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Engine-Embedded Fuselage's Emissivity Optimization for IR-Signature Reduction of Low Flying Aircraft

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Abstract. Low flight altitude missions are a threat due to the combat aircraft's Infrared (IR) Signature Level (IRSL) as seen by ground-based IR-seeker. The bands in which, the aircraft is susceptible to a typical IR-guided Surface-to-Air Missile are 3-5 μm and 8-12 μm. The rear fuselage skin contributes substantially to the overall aircraft IRSL especially in 8-12 μm. The IR lock-on-range (R_{LO}) for an IR-guided missile is computed and the emissivity (ε_{fus}) optimisation technique of rear fuselage skin for its IRSL camouflage is introduced. Optimization of ε_{fus} is effective also because IR-suppression is achieved with minimal performance penalties. The effectiveness of this technique in camouflaging the combat aircraft's rear fuselage skin's IRSL is demonstrated in 3-5 μm and 8-12 μm bands. The earthshine reflected off the aircraft's surface plays a vital role in the effectiveness of this camouflaging technique, especially in 8-12 μm band.

Introduction

An important mission of a combat aircraft is the surface target bombing, for destroying enemy's strategic sites; which is essential for establishing air superiority. Radar was by far the most popular and widely used for aircraft detection; hence, low flight altitude (h_{ac}) helped an aircraft by reducing the radar detection probability. Consequently, low altitude terrain hugging missions were popular with fighter aircraft until the advent of IR-guided missiles in the mid 1960s, e.g. MANPADS [1]. Their global proliferation resulted in the existence of a serious threat to both military and civilian aircraft also from terrorist attack [2]. Low altitude missions now pose a serious threat with respect to the aircraft Infrared (IR) Signature Level (IRSL) [3] and IR Search & Track (IRST) systems (ref. e.g. [4]). It is now crucial to reduce IRSL at the conceptual design stage of 5th generation fighter aircraft for survivability in a human made hostile environment (ref. e.g. [5]). This investigation focuses on IRSL from a typical fighter aircraft on a low altitude mission and analyses the mission feasibility with respect to an IR-guided threat.

Background. The main sources of IRSL in an aircraft are airframe, tailpipe, plume, and rear fuselage skin [6]. The airframe, especially stagnation region of the aircraft nose and wing leading-edges are aerodynamically heated at supersonic speeds [7] and are important sources for all aspect IR-guided missiles. Low altitude mission is performed at a moderate subsonic flight velocity, which ensures that the acoustic signature is low and aerodynamic heating of airframe is insignificant. Due to high temperature and emissivity, engine tailpipe is the most prominent source of IRSL in rear aspect [8]. Tailpipe emits IR-radiation in the entire IR-spectrum, but more prominently in 3-5 μm band relative to 8-12 μm band. In this study, an aircraft on a night time mission, entering inside the enemy's territory in the ingress mode is considered. Hence, the engine tailpipe is not seen by the IR-seeker and mainly the aircraft's forward portion is visible.

Motivation. The rear fuselage skin is heated by the low-bypass engine embedded inside the fuselage. Emissivity (ε_{fus}) of the rear fuselage skin is almost independent of the wavelength (λ) in the wavelength band of interest. The engine exhaust plume is also a source of IR-radiation, as it is much longer than the aircraft and is visible from wider view angles. Hence, from the frontal aspect, which is tactically more important than the rear aspect [9], the rear fuselage skin is a prominent IR source as seen by ground based SAM's IR-seeker in 8-12 μm band. Figure 1 shows the schematic of an aircraft entering into the enemy territory in ingress mode and approaching a SAM site.

Objectives and Scope. The aim of this theoretical study are:

(i) to analyse IRSL of a typical fighter aircraft on a low h_{ac} mission, as seen by an IR-guided missile;

(ii) to identify IR-bands in which, IR-emission is prominent and to analyse aircraft susceptibility with respect to its IRSL in terms of R_{LO};

(iii) to introduce and assess the feasibility of ε_{fus}-optimization, for reducing aircraft susceptibility by linking ε_{fus} to mission accomplishment.

