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Estimation of Effect of Emissivity on Target Detection through Thermal Imaging Systems

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ABSTRACT

The effects of target emissivity on apparent thermal contrast as well as on detection range capabilities of thermal imagers in long wave infrared and middle wave infrared bands were evaluated. The apparent thermal contrast (to be seen by the thermal imager at standoff distance), considering only the emission from target and background, was first computed in both the IR bands in terms of target emissivity and secondly the apparent thermal contrast, considering the background radiation reflected off the target, was also computed. A graphical user interface simulation in MATLAB was prepared for the estimation of total apparent thermal contrast taking into account both the emission and reflection. This total apparent thermal contrast was finally used in night vision thermal and image processing model for predicting the detection range performance of thermal imagers. Results of the analysis show that the effect of target emissivity on thermal contrast estimates is more pronounced in LWIR. The lower thermodynamic temperature difference between target and background at lower values of target emissivity leads to negative thermal contrast which in-turn leads to higher detection ranges.

Keywords: Emissivity; Thermal contrast, Thermal imager; Thermodynamic temperature difference; NVTHERM; Detection range

1. INTRODUCTION

Due to the development of IR detectors during the last couple of decades for the use in missile seekers, surveillance systems, search and track systems, etc, the thermal signatures of military targets normally have to be reduced in-order to avoid detection[1-2]. The development of such sensors continues towards systems with still higher performance concerning detectivity, resolution (spatial, spectral and temporal) and spectral sensitivity in several wavelength bands. Thus controlling of signatures of military vehicles in thermal IR region i.e. at wavelengths 3 μm - 5 μm in middle wave infrared (MWIR) and 8 μm - 12 μm in long wave infrared (LWIR) is of paramount importance for defeating thermal imaging systems[3]. As emissivity is a key parameter in controlling thermal signatures of any surface, therefore this paper concerns the effect of target emissivity on target detection through thermal imaging systems. To the scientific community the most prominent parameter is the temperature difference between target and background (ΔT) while calculating expected detection ranges for thermal imaging systems[4]. A small temperature difference gives small probability of detection, alternatively gives short detection range. A large temperature difference gives relatively higher probability of detection and in-turns long detection range[5].

Most commonly used range performance models for estimating the thermal imager target detection capability assume that the target and background behave as blackbodies with emissivity of 1[6]. Due to this assumption the data scatter was found when comparing these model predictions with experimental results. This may arise because of the difference in thermal contrast between target and background having emissivity of 1 and thermal contrast between target and background with true emissivity. Wolfe[7] shows that relatively large changes in observed radiance may occur for small change in emissivity. Wolfe[7] also shows that for an ambient temperature of 300 K, changes in emissivity of 0.01 correspond to temperature change of about 0.5 K. It follows that thermal contrast incorrectly estimated using an emissivity of 1 for target may then lead to major errors in predicting the thermal imager's target detection capability. As the true emissivity of target ($\varepsilon<1$) may alter the brightness temperature of target, it is therefore imperative to study the effect of emissivity on detection range of thermal imager.

The effect of different target and background emissivities on the detection range estimation has been already shown by Farmer[8]. However, he considered the variation of thermal contrast and detection ranges due to emission only from target and background. He took the reasonable higher values of emissivities of target / background and varied the ratio of target to background emissivity. He did not take into account the low emissivity of target and hence the background radiation reflected off the target.

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The purpose of this paper is to examine the effect of emissivity of target on thermal contrast estimates between target and background with due consideration of background radiation reflected off the target and estimate the effect of emissivity on target detection.

2. THEORETICAL CONSIDERATION

The Planck function for spectral radiance from a blackbody is given by Eqn. (1)

$$L^{BB}(\lambda,T)=\frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T}\right)-1\right]} \tag{1}$$

where λ is the emitted wavelength, T is the temperature and C_1 and C_2 are constants. If we consider a grey body in place of a blackbody then the spectral radiance from a grey body is given by

$$L(\lambda,T)=\varepsilon\frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T}\right)-1\right]} \tag{2}$$

where ε is the emissivity of grey body and it is defined as the ratio of spectral radiance from an object ($L(\lambda,T)$) at a given temperature T and wavelength λ to that of a blackbody ($L^{BB}(\lambda,T)$) at the same temperature T and wave length λ. Thus ε is expressed as

