balance.

Furthermore, many parts of a scene such as a grass meadow, tree bark, brick walls, etc need texturing to account for the surface variations of the reflectance. Textures can be dealt with within CAMEO-SIM in three ways:

Single material for each part of the scene.

Material-classified images, e.g. RGB images of a piece of terrain are associated with a geometrical description of the terrain. By pointing materials to the different parts in the images, the terrain piece will be material classified via an RGB algorithm, where the chosen materials have spectral and scattering information as well as thermal parameters.

Procedural textures are mathematical descriptions of the texture. Procedural textures are created by selecting a certain mixing, introducing materials of interest and choosing spatial frequencies for mixing these materials, again by looking at the RGB result. Procedural textures can not only be used for terrain textures, but for other objects as e.g. camouflage nets (see section 11.2).

Figure 12 shows a terrain created using RGB photographs to the left, and a terrain made using procedural textures to the right. Both terrain models are equipped with 3 dimensional trees. These two ways of creating textures both have disadvantages and advantages. Creating textures using RGB images has the advantage of when rendered from the distance at which the photographs were taken looking very natural, but if rendering is done at a closer distance the pixels of the RGB image shine through the synthetic image, limiting the resolution and the natural look is lost. Procedural textures are on the other hand possible to make independent of resolution as they can be created e.g. at a very close distance (say a distance of 1 m), but can be difficult to make looking natural. The choice of which texturing method to use depends on both information availability and application. Applications with e.g. in-flights are of course difficult to render satisfactorily with RGB image textures, while e.g. over-flights at a more or less constant height could be rendered with satisfactory results. Procedural textures are therefore more flexible in that context, and are a more natural choice for e.g. in-flights. An improvement to the texture methods supported in CAMEO-SIM would be to add some sort of physics based method that relates to the inherent properties of the different materials.

Figure 12. Terrains created using RGB-images (left), and using procedural textures (right).

Targets, such as vehicles, camouflage nets, airplanes etc, can also be modelled directly within CAMEO-SIM. In the case of a vehicle, a CAD model is created as before, different parts of the vehicle is identified and a thermal layer structure is created together with surface characteristics such as spectral reflectance and bi-directional reflectance distribution functions (see section 5). This vehicle model can now be simulated in CAMEO-SIM both in the visual spectral region, as well as in the thermal infrared.

8.2.3 Linking RadThermIR and CAMEO-SIM

As the thermal model in CAMEO-SIM is only 1-dimensional (heat transfer only occur perpendicular to the surface and not laterally) the heat from an internal heat source such as an engine only influences parts either in front of it or behind it. RadThermIR (see section 8.1) on the other hand models in three dimensions, and therefore outputs much more thorough and accurate temperature predictions of the object. Therefore, CAMEO-SIM has been equipped with a link between CAMEO-SIM and RadThermIR (or rather MuSES), where objects modelled within RadThermIR can be imported to CAMEO-SIM. From CAMEO-SIM, there exist possibilities to export weather descriptions and CAD geometries to RadThermIR, and run RadThermIR remotely. The Pbv 401 shown in Figure 12 to the right is imported from RadThermIR. Both the temperatures, as a function of time, and the spectral reflectance are loaded into CAMEO-SIM. The radiometry for the rendering is made in CAMEO-SIM. An example is shown in Figure 29 where the shadow observed in the measurement also appears in the simulation results. The link between RadThermIR and CAMEO-SIM is under development. In the most recent version, not only the vehicle is modelled in RadThermIR but also a close surrounding. Thereby the thermal interaction between vehicle and background is taken into account. The thermal solution of the vehicle and the close surrounding is then exported to CAMEO-SIM for radiometric calculations and rendering.

8.2.4 Calculations and rendering

Weather data has to be either created or downloaded into the program. Weather data is in CAMEO-SIM divided in two parts called the spectral atmosphere and the thermal atmosphere. The spectral atmosphere sets the spectral transmission, spectral background radiance and in the case of sunlight, the direct sunlight. The thermal atmosphere uses all parts that influences the scenes energy balance, such as solar loading, sky shine, wind speed, air temperature, rain rate, humidity etc. The thermal atmosphere has no meaning in the visual domain, i.e. 380-780 nm, and is solely used for infrared image rendering, and only influences the scenes different components' temperatures. Weather modelling can either be done using the MODTRAN standards (see section 6.3) such as 'Sub Arctic Summer', etc, or be imported from weather measurements, e.g. weather stations. In CAMEO-SIM the weather model is a pre-process and ideally it is set up for different wavebands, different geometries, i.e. observer altitudes, angles to the sun, ranges, etc, creating a spectral multidimensional database of the weather.

Before rendering can be set in motion an observer has to be defined. This observer (as well as objects separated from the terrain) can be fixed or rendered with a certain motion. Furthermore, a field of view and resolution has to be defined as well as a spectral response. After these initial steps the scene can be rendered.

8.2.5 Model output and post-processing

When it comes to the output from CAMEO-SIM the standard output is radiance either spectrally or broadband. CAMEO-SIM also delivers other output such as physical surface temperature, apparent temperature, range, RGB (in case of visual output), among other things.
In Figure 13 radiance results from a simulation of the signature of Pbv 401 is shown. Figure 14 shows an example of the output from an airborne sensor at 1500 m at clear weather. In the middle and at the bottom of the image a Pbv401 is present.

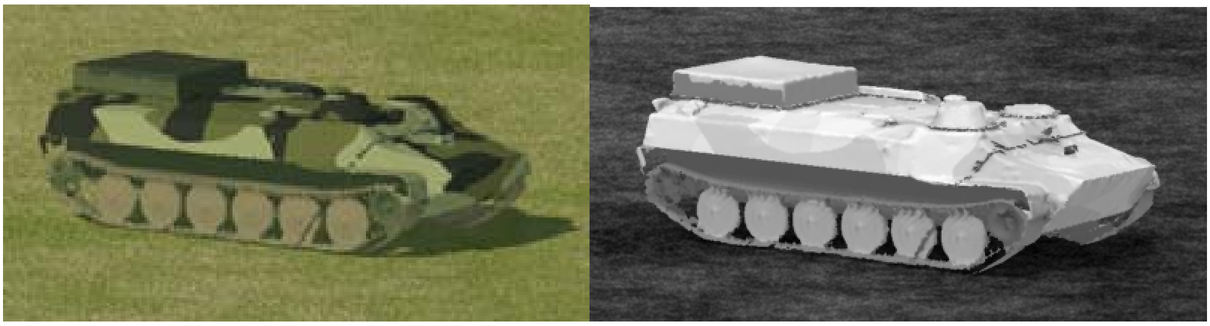

Figure 13. A Pbv401 simulated with CAMEO-SIM in the visible domain (left) and in the thermal IR (right).

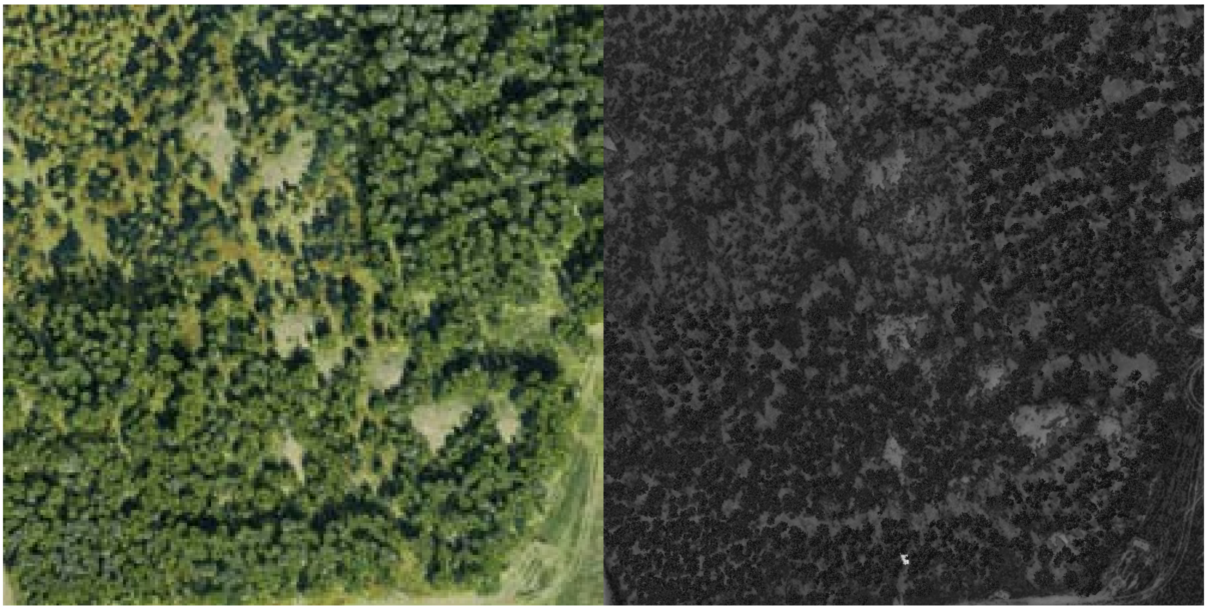

Figure 14. A synthetic airborne scene created with CAMEO-SIM in the visible (left) and in the thermal infrared (right) wavelength domain for a clear summer's day.

8.3 POLARIZATION

Model calculations of polarization properties have been done on a 3-dimensional object, see Ref 4. The description here is a summary of Ref 4 and describes an attempt to build a set of computer programs that can calculate the polarization reflectance from an object and include the background and effect of the sun into the total reflectance. It includes a package that defines the object as a mosaic of small flat surfaces for example calculated from a CAD program. The descriptions of the objects in terms of facets make it possible to use ray tracing geometrical optics as a technique to calculate the scattering from the objects. It also includes a package that defines the model of the Directional Reflectance Distribution Function (BRDF). The model of the BRDF can be either obtained from first principle calculations or be a parameter calculation from measurements of BRDF. Further packages include ray tracing, a model calculation of the reflectance and inclusion of the background.

A simple model of a vehicle consisting of rectangular surfaces with known end points and a normal vector to every surface has been constructed. That can be considered as a simple CAD model of an object and can of cause be made more advanced, see Figure 15.