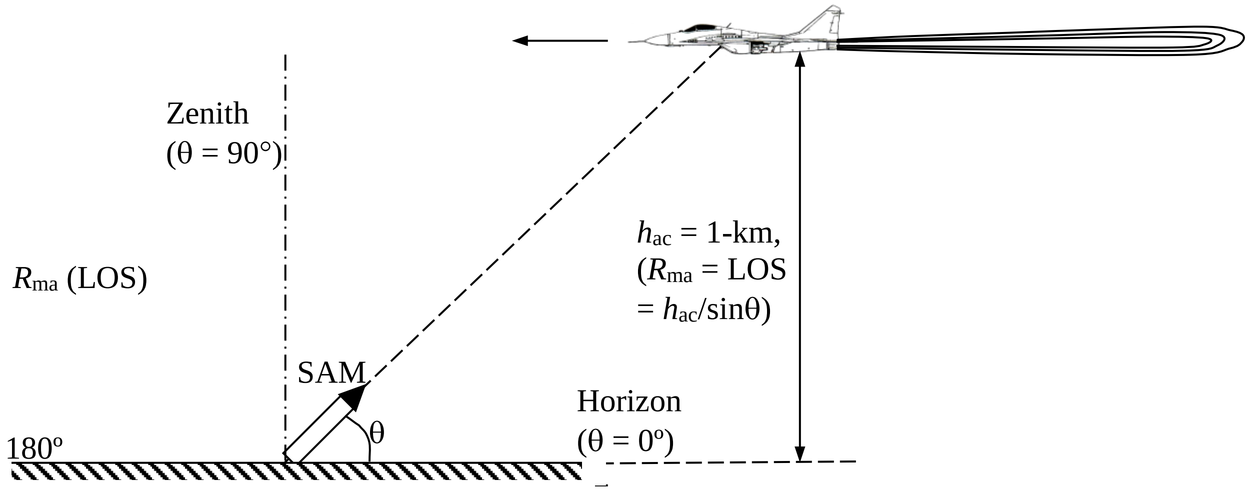


Fig. 1. Schematic of aircraft flying over a SAM site

Aircraft's IR Lock-On Range

The combat aircraft's spectral irradiance incident on the missile's IR-seeker (H_λ) and sensitivity of IR-seeker determine the condition for IR lock-on. The aircraft's spectral lock-on range ($R_{LO,\lambda}$) is obtained after modulation for differentiating its IR-radiance with the intensity of background IR-radiance (I_{bg}) in the instantaneous field of view of IR-detector. Results in Fig. 2 are obtained for tropical conditions for three different elevation angles (θ) measured relative to the horizon (θ = 0°), for the aircraft rear fuselage skin and engine exhaust plume. The engine exhaust plume's IR-radiation in non-afterburning mode is prominent only in the narrow bands, 4.15-4.20 and 4.45-4.80 μm [10]. In Fig. 2(*a*), H_λ on missile's IR-seeker after modulation for differentiating with the background IR-radiance in the instantaneous field of view is given as (e.g. [8]),

$$H_\lambda = \tau_{atm,\lambda}\cdot\left\{\sum_{i=1}^{N_{pl}}\Omega_{i,pl}\cdot\left[B_{i,pl,\lambda}-I_{bg-i,pl,\lambda}\cdot\left(1-\tau_{i,pl,\lambda}\right)\right]+\sum_{i=1}^{N_{fus}}\Omega_{i,fus}\cdot\left(J_{i,fus,\lambda}-I_{bg-i,fus,\lambda}\right)\right\}. \quad (1)$$

In Eq. (1):