$$\varepsilon=\frac{L(\lambda,T)}{L^{BB}(\lambda,T)} \tag{3}$$

As thermal camera usually detects the radiation emitted from a target as well as background radiation reflected off the target, therefore the ir-radiance at the optics of thermal camera, produced by a target placed in the background will be

$$L(\lambda,T)=\varepsilon_T L^{BB}(\lambda,T_T)+(1-\varepsilon_T)L^{BB}(\lambda,T_B) \tag{4}$$

where $L^{BB}(\lambda,T_T)$ is the equivalent blackbody radiance at target temperature T_T, $L^{BB}(\lambda,T_B)$ is the equivalent blackbody radiance at background temperature T_B.

Equation (4) can be re-written in following way

$$L(\lambda,T)=L_T^{Emis}(\lambda,T_T)+L_T^{\mathrm{Ref}}\left(\lambda,T_B^{\mathrm{Ref}}\right) \tag{5}$$

where $L_T^{Emis}(\lambda,T_T)=\varepsilon_T L^{BB}(\lambda,T_T)$ is the emitted radiation from the target, $L_T^{\mathrm{Ref}}\left(\lambda,T_B^{\mathrm{Ref}}\right)=(1-\varepsilon_T)L^{BB}(\lambda,T_B)$ is the background radiation reflected off the target and T_B^{Ref} is the background temperature reflected off the target.

$$L_T^{\mathrm{Ref}}\left(\lambda,T_B^{\mathrm{Ref}}\right)=(1-\varepsilon_T)L^{BB}(\lambda,T_B) \tag{6}$$

$$\text{As } L^{BB}(\lambda,T_B)=L_B(\lambda,T_B)/\varepsilon_B \tag{7}$$

where ε_B is the emissivity of background and for mathematical calculation we assume that the emissivity of background is of 1 i.e., $\varepsilon_B=1$. The background of the target is generally Sand, Vegetation, Rocks, Stones etc. and these background elements have emissivity values more than 0.91[9]. Hence for the sake of simplicity of calculation, $\varepsilon_B=1$ has been considered.

To illustrate the effect of target emissivity we further assume that in the spectral band of interest the reflected radiance is much less than the emitted radiance. It is therefore for the sake of simplicity and also to avoid cumbersome mathematics, first of all we only consider the emitted radiation in Eqn. (5) and find out the apparent thermal contrast (Thermal Contrast to be seen by the thermal imager at standoff distance) between target and background due to emitted radiation for a given true temperature difference between target and background.

By neglecting the reflected component in Eqn. (4) we have

$$L_T(\lambda,T_T)=L_T^{Emis}(\lambda,T_T)$$

$$L_T(\lambda,T_T)=\varepsilon_T\frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T_T}\right)-1\right]} \tag{8}$$

The temperatures of target and background are such that the Wien approximation to the Planck function can be applied. Then the emitted ir-radiance from the target in the field of view (FOV) of thermal imager will be

$$L_T(\lambda,T_T)=C_1\varepsilon_T\frac{1}{\lambda^5}\exp\left(-\frac{C_2}{\lambda T_T}\right) \tag{9}$$

Similarly we can write for emitted background ir-radiance in the FOV of thermal imager

$$L(\lambda,T_B)=C_1\frac{1}{\lambda^5}\exp\left(-\frac{C_2}{\lambda T_B}\right) \tag{10}$$

2.1 Thermal Contrast by Taking into Consideration only the Emission from Target and Background

Using the Wein approximation at Eqns. (9) and (10), the reciprocal of target and background temperature corresponding to given ir-radiance can be written as

$$\frac{1}{T_T}=-\frac{\lambda}{C_2}\ln\left[\frac{\lambda^5 L_T(\lambda,T_T)}{\varepsilon_T C_1}\right] \tag{11}$$

$$\frac{1}{T_B}=-\frac{\lambda}{C_2}\ln\left[\frac{\lambda^5 L_B(\lambda,T_B)}{C_1}\right] \tag{12}$$