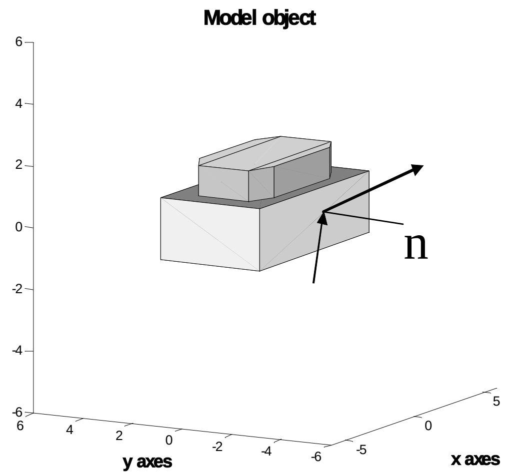

Figure 15. The object used for polarization modelling .

The Bidirectional Reflectance Distribution Function (BRDF) for different polarization states have been used to describe the reflectance at a certain facet. By using Monte Carlo calculations, performed with a ray tracing technique, the scattering from all the facet surfaces of the object can be obtained. The total reflectance from a certain facet and in a certain reflectance angle includes reflected radiations from the ground, the sky and the sun. Thus the total reflectance can be obtained for different polarization states and for different angles of reflectance. Comparison is made with field measurements of a vehicle.

To illustrate the set of computer programs developed, a parameterized BRDF model (Ref 21) adapted to measured BRDF have been used. The used BRDF measurements have been done at DERA, Malvern in England, on a commission for FOA. The model has been used and described earlier, see Ref 21. A Gaussian height distribution function for the rough surface is assumed here. It also assumes that the radiance can be separated into a specular and a diffuse part. The model takes shadowing and masking into account. Figure 16 shows the model of the BRDF function, calculated with a Monte Carlo calculation.

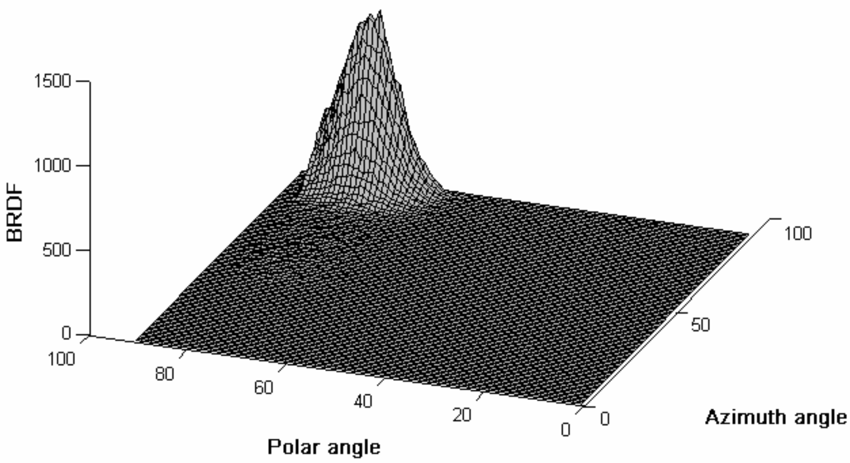

Figure 16. The model scattering function (BRDF) for incidence angel 60° used in this work.

The Degree of Linear Polarization (DoLP) is a parameter that is calculated from the radiance of the horizontally, vertically and 45° polarized components of the radiation. The DoLP of the calculated model with calculations from only one surface is presented in Figure 17. This surface can be compared to the model object also shown in Figure 17 to the right and bottom. For illustration purposes the comparable surface has a darker colour in the object model. The shape is about the same. In Figure 17 to the right and on top is a measured image of the vehicle showing the DoLP.

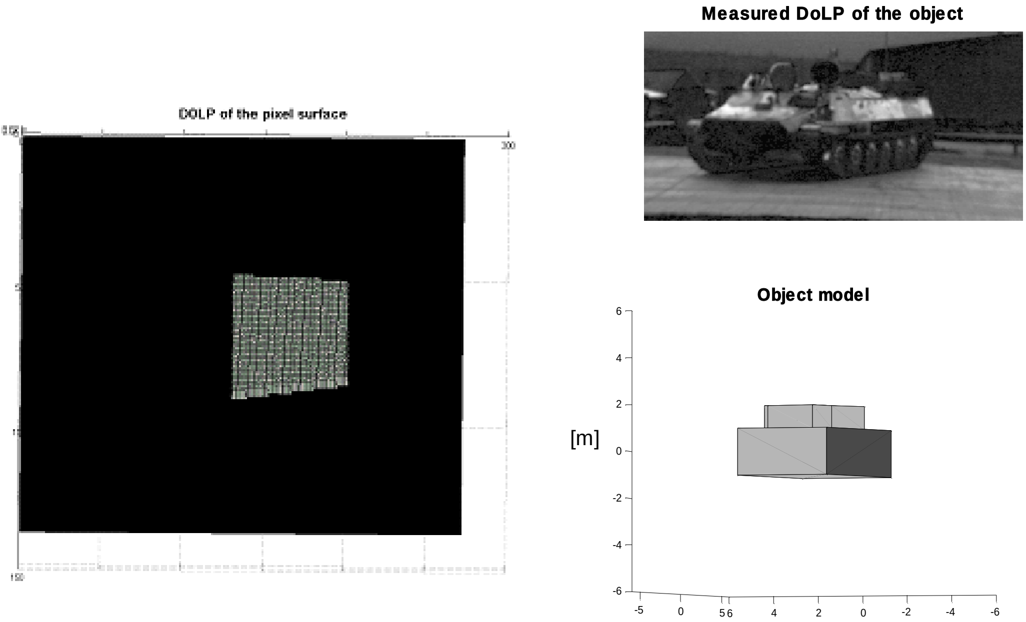

Figure 17. A Monte Carlo calculated object (left), the object model (right bottom) and the real object (right top).

In Figure 18 (left) an IR picture of the vehicle in the wavelength range 8-12 µm is shown. To the right the polarization parameter DoLP for the same vehicle is shown. The flat surfaces on the side and in the front are more clearly visible in the DoLP-picture.

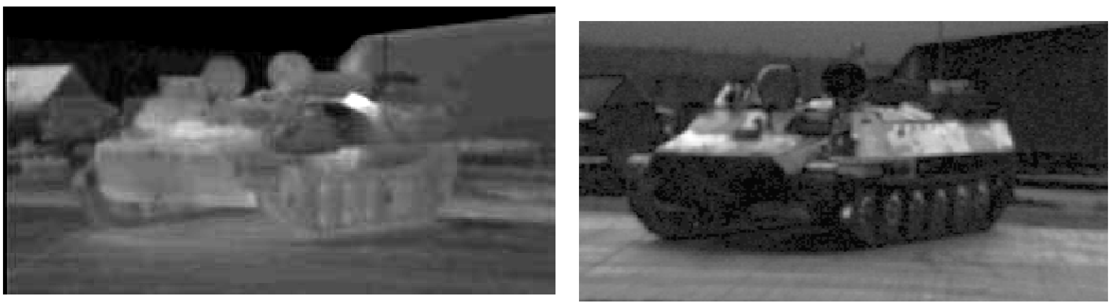

Figure 18. The vehicle measured without polarizer (left). DoLP of the vehicle (right).

8.4 OTHER PROGRAMS

Models and computer programs for prediction of thermal IR signatures, such as CAMEO-SIM and RadThermIR, usually require large amounts of input parameters, such as thermo-physical and optical material parameters. The work needed to properly assign values to these parameters should not be underestimated. In a semi-empirical model, on the other hand, the thermo-physical parameters quantifying the heat transfer mechanisms of a considered background or surface element are determined by curve-fitting the model to time histories of measured element radiance or surface temperature. Therefore it can for some applications be favourable to use a semi-empirical model. A relatively simple semi-empirical model for prediction of thermal signatures from targets and backgrounds has previously been developed at FOI, see Ref 25. However, no results from using the semi-empirical model are presented in the present report.

9 SENSOR MODEL

In section 8, several commercial software tools were discussed and briefly described. In fact, it can be concluded from section 8 that FOI has quite a good group of optical synthetic scene and target generation programs, especially for optical signature assessment. However, most of these software tools do not contain satisfactory sensor modelling functionality. For instance, in the case of the synthetic scene generator CAMEO-SIM the radiation is only simulated up until the optical entrance aperture of the sensor. Image degradation due to lens imperfections and detector imperfections etc is not included. The same can be said for other signature estimating software such as RadThermIR and McCavity, which lack of sensor models.

Still, sensor modelling is important for not only intrinsic sensor issues such as responsive band choices, spectral and spatial resolution etc, but also for signature assessment, answering questions such as detection ranges and algorithm applications. Therefore, as a simple but accurate enough post-processing tool, sensor models are being developed for describing the degradation of synthetic imagery. In short, relevant and important sensor characteristics are described using so called Modular Transfer Functions (MTFs), and those MTFs are applied onto synthetic imagery (*Ref 39*). Noise and sensor dynamics are also considered. In Figure 19, synthetic imagery has been modelled using CAMEO-SIM in the infrared wavelength domain with 32-bit raw imagery to the left and 14-bit degraded imagery to the right. MTF descriptions for diffraction, lens imperfections and random motion blur (vibrations) were used. Note the vehicle in the centre of the images in the figure.

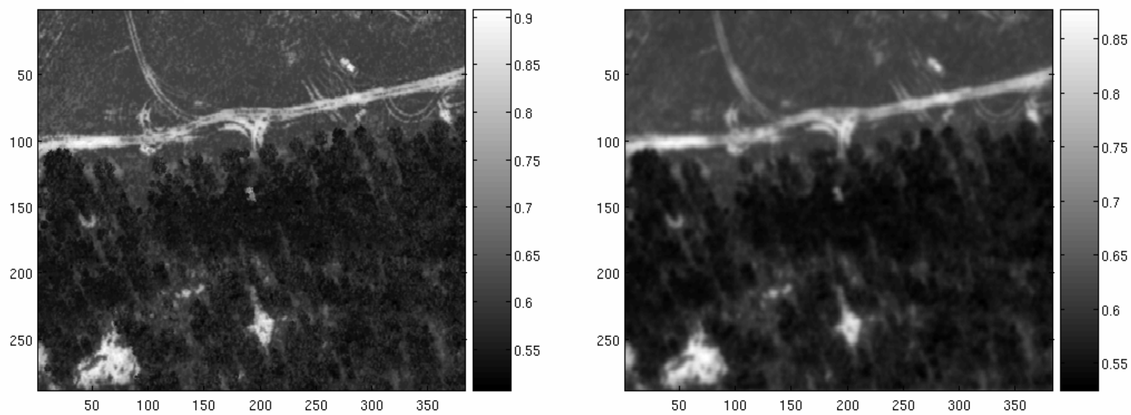

Figure 19. Synthetic imagery of an airborne scenario in arbitrary units (left), and the image degraded using an MTF including diffraction, aberration, and vibration.