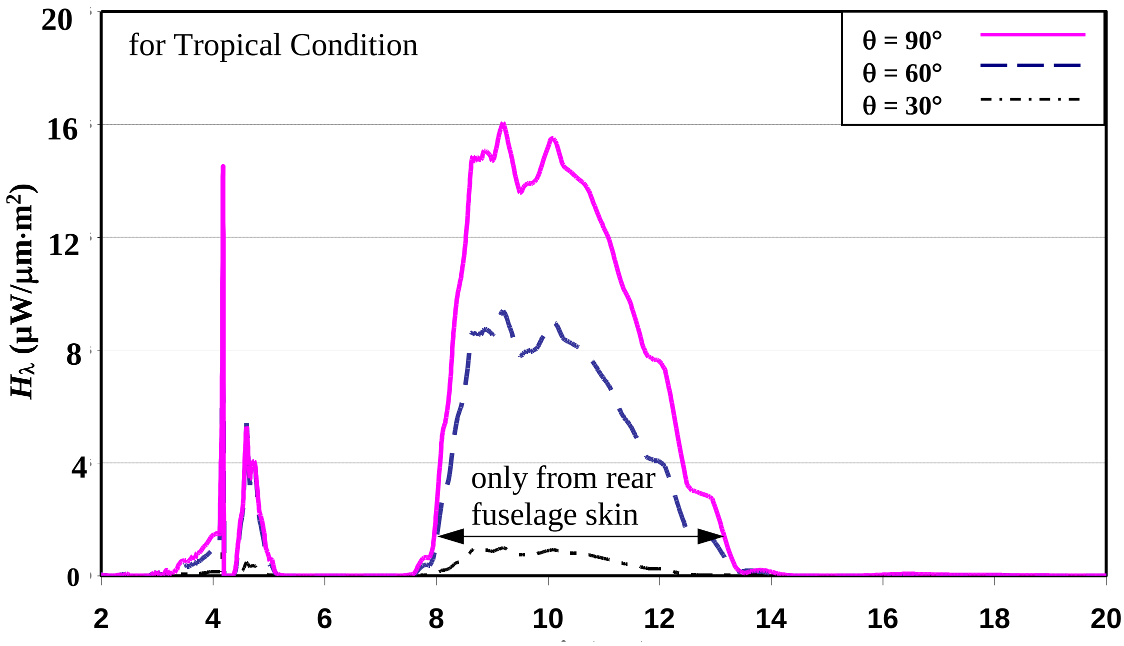
(*a*) the fuselage's IR-radiance term,

$$J_{i,fus,\lambda} = B_{i,fus,\lambda} + (1-\varepsilon_{i,fus})\cdot H_{es,\lambda}; \quad (1.1)$$

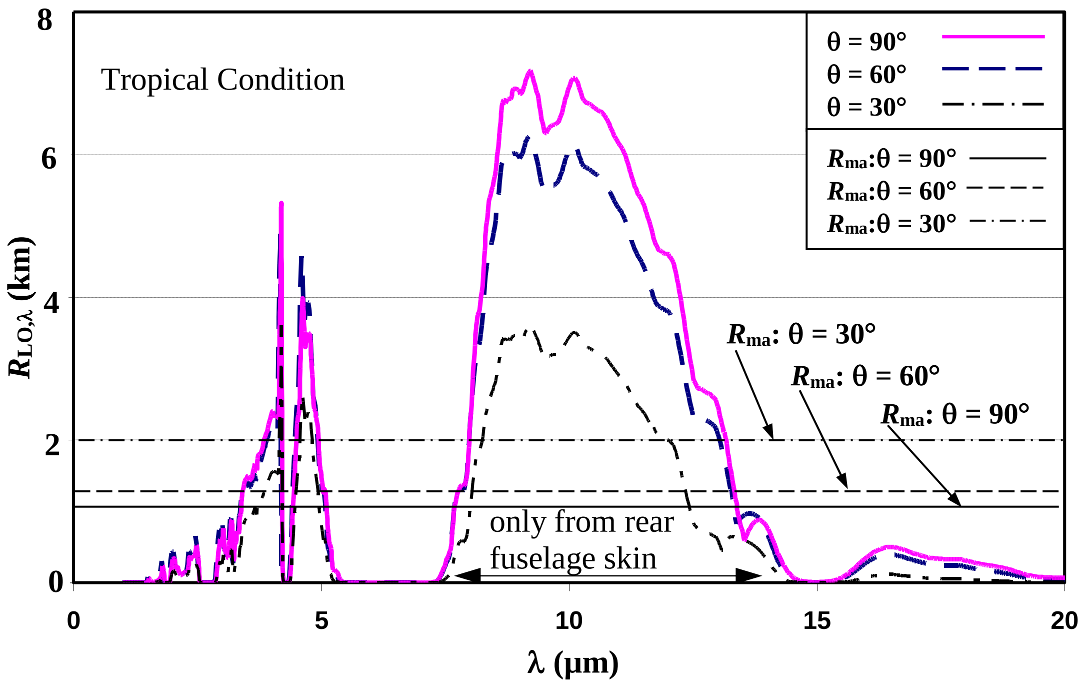
has two components (*i*) based on its temperature-based radiance ($B_{i,fus,\lambda}$), (*ii*) reflection of incident earthshine ($H_{es,\lambda}$). The design parameter, $\varepsilon_{i,fus}$ (= $\alpha_{i,fus}$) can be optimized for minimizing the rear fuselage skin's IRSL.