The relative difference between the estimated thermal contrast by using equivalent blackbody temperatures for ε_T and $\varepsilon_B=1$ and true thermodynamic temperatures for true target emissivity, be defined according to a difference function D[8]

$$\mathrm{D}=\frac{\left(\frac{1}{T_B}-\frac{1}{T_T}\right)_{\varepsilon_B=1,0<\varepsilon_T<1}-\left(\frac{1}{T_B}-\frac{1}{T_T}\right)_{\varepsilon_B,\varepsilon_T=1}}{\left(\frac{1}{T_B}-\frac{1}{T_T}\right)_{\varepsilon_B,0<\varepsilon_T<1}} \tag{13}$$

It should be noted that the terms within the different parenthesis are defined relative to the subscript outside the parenthesis. The first set of parenthesis in the numerator contains the true thermal contrast (expressed in terms of reciprocal temperature) between a target with true emissivity and background with unit emissivity. The second set of parenthesis represents the equivalent blackbody thermal contrast (Brightness thermal contrast) between target and background for an assumed emissivity of 1.0. The denominator normalises the difference between true thermal contrast and brightness thermal contrast.

Equation (13) can be further simplified by assuming that the product of target and background temperatures is approximately same for any of the emissivity of interest for target[8].

$$(T_T T_B)\varepsilon_T=(T_T T_B)\varepsilon_{T=1} \tag{14}$$

By using the assumption at Eqn (14), the Eqn (13) can be written as

$$D=\frac{(\Delta T)_{\varepsilon_T}-(\Delta T)_{\varepsilon_T=1}}{(\Delta T)_{\varepsilon_T}} \tag{15}$$

The thermal contrast between target and background may be defined as

$$\Delta T=T_T-T_B \tag{16}$$

By using Eqn. (11) and Eqn. (12) and performing some algebraic calculation, the difference in the reciprocal temperature difference between target and background is

$$\frac{1}{T_B}-\frac{1}{T_T}=-\frac{\lambda}{C_2}\ln\left[\frac{L_B(\lambda,T_B)\varepsilon_T}{L_T(\lambda,T_T)}\right] \tag{17}$$

The difference function D may be written as

$$D=-\frac{T_T T_B}{C_2}\left(\frac{\lambda\ln\varepsilon_T}{\Delta T}\right) \tag{18}$$

Thus thermal contrast between target and background considering only the emission from target and background is given by difference function D at Eqn. (18). The in-band thermal contrast i.e. the thermal contrast between wavelength λ_1 to λ_2 can be estimated by integration of Eqn. (18) and given by Eqn. (19)

$$\Delta T^{Em}=-\frac{T_T T_B}{C_2\Delta T}\int_{\lambda_1}^{\lambda_2}\lambda\ln\varepsilon_T\, d\lambda \tag{19}$$

2.2 Thermal Contrast with Consideration of Background Radiation Reflected off the Target

From Eqn. (6) we have

$$L_T^{Ref}\left(\lambda,T_B^{Ref}\right)=\left(1-\varepsilon_T\right)L^{BB}\ (\lambda,T_B)$$

Considering the Wien approximation law and according to Eqn. (11) the above equation can be written as

$$\frac{1}{T_T^{Ref}}=-\frac{\lambda}{C_2}\ln\left(\frac{\lambda^5 L_B\left(\lambda,T_B\right)}{\left(1-\varepsilon_T\right)C_1}\right) \tag{20}$$

The relative thermal contrast between target and background due to background radiation reflected off the target can be defined with respect to background and given by

$$\frac{\left(\frac{1}{T_B}-\frac{1}{T_T^{Ref}}\right)}{\left(\frac{1}{T_B}\right)}=-\frac{\lambda}{C_2}\ln\left(1-\varepsilon_T\right) \tag{21}$$

Equation (21) can be further simplified as

$$\Delta T_T^{Ref}=-T_T^{Ref}\frac{\lambda}{C_2}\ln\left(1-\varepsilon_T\right) \tag{22}$$

As we know that the observed brightness temperature is the emissivity times the actual temperature. Hence the background temperature reflected off the target may be approximately expressed as

$$T_T^{Ref}=\left(1-\varepsilon_T\right)T_B \tag{23}$$

The Eqn. (22) can be integrated for the estimation of in-band reflected thermal contrast (between λ_1 to λ_2) and can be expressed as

$$\Delta T_T^{Ref}=-\left(1-\varepsilon_T\right)T_B\int_{\lambda_1}^{\lambda_2}\frac{\lambda}{C_2}\ln\left(1-\varepsilon_T\right)d\lambda \tag{24}$$