10 VALIDATION

In order to obtain confidence in computational predictions it is important that the methods and programs used are validated with measurements. The aim is to determine how close the model results are to the real-world outcome and for what conditions the model is applicable. A few different types of validations have been carried out in the project.

This chapter on validation starts with section 10.1 which give an overview of the data used for the validation efforts. The most straight-forward method for validations is usually referred to as *Best estimate*. Based on a set of input data for at certain case a prediction of temperature or radiance is made. The results are compared to the results of a measurement of the same case. One earlier work on validating the commercial signature prediction programs at FOI based on this method has been previously reported for simple targets, see Ref 9. In the present project the same method is used for validation of radiance predictions with CAMEO-SIM, see section 10.2.

In order to obtain confidence in computational predictions of optical signatures it is important that the “error”, or uncertainty, in these predictions can be credible bounded. The process of validating a model or computer program is fundamentally statistical in several respects. For instance, there are statistical uncertainties in the input data used in the simulations as well as in the measurement data to which the computational predictions are compared. Methods to study the error-propagation through a model have been shown in the project and are reported in section 10.3.

Another aspect of validating signature predictions is that the computational results are often obtained as “images” (radiance maps in some wavelength band) which can be compared to measured (calibrated) images. In assessing optical signatures, a main interest is to find features in such images that are important when it comes to detection, classification and identification. Since it is the features that are relevant for assessing signatures, it is natural that it is these features that are studied in a validation of computer programs for prediction of optical signatures. Work with validation of image statistics is reported in section 10.4.

10.1 MEASUREMENT DATA

For the validation of methods and computer programs adequate measurement data sets must be available. The data can be obtained through specifically designed experiments or from other types of measurements for mainly other purposes. The type of data and experiments to be used can be grouped in classes. Some of the most important are listed here and the three first are further described in the following sections.

Basic phenomenology Experiment with simple targets and backgrounds that are well characterized. The measurement distance is short and the test conditions well known. See section 10.1.1 and section 10.1.2.

Complex targets in background, static conditions Trials with vehicles or other complex targets in a background. The targets and the background are characterized in as much detail as possible. The measurement distance is relatively short and the test conditions known. Effects of sun heating and shading can be studied. Different engine states (on or off) could be used. See section 10.1.2 and section 10.1.3.

Vehicles with engines under dynamic conditions Trials with the aim of studying the heating of vehicles under operating conditions. Internal heating (engine, transmission, wheels etc.) is the dominating IR signature contribution for a moving vehicle. The heat conduction in the vehicle affects the temperature distribution on the body. Measurement of the state of the vehicle is important for the experiment. See section 10.1.4.

Tactical / long range measurements under tactical conditions. The sensor system is tactical or equivalent and realistic distances are used. These data can be used for validation of a complete simulation suite covering the entire chain from target to a real operating sensor in a platform. See 10.1.2.

10.1.1 Panel measurements at FOI

The experiment was carried out within a previous project at FOI and is described in Ref 9. In the experiment simple targets in terms of panels were used consisting of different layers, which formed flat surfaces of 1 x 1.2 m^2. Thereby, the heat conduction problem became essentially one-dimensional. The surface scattering was also simplified since no internal reflections could occur between different parts of the target. The two panels used for this experiment were coated differently. One of them was painted with standard dark green camouflage paint and the other had a dark green low emissive foil attached to the front surface. The panels were mounted on stands of Aluminium. On each panel there was a Pt 100 temperature sensor mounted inside the front Aluminium sheet, close to the front surface. The temperature was recorded on a logger.

A Thermovision System 900 with two cameras, LWIR and MWIR, measured the radiance continuously. The panel signature was studied for a complete 24-hour period to emphasize the influence of a varying solar irradiance and sky cloud coverage. A weather station was used and the data logged.

10.1.2 The Kvarn Trial

In 2003 an international joint trial was carried out at Kvarn from May 26 to June 14, see Ref 33. The trial was a part of the joint program WEAG JP.8.10 on Spectral Imaging, which had the aim to assess the benefits brought by spectral imaging technologies to improve the possibilities for detection, recognition and identification for military applications.

The purpose of the Kvarn trial was to find new ways of looking at targets and backgrounds using multispectral and hyperspectral sensors. A database of measurement results was obtained that covered the whole chain from detailed surface measurements to ground and airborne sensor measurement data of targets in varying backgrounds. A lot of this data have been useful for validation exercises. Specifically, data from a ground based Thermovision System 900 and from a Norwegian airborne hyperspectral imager (ASI) have been used in the validation of CAMEO-SIM.

10.1.3 SEMARK

A joint airborne-sensor trial carried out during two weeks in September 2004, see Ref 35. The main purpose of the trial was not to collect data for validation of signature models but some of the collected data could serve that purpose. The scenario contained several armoured vehicles – both wheel and tracked types – placed in different hide states ranging from open field to deep forest. The vehicles' states included: engine on and off, with and without camouflage, moving and static. For the study reported here a static T72 in an open field with engine off and no camouflage was used. A number of sensors were involved: focal-plane array sensors in MWIR and LWIR, 3D laser radar and SAR. The data used for model validation was collected from an airborne UAV reconnaissance demonstrator called MASP (Modular Airborne Sensor Platform). The MASP, which was lifted by a helicopter, was equipped with a FLIR Systems ThermaCam SC3000 with a 320x240 pixels QWIP detector in 8-9 µm, and a temperature resolution of 0.02 °C. The flying altitude was about 50 m giving a footprint of approximately 5 cm x 5 cm. An acquired image is shown in Figure 29. The ThermaCam was mounted in a gyro-stabilized turret on the MASP. Simultaneously, ground truth data was collected in terms of contact temperatures of reference panels and of some of the vehicles. A weather station collected data during the entire trial including both standard parameters and different radiation values.

10.1.4 Measurements of vehicle heating

The purpose of the experiment was to perform a detailed signature and temperature measurement of vehicles. Three vehicles were included in the experiment: Pbv 401, T72 and Tgb11. The IR-signature was measured periodically during heating were the vehicles drove a specified distance between each measurement. Several IR-sensors were used to be able to measure the signature as fast as possible and thereby decrease the stop time, see Figure 20 and Figure 21. After that, measurements were made during a cooling period of about 6 h. Contact temperature probes were mounted on the vehicles as well as position and engine load sensors.

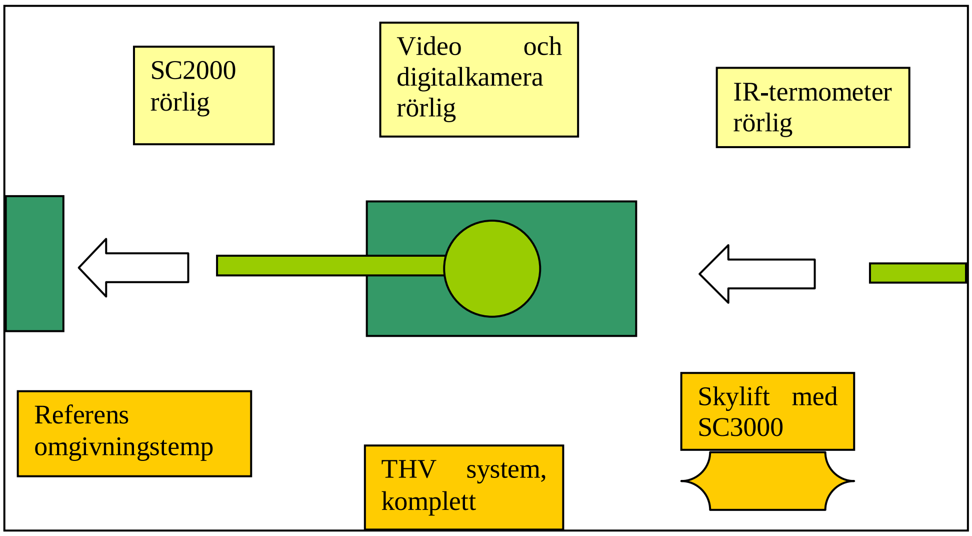

Figure 20. Schematic view of the measurement location for the heating phase of the experiment.

Figure 21. A T72 during a stop at the measurement location.

Some results from the heating phase are shown in Figure 22. The exhaust outlet is saturated in the image. The engine heating the wall side can be seen as well as the friction heated wheels and tracks. Measurements were made during a hot sunny summer day but the driveway was partly shaded to reduce the influence of sun.

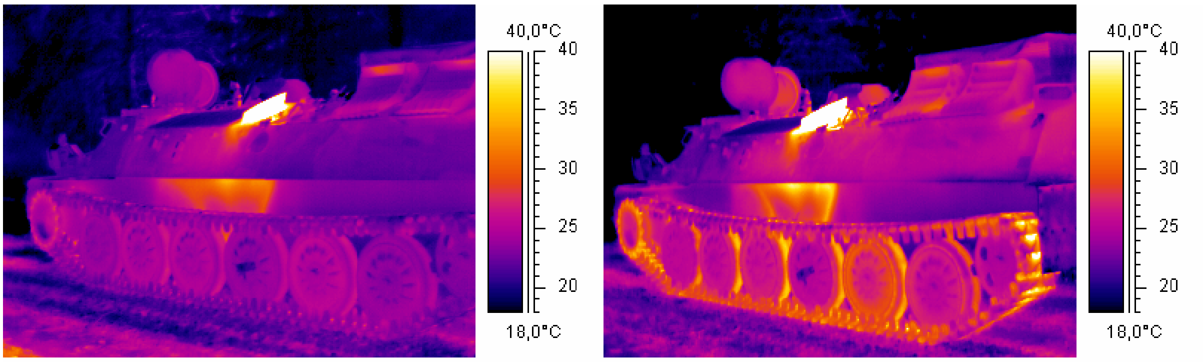

Figure 22. Radiance in LWIR of the Pbv401 armored vehicle during the heating phase. ThermaCam SC2000 sensor. Note the elevated temperature due to the engine and the track friction.