(*b*) the subtended solid angle can be approximated based on, LOS = Line-Of-Sight (distance between missile and aircraft), $R_{ma} = R_{LO,\lambda}$ as, $\Omega_{i,pl} = A_{i,pl}/R_{LO,\lambda}^2$ and $\Omega_{i,fus} = A_{i,fus}/R_{LO,\lambda}^2$ (where, condition for lock-on is, $R_{ma} \le R_{LO,\lambda}$). The $A_{i,pl}$ and $A_{i,fus}$ are the planar projected areas of discretised elements of plume and rear fuselage skin, respectively. Figure 2(*a*) shows that for given λ, H_λ increases with increasing θ (along approach) and 8-12 μm is the widest band. Hence, IRSL in 8-12 μm is more prominent than in 3-5 μm band; where, the contribution in 8-12 μm band is only from the rear fuselage skin (none from plume). From Eq. (1),

$$R_{\mathrm{LO},\lambda} = \left\{\frac{\tau_{\mathrm{atm},\lambda}}{NEI\cdot\xi_{\min}}\cdot\left[\sum_{\mathrm{i=1}}^{N_{\mathrm{pl}}} A_{\mathrm{i,pl}}\cdot\left[B_{\mathrm{i,pl},\lambda} - B_{\mathrm{bg-i,pl},\lambda}\cdot\left(1-\tau_{\mathrm{i,pl},\lambda}\right)\right] + \sum_{\mathrm{i=1}}^{N_{\mathrm{fus}}} A_{\mathrm{i,fus}}\cdot\left(J_{\mathrm{i,fus},\lambda} - B_{\mathrm{bg-i,fus},\lambda}\right)\right]\right\}^{0.5}. \quad (1.2)$$



(*a*) Spectral irradiance on IR-guided SAM's seeker (H_λ)



(*b*) Spectral lock-on range ($R_{\mathrm{LO},\lambda}$)

Fig. 2. Spectral variation of IR-signature parameters based on rear fuselage skin and plume radiance