Wolfe[7] shown that a change in emissivity of 0.01 leads to a change in temperature of 0.5 K at 300 K. Thus to find out the accurate thermal contrast due to reflection, ΔT_T^{Ref} should be multiplied by a compensation factor (CF). The compensation factor may be written as

$$CF=\left(\frac{1-\varepsilon_T}{0.01}\right)0.5 \tag{25}$$

Hence accurate thermal contrast due to reflection may be written as

$$\Delta T^{Ref}=\Delta T_T^{Ref}\ \mathrm{X}\ CF \tag{26}$$

Now the true apparent thermal contrast between target and background can be given below

$$\Delta T=\left(\Delta T\right)_0+\Delta T^{Ref}-\Delta T^{Emis} \tag{27}$$

$\left(\Delta T\right)_0$ is the true thermodynamic thermal contrast between target and background. As thermal contrast due to reflection is to be reflected off the target, that is why it is to be added in thermodynamic thermal contrast.

3. MATHEMATICAL SIMULATION AND GRAPHICAL USER INTERFACE

For the simulation of effect of target emissivity on the estimation of thermal contrast between target and background, a graphical user interface (GUI) in MATLAB was prepared using the above mentioned theoretical framework. Using this GUI, the effect of target emissivity on apparent thermal contrast between target and background for a given thermodynamic temperature difference between target and background, was simulated.

Figures 1 and 2 plot the apparent thermal contrast between target and background in MWIR and LWIR band with respect to target emissivity for given thermodynamic temperature difference between target and background of 5 K, 6 K, 7 K, 8 K, and 9 K.

It is clear from the Figs. 1 and 2 that as the thermodynamic temperature difference between target and background decreases, the effect of target emissivity on the estimation of apparent thermal contrast become more pronounced. The effect of reducing the target emissivity on apparent thermal contrast

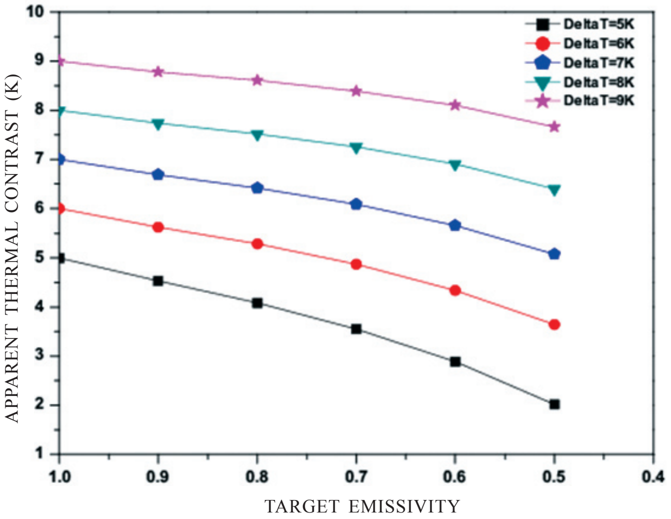

Figure 1. Effect of target emissivity on thermal contrast estimates in MWIR.

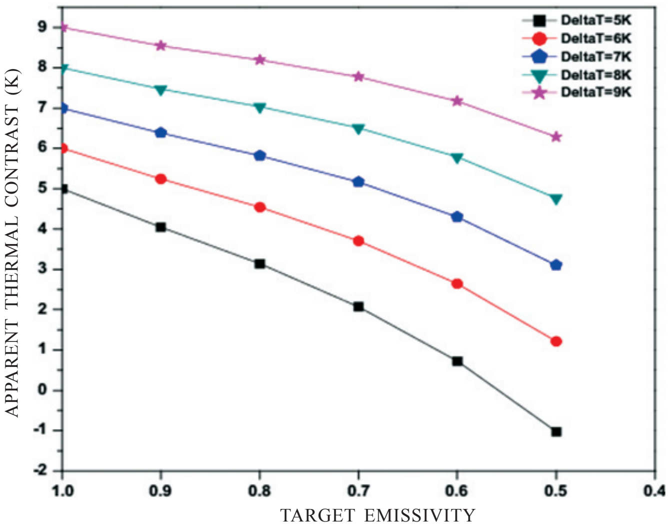

Figure 2. Effect of target emissivity on thermal contrast estimates in LWIR.