Figure 23 shows some results from the cooling phase. The engine of the vehicle maintains its heat for several hours. The vast amount of data achieved from the experiment has only been used to a limited extent in the present project. The data will find more use as modelling support in the projects starting in 2006. The experiment is reported in Ref *13*.

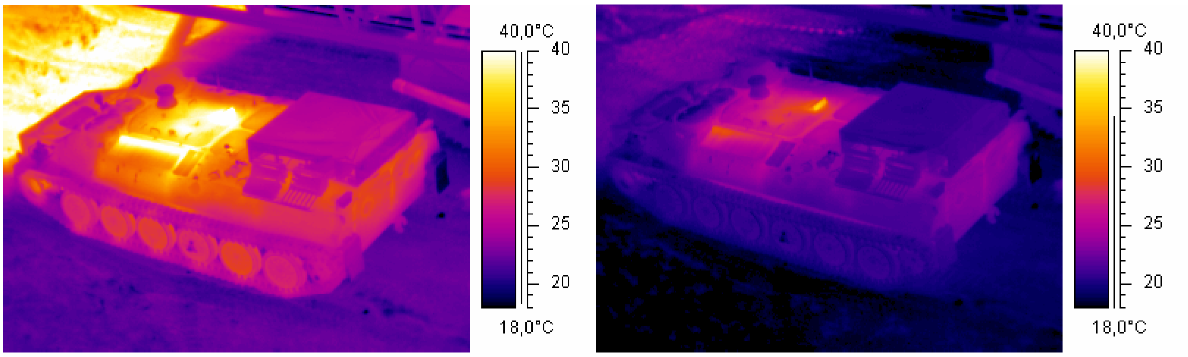

Figure 23. Radiance in LWIR of the Pbv401 armored vehicle from sky lift during the cooling phase. ThermaCam SC3000 sensor. The interval between the measurements is 4 h.

10.2 BEST ESTIMATE

10.2.1 The IR domain

FOI has developed dedicated vehicle models of the Pbv 401 and of camouflage nets within the collaboration WEAG JP.8.10 on Spectral Imaging, see Ref 17. The purpose of these models was to be good enough to be used for hyperspectral synthetic representation in CAMEO-SIM. As the scenarios were detection from elevated airborne platforms, sensors would only have 10-20 pixels on the targets. Therefore, both vehicle and camouflage net models only had to have good properties on average, such as their camouflage pattern.

The geometrical models came from laser measurements and were afterwards associated with true measurements of their spectral reflectance, and in the case of the Pbv 401 also with measured BRDFs in the MWIR, and LWIR. The average camouflage patterns were created using CAMEO-SIM's procedural texturing, where also holes were used in the case of the camouflage nets. In Figure 24, an example of a camouflage net seen from 1500 m is shown with a pbv 401 underneath to the left, and a Pbv 401 without net to the right.

Figure 24. Synthetic simulated camouflage net with Pbv 401 underneath (left) seen from 1500 m, and a Pbv 401 with an averaging camouflage pattern (right).

It was considered to be good enough that the colour patches were of about the same total size as in reality, while the exact pattern was not of interest. A simple thin layer structure of the camouflage net was created to be used for thermal modelling, and the same was constructed for the Pbv 401. This was used for solar dominating heating for both objects, while in the case with scenarios late at night and scenes with overcast skies and internal heat sources (such as the engine of the Pbv 401, and hot exhaust plumes heating the camouflage net) fixed temperatures were used. Comparisons between measurements using the Thermovision system 900 and simulations were carried out. By altering a few of the thermal parameters such as solar absorption, satisfactory models for 5 different scenarios could be created to be used for the JP8.10 THALES program's synthetic modelling (Ref 17). The exact results are not reported here because of confidentiality.

10.2.2 The Visual domain

A validation of CAMEO-SIM in the visual domain was performed for a scenario at the Kvarn trial as a part of the international collaboration WEAG JP.8.10 on Spectral Imaging, see section 10.1.2. The targets chosen were two of the panels, the Pbv 401 and a grass area. The optical sensors were a portable spectrometer and the airborne ASI. Data from the weather stations were also used for the validation. To exclude the difficult case of varying weather conditions two measurement sessions with clear sky were chosen. The validation was made in the visual range 400-1000 nm. The validation exercise covered the radiometric and spectral properties and not the spatial properties of the simulation. Furthermore, no sensor model was applied to the simulation results since the measurement data used was calibrated. The validation is described in Ref 11.

The validation was made with respect to airborne sensors and only horizontal surfaces were used. The validation was performed at three different stages (Figure 25):

1. Incident sun irradiance on the ground, both direct and scattered in the atmosphere. Two sets of measurement data were used: The measured sun irradiance by the weather station and radiance measurement of a Spectralon reflectance reference.
2. Reflected radiance at ground level. A few target and backgrounds were chosen.

3. Reflected and transmitted radiance at ASI level. A few targets and backgrounds with different properties were chosen. ASI-data was used for the validation.

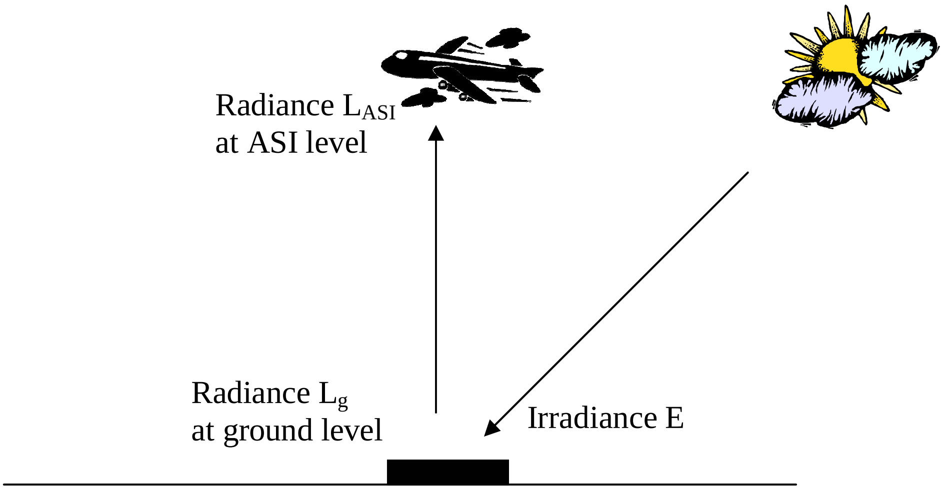

Figure 25. Different levels of validation

It was found that the agreement between simulations and measurements was acceptable for the incident sun irradiance and radiance at ground level. The radiance at ASI level did not provide a satisfactory agreement. Neither the simple panel targets nor the more complex vehicle and grass targets agreed very well. Problems related to the modelling of grass and atmospheric scattering were identified and for the case of atmospheric scattering a solution was found.

10.3 STATISTICAL ERROR PROPAGATION

There are usually several sources for uncertainties and errors in the results from a computational prediction of optical signatures (and of course computational predictions in general). Here we focus on the uncertainty in the result from a computational prediction that can be characterized as being due to uncertainties in the model inputs. We usually have some uncertainty in the input parameters (see Sections 3, 4 and 5) used in predictions of optical signatures. Besides contributions to uncertainties in the model output emanating from uncertainties in input parameters, we also have contributions from model uncertainties and errors, due to deficiencies in the specification of the form of the actual model. Furthermore implementation errors, due to errors and approximations in the (numerical) implementation of models, also contribute to the total prediction error. Model uncertainties and implementation uncertainties are not addressed explicitly here. However, knowledge about uncertainties in results from computational predictions which originates from uncertainties in input data is essential for quantifying the other sources of uncertainties and errors in a validation process.

If we describe the uncertainties in input data by statistical distributions we may schematically illustrate the propagation of uncertainties in input data to uncertainties in output as in Figure 26.

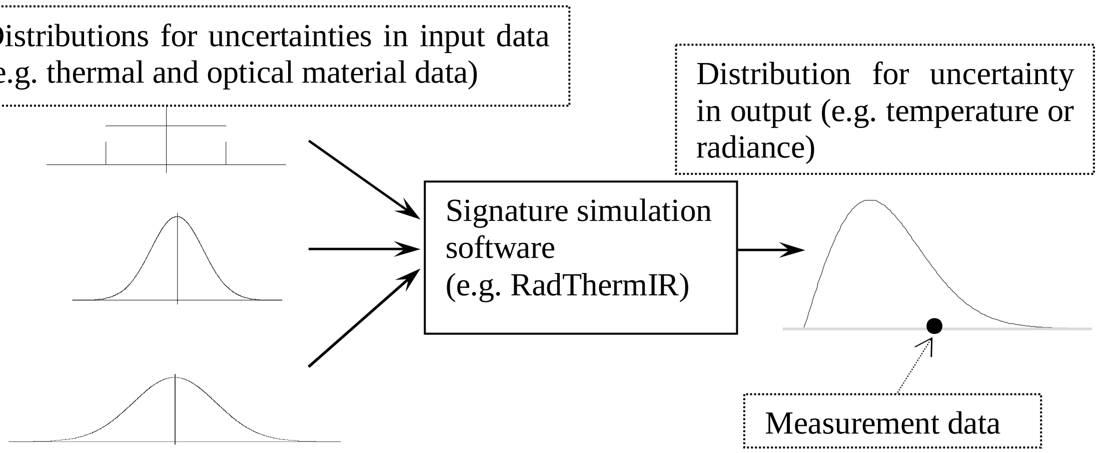

Figure 26 Schematic illustration of the propagation of uncertainties in input data to uncertainties in output data in a computational prediction of optical signatures.