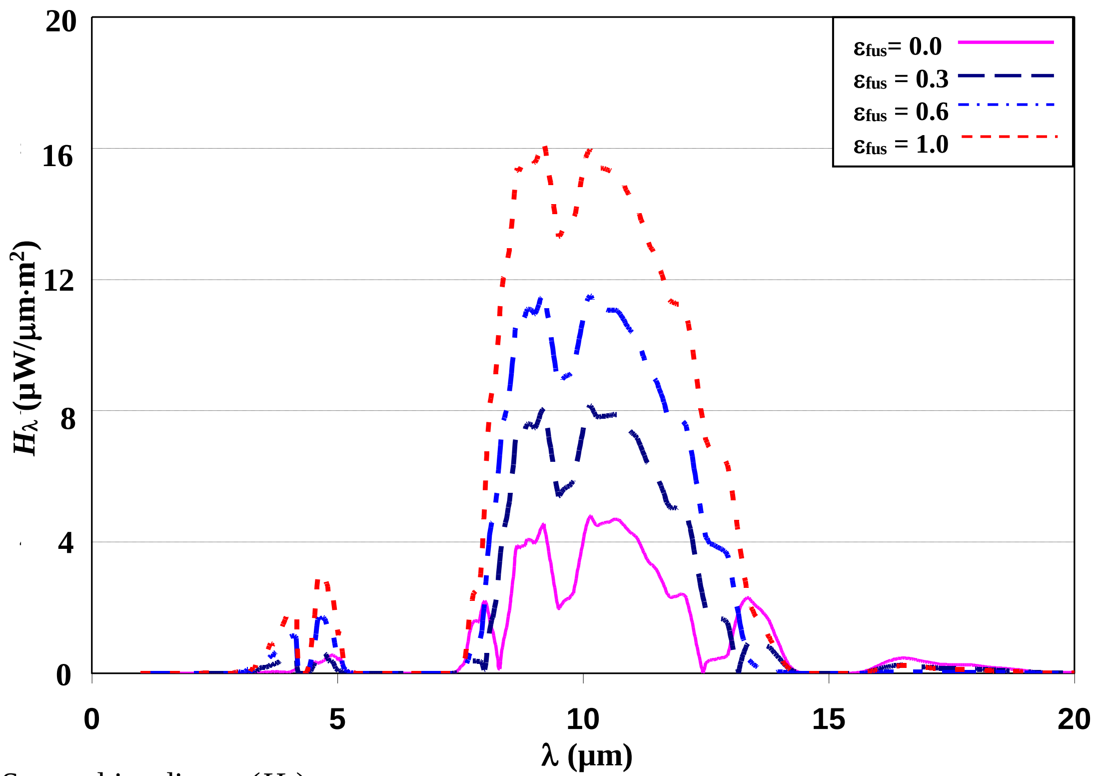
The $R_{LO,\lambda}$ variation for a typical IR-guided SAM in Fig. 2(*b*) is a function of – (*i*) aircraft parameters ($B_{i,pl,\lambda}$, $J_{i,fus,\lambda}$, $A_{i,pl}$, $A_{i,fus}$), (*ii*) missile's IR-seeker parameters [*NEI* (Noise Equivalent Irradiance), ξ_{min}(minimum signal-to-noise ratio needed for lock-on)], (*iii*) IR-characteristics of atmospheric ($\tau_{atm,\lambda}$, $B_{bg,pl,\lambda}$, $B_{bg,fus,\lambda}$), (*iv*) $H_{es,\lambda}$. The $R_{LO,\lambda}$ and H_λ are used to analyse the aircraft's IRSL and the wavelength band averaged values, R_{LO} $\left(= \frac{\int_{\lambda_1}^{\lambda_2} R_{LO,\lambda} \cdot d\lambda}{(\lambda_2 - \lambda_1)}\right)$ and H are used for analysing aircraft's susceptibility in the atmospheric windows, 3-5 μm and 8-12 μm. The LOS, $R_{ma} = h_{ac}/\sin\theta$, is shown by three horizontal lines for θ = 90° (R_{ma} = 1-km), 60° (R_{ma} = 1.2 km), 30° (R_{ma} = 2 km) in Fig. 2(*b*), for aircraft flight altitude, h_{ac} = 1-km. For given h_{ac}, Fig. 2(*b*) shows that with θ increasing (along approach), R_{ma} decreases and $R_{LO,\lambda}$ increases; i.e. the probability of aircraft's IR lock-on increases. Hence, for given h_{ac} and λ if, $R_{ma}(\theta=90°) > R_{LO,\lambda}(\theta=90°)$, i.e. if IR lock-on does not occur for θ = 90° then lock-on will also not occur for θ < 90° (during approach). Hence, Fig. 2(*b*) shows that the missile cannot lock-on to the aircraft flying at h_{ac} = 1-km in 3-4 μm band, though the IR-seeker can have a non-zero responsivity in this band.