is also more prominent in LWIR as compared to MWIR. These curves show that substantial differences result in the apparent thermal contrast estimates due to the variation of target emissivity from 1.0 to 0.5. it is also vivid from Figs. 1 and 2 that if the temperature difference between target and background is ≤ 5k and we reduce the target emissivity beyond 0.7 (i.e. 0.6, 0.5 etc) then the emission from the target reduces by 40 per cent (at 0.6) or by 50 per cent (at 0.5) and simultaneously the reflection of background radiation (Which is already cooler than the target) increases by 40 per cent and 50 per cent, respectively. Therefore, target will produce a negative contrast at thermal imager for lower temperature difference between target and background for much lower emissivity values.

4. EFFECT OF EMISSIVITY ON DETECTION CAPABILITIES OF THERMAL IMAGING SYSTEMS

Intuitively, we understand that the probability of detecting an object in a background via thermal imager varies as the apparent thermal contrast between the target and background varies. This section briefly discusses how the range performance of a thermal imager can be predicted.

There exist a number of models for range performance prediction of thermal imager (e.g. Acquire, TRM3 and NVTHERM etc.) but it is beyond the scope of this paper to discuss in depth the theoretical foundation for these models. In the most commonly used models, the thermal contrast between target and background is represented by a single number i.e. the temperature difference ΔT[10]. The radiation from both target and background is absorbed and scattered as the radiation propagates through the atmosphere between target and imager. Though the atmospheric transmission is dependent on wavelength of radiation but for just proving the concept an average value for the atmospheric transmission τ may be used[11]. Apparent temperature difference between target and background at a distance R from the target is $\Delta T_R=\tau^R\Delta T$[12]. For conditions with good visibility, the value of $\tau=0.9$/km is often used i.e. the temperature difference decreases to 90 per cent for every kilometer distance to the target. The correct value of atmospheric transmittance (τ) can be estimated using MODTRAN or PcModWin atmospheric transmittance package.

Thermal Imaging systems are often characterised by a function called, minimum resolvable temperature difference (MRTD)[13]. This function gives the system's minimum resolvable temperature difference as a function of the target's spatial frequency. For a given target size, spatial frequency can be converted into range[14]. The largest possible detection range for a target is therefore the distance, where the system's effective temperature resolution (MRTD) equals the apparent thermal contrast between target and background[15]. This is illustrated in Fig. 3.

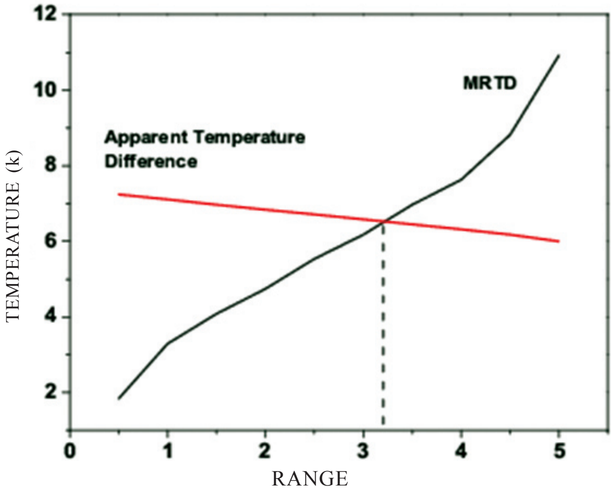

Figure 3. Detection range for a typical thermal imaging system.

The input parameters are tabulated at Table 1 for NVTHERM[16]. With these input parameters and using apparent thermal contrast between target and background for different target emissivity values in NVTHERM, the detection range of LWIR and MWIR thermal imager with 200 mm lens for a target of size 2.3 m x 2.3 m were predicted and presented at Figs. 4 and 5.

Figures 4 and 5 plot the effect of target emissivity on detection range of thermal imager in MWIR and LWIR bands.