The work on propagation of uncertainties in optical signature simulation software has resulted in a number of proposed methods, Ref 5 and Ref 9. The proposed methods can be divided into two classes: Error propagation methods and Monte Carlo methods. The major advantage with the error propagation methods is that they are easier to implement than the Monte Carlo methods and also that they require (much) less computer power. The Monte Carlo methods, however, have fewer limitations than the error propagation methods and therefore they can give more reliable results.

A first test case using the error propagation method and Monte Carlo methods has been performed in validation of the thermal signature simulation software RadThermIR, Ref 5 and Ref 9. The considered validation case is predictions of the measured surface temperatures on one of the flat tilted panels described in section 10.1.1. Input data to the calculations consist of expectation values (best-estimate) and estimated uncertainties (standard deviations or density distribution functions) of the input data used in RadThermIR simulations of the panel (see Ref 9). Examples of results from the performed analysis of propagation of uncertainties using the error propagation method are shown in Figure 27. A corresponding result using a Monte Carlo method is shown in Figure 28.

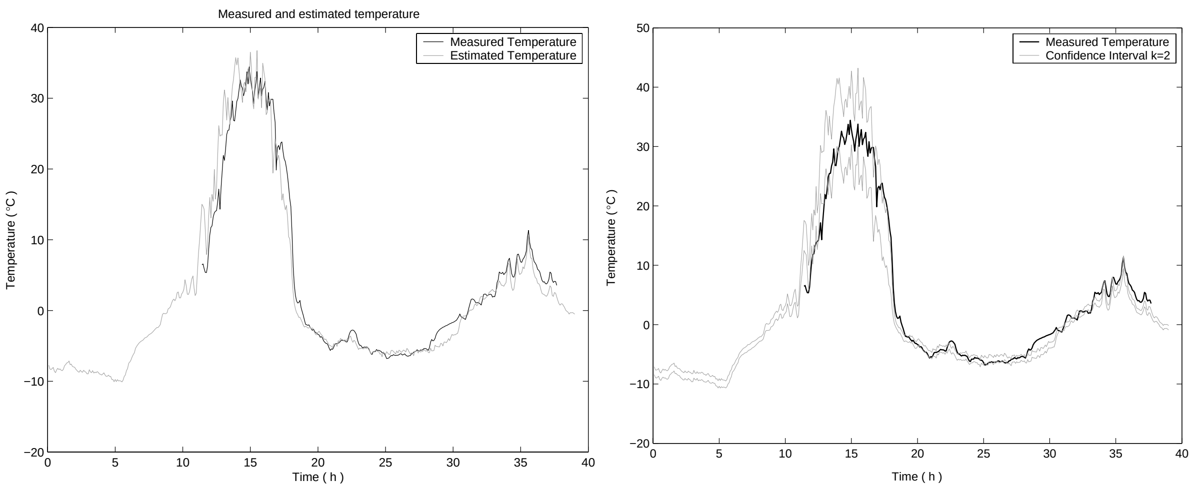

Figure 27 Left diagram: Measured contact temperature and predicted mean temperature. Right diagram: Measured contact temperature of the panel and a +/- two standard deviations confidence interval calculated with linear error propagation.

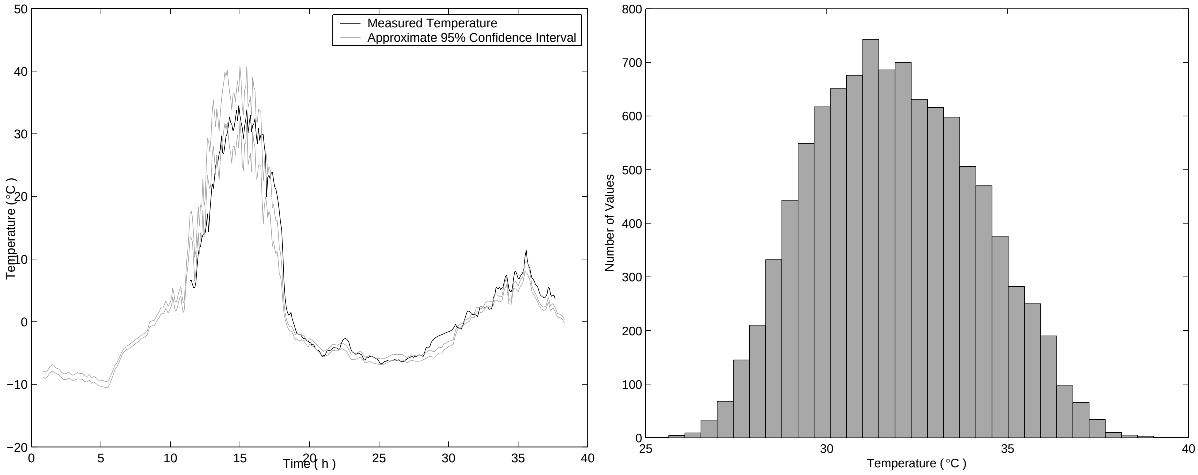

Figure 28: Left diagram: Measured contact temperature of the panel and a 95 % (+/- two standard deviations confidence interval) calculated with a Monte Carlo method. Right diagram: Calculated histogram for surface temperature at time 15:00.

From the results it can be seen that the majority of measured data are covered by the plus/minus two standard deviations (coverage factor 2) predictions both when using the linear error propagation method and when using the Monte Carlo method. However, it can be noted that the confidence interval obtained using the error propagation method for most times is somewhat broader than the confidence interval obtained with the Monte Carlo method. The fact that not all measurements lie within the confidence limits can be attributed to a number of contributing factors and the fact that model errors have not been accounted for is one of them. It should be noted that even though the Monte Carlo simulation is likely to provide more accurate results it is usually much more computationally expensive than linear error propagation.

The results obtained for the considered test case indicate that much of the discrepancy between predicted and measured temperatures can be attributed to uncertainties in input data. It is not unlikely that this is also the case in other examples of optical signature predictions. However, in order to confirm this conjecture more validation test cases, where propagation of uncertainties in input data is analyzed, should be performed. It is however quite clear that it is always a good practice to have control over, and if possible reduce, the uncertainties in input data in computational predictions of optical signatures.

The sensitivity of the temperature to changes in the different input parameters agrees with the experiences summarized in Table 1.

10.4 SPATIAL STATISTICS

Images of vehicles generated from modelling software, e.g. CAMEO-SIM, and from field registrations differ in certain aspects. The main interest here is to find differences in those aspects that are important when it comes to detection, classification and identification. Here we will mostly deal with detection of vehicles. In this case detection means to find an object, some military vehicle, in the terrain.

In order to characterize the vehicle, several features are computed from the image. A set of features, Ref 31, is computed at each pixel. From the local responses invariant features are calculated. For a more complete description of the vehicle, several features should be used. A demand when comparing with perception experiments has always been that the features should have a simple and direct connection with a physical property. However, this is not the only goal in the current context. We may also want to characterize the differences between modelled and real images when this imagery is used in automatic target recognition.

To quantify the property differences between target and background, or in the validation case between two targets, a similarity measure is computed (Ref 12). This measure, denoted GSNR, has the form of a signal-to-noise ratio with two terms, related to the difference in mean value and standard deviation respective. A nice feature is the inherent normalization which, for example, allows measurements in different wavelength bands to be combined in a simple way. The total distance is simply the sum of the individual distances for each feature.

In a simple example, feature values have been computed for several Gabor features. Two vehicles, one imaged and one modelled, from above are shown in Figure 29, where both images show apparent temperature. The left part is a real registration and a CAMEO-SIM model is shown to the right. Inspecting Figure 29, clear differences are observed between the real and modelled imagery. Some of the modelled vehicle details do not exist on the real vehicle and vice versa. Furthermore, as the modelled vehicle does not have the exact matching orientation with respect to heading, pitch and roll due to uncertainties, solar loading and thermal shadowing will differ between real and modelled imagery. The terrain was modelled as a plate with terrain materials such as different types of grass and soil which is a simplification. With respect to the large scale used, sensor effects were not simulated. The purpose of the comparison was to illustrate the method of validation of spatial statistics and the obvious differences between the synthetic and real images in Figure 29 are not further analyzed here.

Figure 30 shows some feature measures. For each feature, the two terms (mean and deviation) in GSNR are computed. The lower part (blue) of the bars shows the GSNR for mean value differences and the upper (yellow) part shows the GSNR for standard deviation differences. The left axis is the GSNR value, where 0 indicates no differences.

Since the background in the modelled image is not modelled after the real world the GSNR is here used to measure the similarity between two targets instead of between target and background, which is the common way to use this measure. Gmean is simply the part from the mean value difference, while Gdev is the standard deviation part

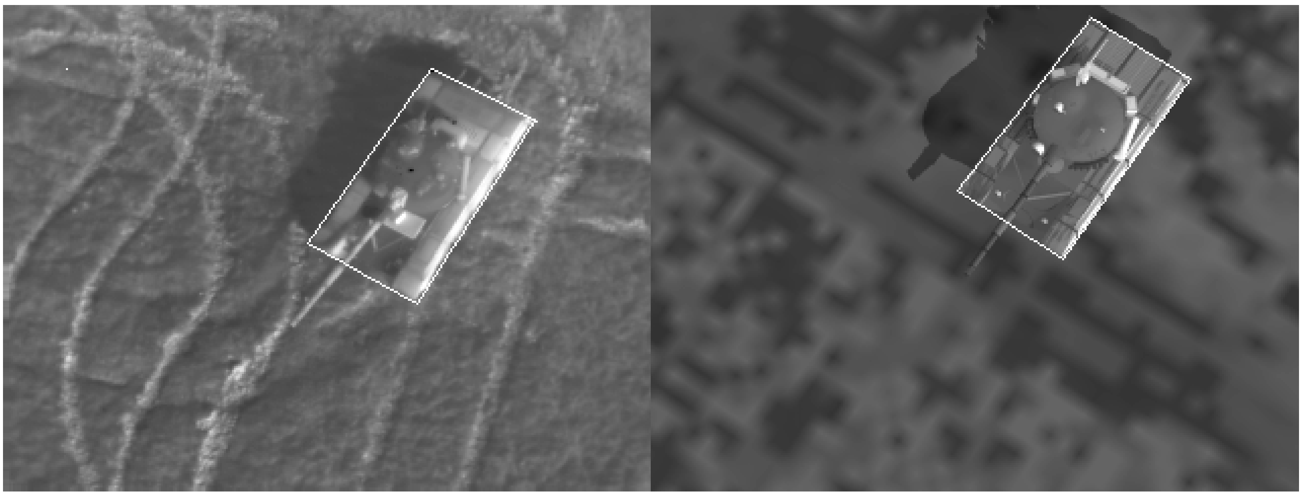

Figure 29. Measured (ThermaCam SC3000) and modelled (RadThermIR and CAMEO-SIM) vehicle used for signature comparison.

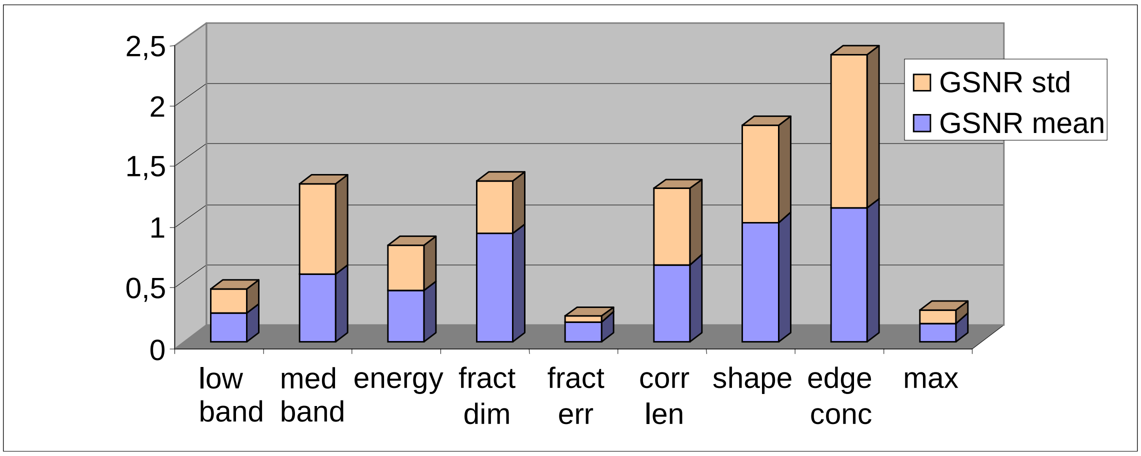

Figure 30. Feature values for image and modelled vehicle.

The correlation length feature values indicate a substantial difference between the real and the modelled vehicle. The correlation length factor has high values in uniform areas and low values for areas with a lot of variation. Also the edge concentration feature indicates a difference at edges for the two vehicles. This is not very surprising since modelled edges are normally very straight.

Since no sensor model was employed some differences in the spatial statistics were expected. The edges are extremely sharp due to the lack of modelling of several sensor effects such as: camera movement (vibrations), optics, detector fill-factor. The dynamic range was lower for the measurements (14 bit compared to 32 bit). There are also target modelling issues: The T72 paint was aged and worn resulting in considerable variations over the body which was not fully represented by the reflectance inputs to CAMEO-SIM and RadThermIR. The identified orientation differences might also have influenced the results.

11 CASE STUDIES

Two case studies have been performed to show the possibilities with optical signature modelling.

11.1 RADTHERMIR

Simulations with the Pbv 401 were performed with local weather on the 21 July 2005 in Stockholm, Baghdad and Kabul. Weather data was used from Ref 40. No solar flux data was available and instead it had to be modelled with the RadThermIR internal method. The only parameters that have to be set to calculate solar irradiance is latitude, longitude and height above sea. All simulations were performed with tall grass as ground.

Below are a couple of snapshots from different times of the day (and night). There are also a few examples of threshold images. Neither sensor nor atmospheric transmittance effects are applied to the images. Please note that the radiance scales are different for the images. Together with the simulated images the temperature for a selected element of the vehicle is plotted as a function of time. Figure 31 shows where the selected element is situated.

Avi-films of the simulations as well as details on the weather data used are available on a CD that can be obtained from FOI. Please contact Andreas Persson or any other of the authors.

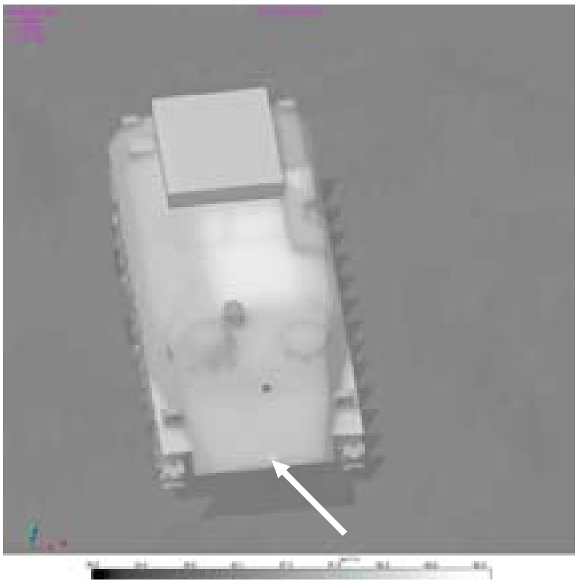

Figure 31. Pbv 401 with element 7691 highlighted in white. Scale is in physical temperature.