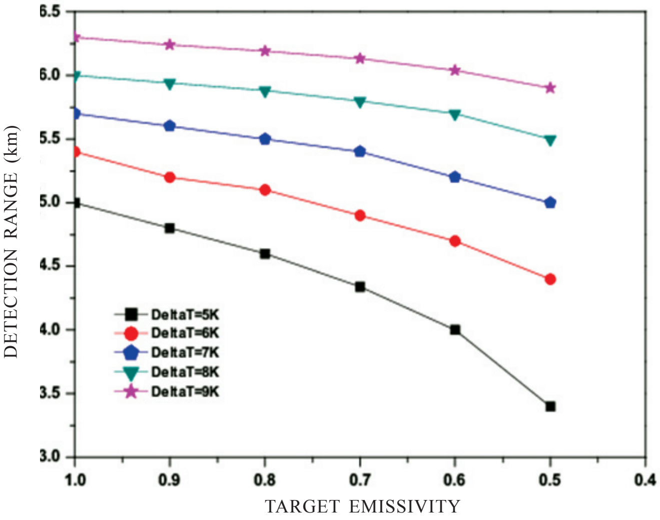

Figure 4. Effect of target emissivity on detection range of MWIR thermal imager.

It is clear from Fig. 5, if the thermodynamic temperature difference between target and background is low then decreasing the value of emissivity more than a particular value, may lead to negative contrast and it may even higher than the actual thermal contrast which in-turn leads to longer detection range. That is why the last curve in Fig. 5 for 5K shows unusual behaviour at target emissivity of 0.5. The effect of target emissivity on detection range of thermal imager is more pronounced in LWIR as compared to MWIR. As soon as the thermodynamic temperature difference between target and background increases the variation from maximum detection range (with target emissivity of 1) to minimum detection range (with target emissivity of 0.5) decreases. This trend is more effectively visible in LWIR in comparison to MWIR.

Table 1. Input parameters for NVTHERM

Sensor	Staring
FPA format	320 X 240
Detector size	30 µm X 30 µm
Spectral range	3.7 µm – 4.8 µm (MWIR) 7.7 µm – 9.5 µm (LWIR)
Optics	F/2
Focal length	200 mm
Field of view	2.45º X 1.85º (MWIR) 2.55º X 1.88º (LWIR)
Frame rate	50 Hz
Atmospheric transmission	0.9/km
Target size	2.3 m X 2.3 m
Target contrast	Selected from the Figs. 2 and 3 as per emissivity values in corresponding wave band
Maximum range	10 km
Range increment	200 m
Minimum scene contrast temperature (SCN_{temp})	15 ºC
Display type	Flat panel

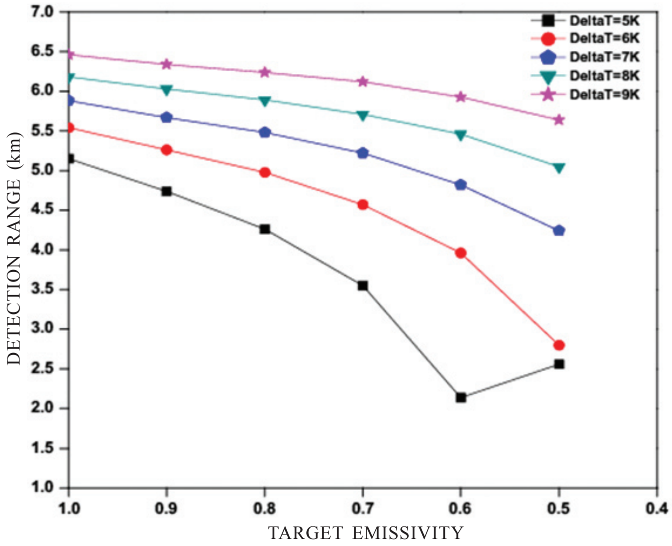

Figure 5. Effect of target emissivity on detection range of LWIR thermal imager.

5. CONCLUSIONS

This analysis may work as a guide for camouflage system/paint developer as it represents the effect of reducing the target emissivity on detection range via thermal imager. This analysis also indicates that major errors may occur in the range performance prediction of thermal imager if the actual emissivity of the target would not be taken into account. This work serves as a good framework prior to thermal signature management of military vehicles using Low Emissivity Coatings. This analysis also leads to an important conclusion that much lower emissivity values are required in MWIR as far as the thermal signature suppression of military vehicles is concerned and it why the signature management in MWIR is more difficult to achieve.

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His contribution in the current study is, in overall guidance during the work and conclusions through results.