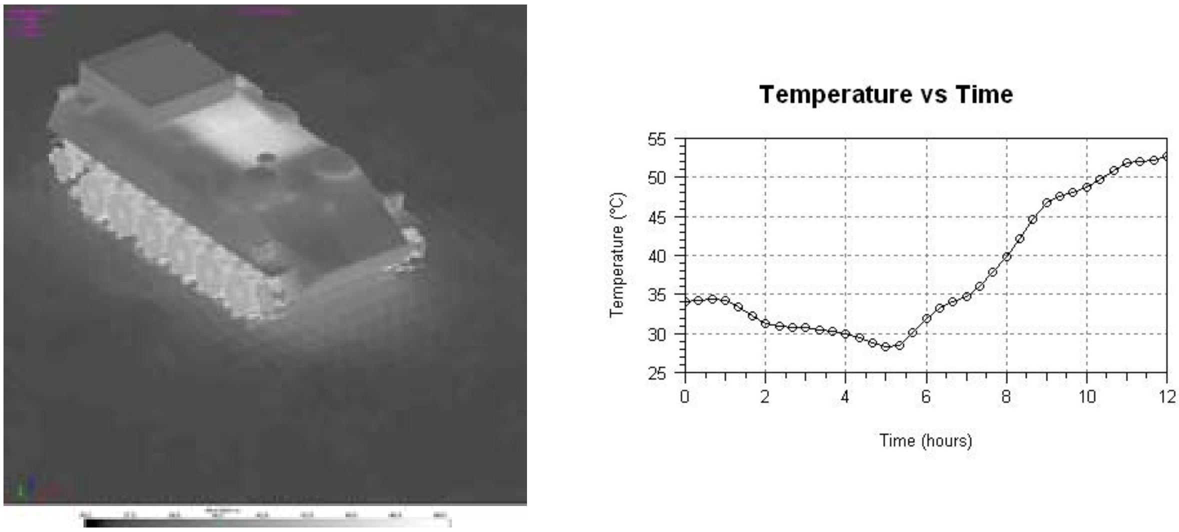

Figure 32. Baghdad 8-12μm night-morning 21 July 2005. Image at 04:20

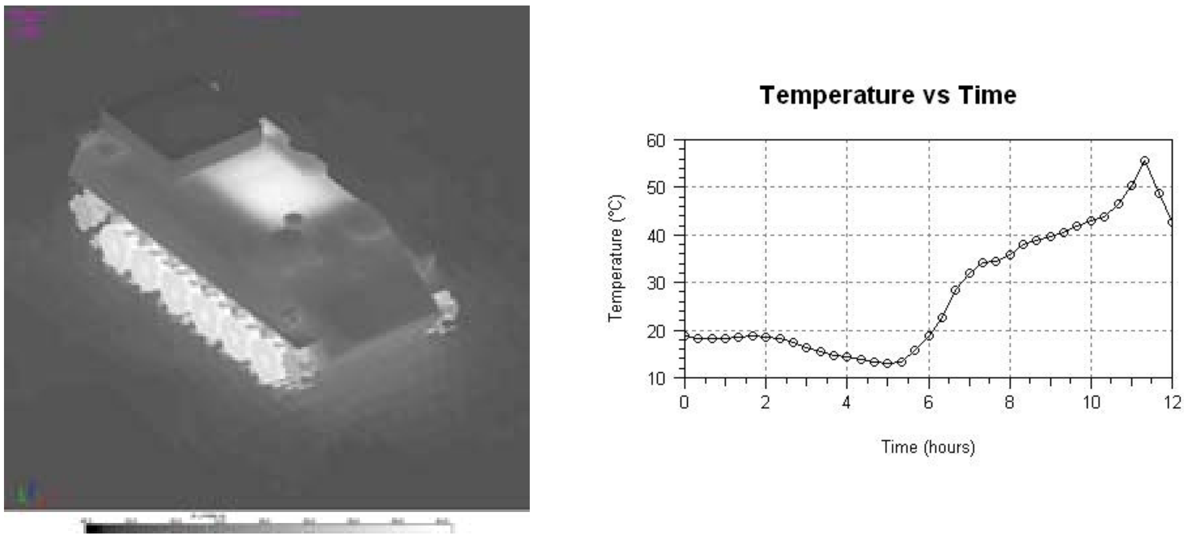

Figure 33. Kabul 8-12μm night-morning 21 July 2005. Image at 04:20

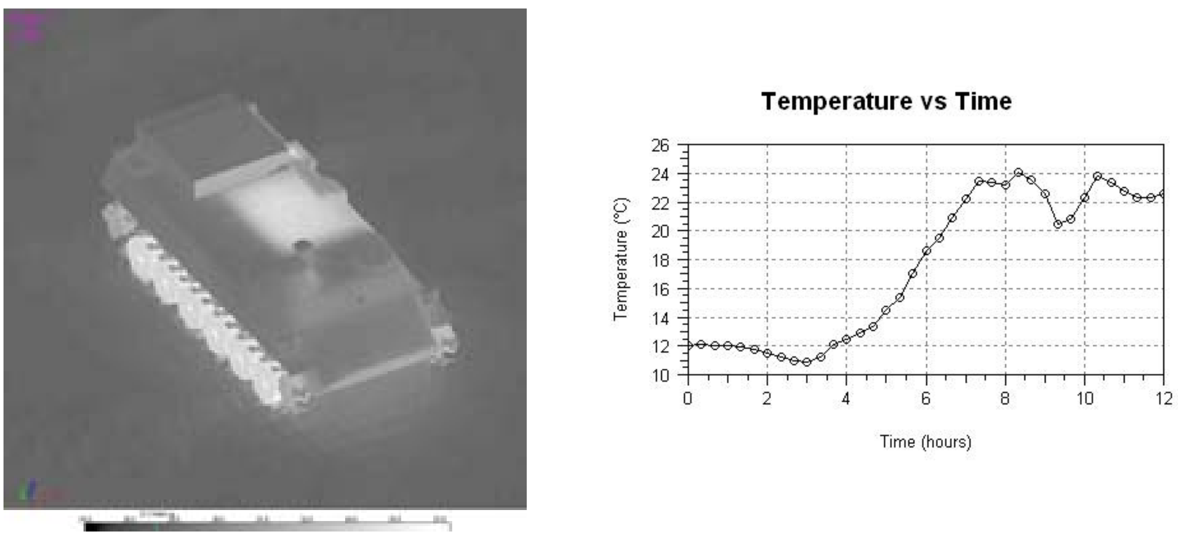

Figure 34. Stockholm 8-12μm night-morning 21 July 2005. Image at 04:20

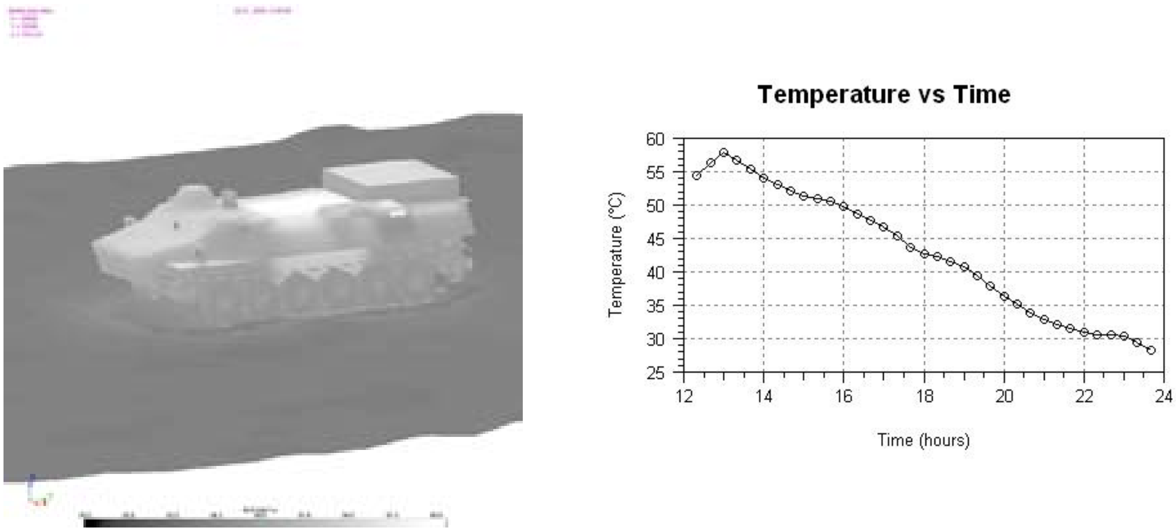

Figure 35. Baghdad 8-12μm afternoon-evening 21 July 2005. Image at 12:00.

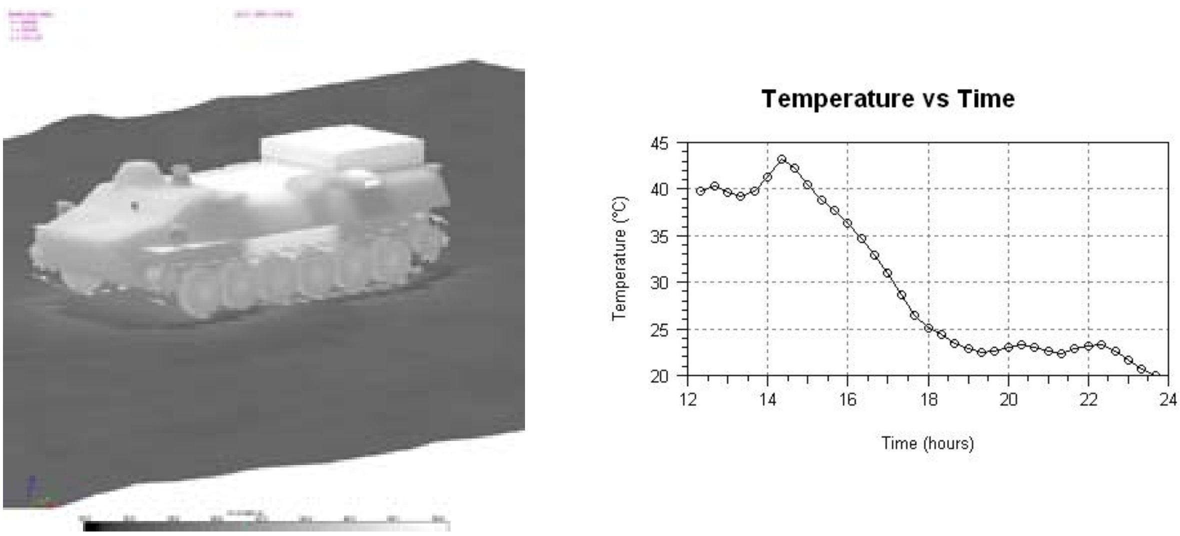

Figure 36. Kabul 8-12μm afternoon-evening 21 July 2005. Image at 12:00.

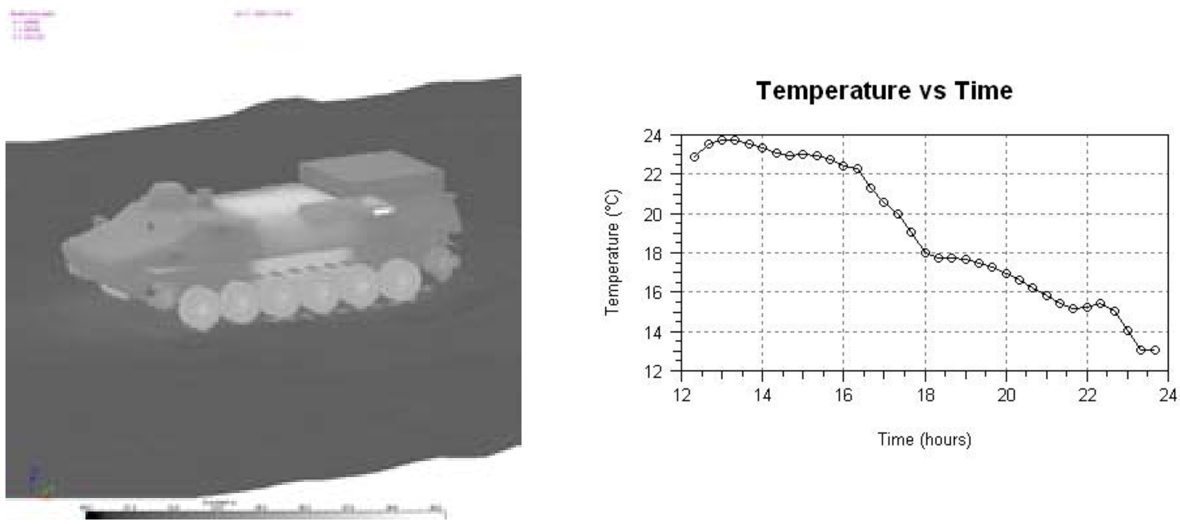

Figure 37. Stockholm 8-12μm afternoon-evening 21 July 2005. Image at 12:00.

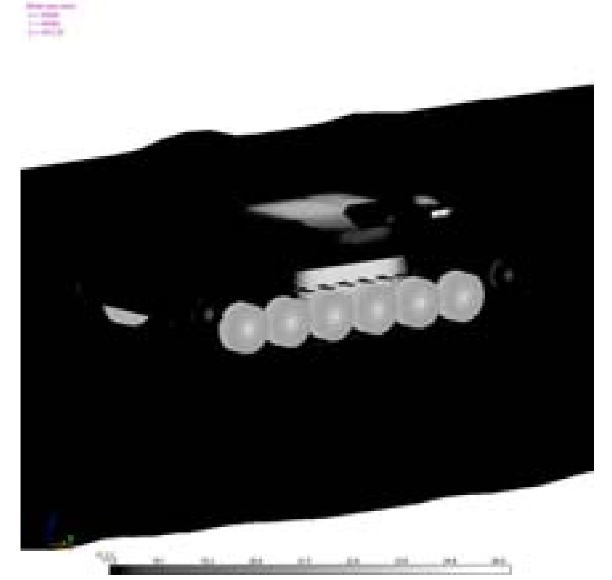

Figure 38. Stockholm Physical temperature 01:00 21 July 2005, threshold 5 degrees above grass terrain.

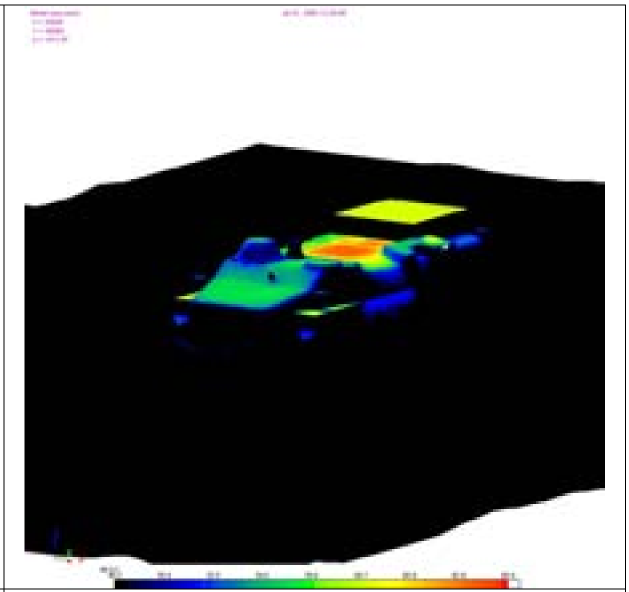

Figure 39. Baghdad Physical temperature 12:20 21 July 2005, threshold 5 degrees above grass terrain.

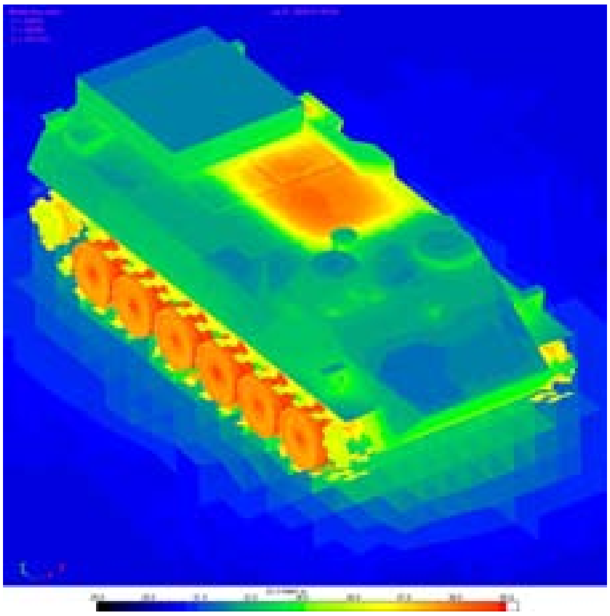

Figure 40. Kabul Radiance 8-12μm at 01:00. To some extent displaying the effect in radiance level of the three different camouflage paints.

Further analysis of simulations above may include subtraction of a Stockholm simulation from a Baghdad simulation. The simulations show how large impact the weather has on the IR-signature. Depending on whether the Pbv 401 is in Stockholm, Baghdad or Kabul on the 21 of July 2005 the difference in temperature may become as much as than 30 degrees or even more.

In Baghdad and Kabul desert sand would probably be a more likely ground than the used tall grass. That might change the relative contrast between the object and the ground for Kabul and Baghdad. The fast changing signature of the thin PVC tarpaulin, placed around the box back on the roof, can be seen and the slow changing of thick armour. A quick analysis indicates that at certain times of day the need for signature reduction is larger in Baghdad and Kabul than it is in Stockholm. Future work could include testing of different insulation material in the engine compartment as compared to other signature reduction measures such as camouflage net over the chassis or double steel hulls with circulating air between.

11.2 CAMEO-SIM

A parameter study has been carried out with CAMEO-SIM to illustrate the effect of different weather conditions. A vehicle (Pbv 401) has been modelled in the edge of the wood at a clear day, and at a very rainy day. This type of signature estimation is quite easily done using CAMEO-SIM, and the connection to RadTherm as mentioned in section improves the target modelling. Figure 41 shows the result of modelling the Pbv 401 in two vey different weather conditions, clear day and very rainy at two different distances, 600 m and 350m.

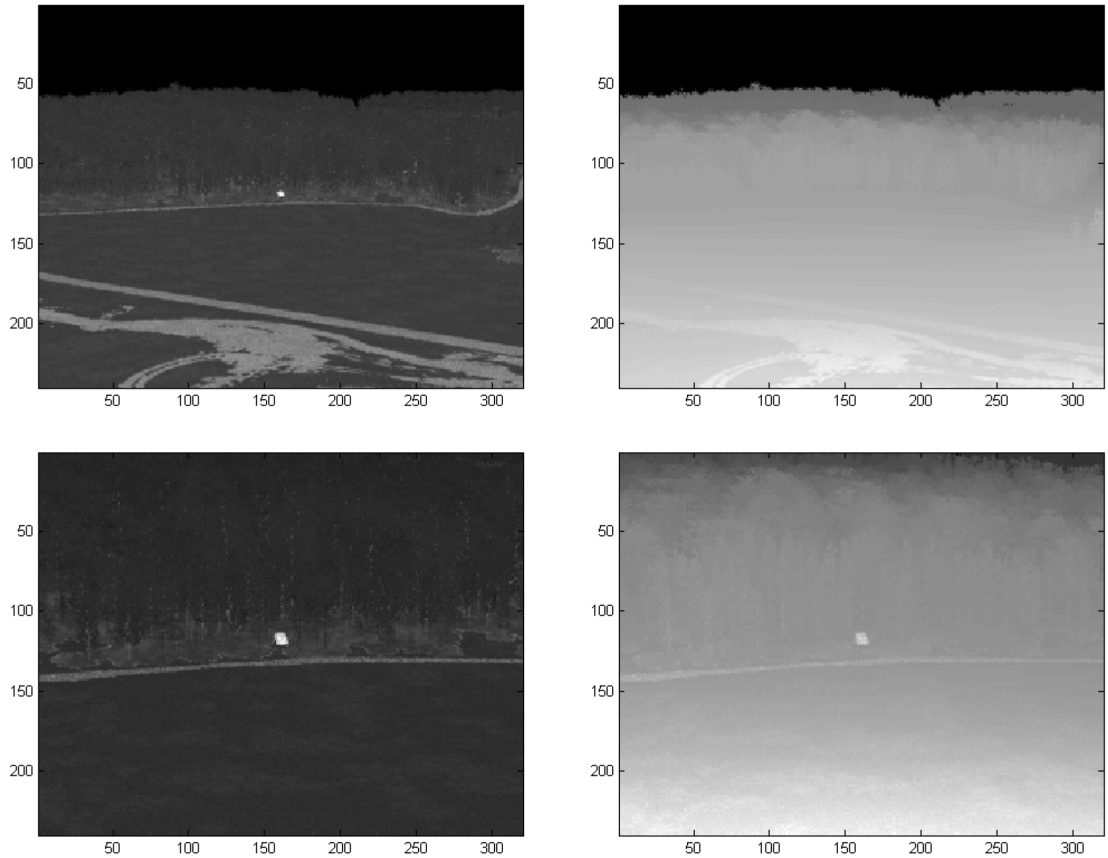

Figure 41. Thermal infrared modelling with CAMEO-SIM of a Pbv 401 at the edge of the wood at a clear day (left) and at a rainy day (right) at a distance of approximately 600 m (top) and 350 m (bottom).

12 CONCLUSIONS

This report has described how the set-up, simulation and validation can be performed for the modelling of the optical signature of Pbv401. The different aspects have been addressed and examples of results have been given. The main conclusion of this work is that a basic modelling capacity of optical signatures now is available at FOI for different applications relevant for the Swedish armed forces. These include design work of platforms and sensor systems as well as studies and assessment of tactical behaviour in new environments. The natural next step would be to apply the modelling and assessment capacity to issues of immediate importance for the armed forces such as new and operational platforms under relevant conditions.

With reference to the initial goals of the projects some more specific concluding comments could be given:
An extensive data base of reflectance data of materials is available to a large extent through international collaborations. This data base is continuously increasing as more material characterizations are included. The most demanding task in terms of getting input data concerns the background. The variability is huge and new environments raises new needs. In terms of geometry input data, three military platforms are available: Pbv401, T72 and Tgb11. These vehicles, of different characteristics, could be used for different kinds of fundamental studies. For studies of other specific platforms, geometry and surface data is needed.

The methods for setting up simulation cases with CAMEO-SIM and RadThermIR have improved during the project time. By performing different simulation tasks and studies FOI has gained experience that could be used in further studies. The link between these two programs has been explored and provides improved capability in terms of advanced thermal signature modelling in a complex environment. At the same time the individual programs have extended their capability: RadThermIR including more background effects, CFD-interface and an engine model and CAMEO-SIM including gas plumes and improved thermal modelling.

A preliminary study of modelling of polarized optical signature has been performed leading to a concept and program for the modelling of simple targets.

Validation of the programs has been an essential part of the project and a few different activities have been performed. Most fundamental is the "best estimate" validation of radiance in images that reviled the accuracy that could be obtained in a simulation. A method to characterize the sensitivity to uncertainties in input parameters has also been shown. Finally, a method to validate the spatial statistics of synthetic simulated images was demonstrated.

Some parts of the project have been performed in international collaboration. The work with CAMEO-SIM has had a strong connection to DSTL within the Thales JP8.10 project concerning the development and validation of the Pbv401-model. Project members have also taken part in CAMEO-SIM international user group meetings. The international collaborations will continue.

13 FURTHER WORK

The modelling capacity at FOI in the area of optical signature modelling will continue to develop. There are several directions possible for the development and those that are most relevant to the customers and users will be explored first. In terms of the different services of the armed forces the present project has had a focus on ground applications even though the major part of the work not specifically was directed to vehicle applications. In a parallel project carried out during the last two years, the signature of airborne platforms has been studied both with CAMEO-SIM and with a program called McCavity which is specifically designed optical signature modelling of aircrafts with jet engine. Some previous work has been made in the area of ship signature modelling. Through recent improvements in the modelling of water surfaces the capability of both CAMEO-SIM and RadThermIR is better today. Therefore studies of ship signatures would be a natural next step for FOI to take on.

An up-coming project at FOI for 2006 will treat issues related to the analysis of the optical signature of Swedish troops in international arenas. The analysis will include modelling for environments different from those in Sweden. For this a certain amount of measurements are necessary, both as inputs to the modelling and as data for validation of the simulations. The assessment of the signature on a basis of the threat sensor characteristics will be essential.

FOI will also continue to explore the new functionality that is included in the programs used. RadThermIR has a lot of promising features that have not been used at FOI so far. The MUSES program, which has limited distribution, includes even more valuable functions. It includes import of results from computational fluid dynamics (CFD) which is relevant for analysis of complex convection cases such as heating by exhausts, wind cooling, and aerodynamic heating. An interaction is also possible between RadThermIR and the CFD-program Fluent. Another useful facility that will be looked into next year is an engine model that provides a way of modelling the engine of a vehicle by representing the heat flow of the engine. Furthermore, links to optimization tools are available for the treatment of optimization problems in the design process. WIDA is an on-board tool for signature awareness and signature management of vehicles and vessels that is based on RadThermIR/MUSES. The distribution is limited.

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