Emissivity (ε_{fus}) Optimization of Rear Fuselage Skin

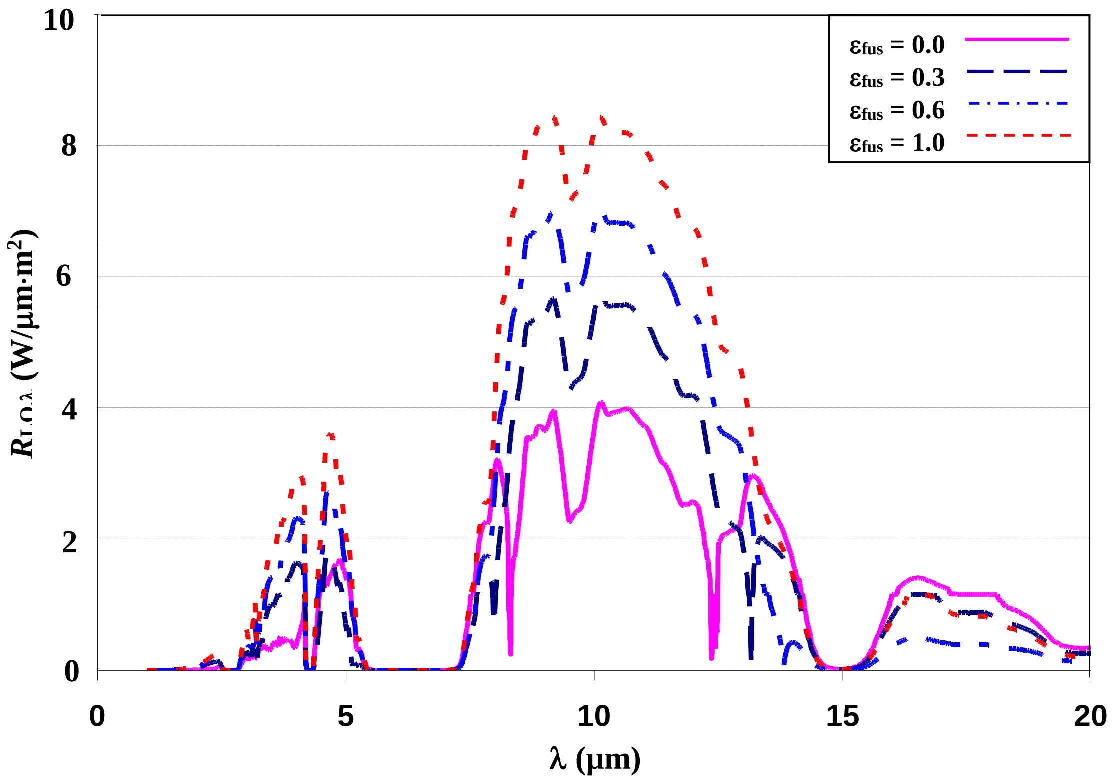
Most known techniques for reducing aircraft IR signature are associated with performance penalties; e.g. additional weight, increased aerodynamic drag, higher engine back pressure, reduced engine stability, etc. As an illustration, the 2-D slit-type nozzle exit is known to increase the engine back pressure considerably and to also reduce engine stability in terms of compressor surge and stall [11]. The rear fuselage skin contributes substantially to the overall aircraft IRSL especially in 8-12 μm, as seen from Fig. 2. Hence, suppressing rear fuselage skin's IRSL can reduce aircraft susceptibility to IR-guided missile from the aircraft's frontal aspect. As an illustration, the notion of modulating aircraft's IRSL based on the anisotropic emission behavior of aircraft skin is proposed by Huang & Cui [12]. They showed that changing the angular emission behavior of aircraft skin can modulate the directionality and contrast characteristics of IR signatures.

Another feasible technique for reducing IRSL from a metallic surface (a grey body) is ε_{fus} optimisation. The IR-radiance from the rear fuselage skin is determined by its temperature and ε_{fus} (ε_{fus} determines its reflectivity). Hence, the extent of reflection of external sources of IR-radiation e.g. earthshine, is also based on ε_{fus} [13]. The ε_{fus} is a property of the material of the surface, which can be changed by surface treatment (physical and / or chemical), or by applying a paint / coating to the rear fuselage. The basic advantage of this technique is the negligible performance penalties, e.g. the weight addition is negligible as the thickness of these paints is insignificant. The other advantage of this technique is that it can be applied to existing aircraft, with minimal modifications. The applicability of this technique to rear fuselage skin's IRSL reduction is now explored for an IR-guided SAM.

Aircraft Susceptibility against IR-guided SAM. Rear fuselage skin's IR-radiance comprises of temperature-based emission and reflection of incident earthshine. The models described in earlier sections are used to compute aircraft IR-irradiance on the missile's IR-detector. Figure 3(a) shows that H_λ decreases with decreasing ε_{fus}; hence, $R_{LO,\lambda}$ also decreases with decreasing ε_{fus} [ref. Fig. 3(b)]. For ε_{fus} = 0, temperature-based IR-emission from the rear fuselage skin is absent; but its surface now behaves as a perfect reflector by reflecting the entire incident earthshine. Since, H_λ is much above the considered threshold value of 0.25-μW/m^2, the aircraft is susceptible to IR-guided SAM even for, ε_{fus} = 0. Hence, there exists a minimum R_{LO} dictated by the reflection of earthshine from the rear fuselage skin's lower surface, for ε_{fus} = 0. The rear fuselage skin's temperature increases insignificantly with decrease in its emissivity, due to reduction in its radiative cooling. It is inferred from Figs. 3(a) and 3(b) that optimisation of ε_{fus} can effectively reduce R_{LO} especially in 8-12 μm band.

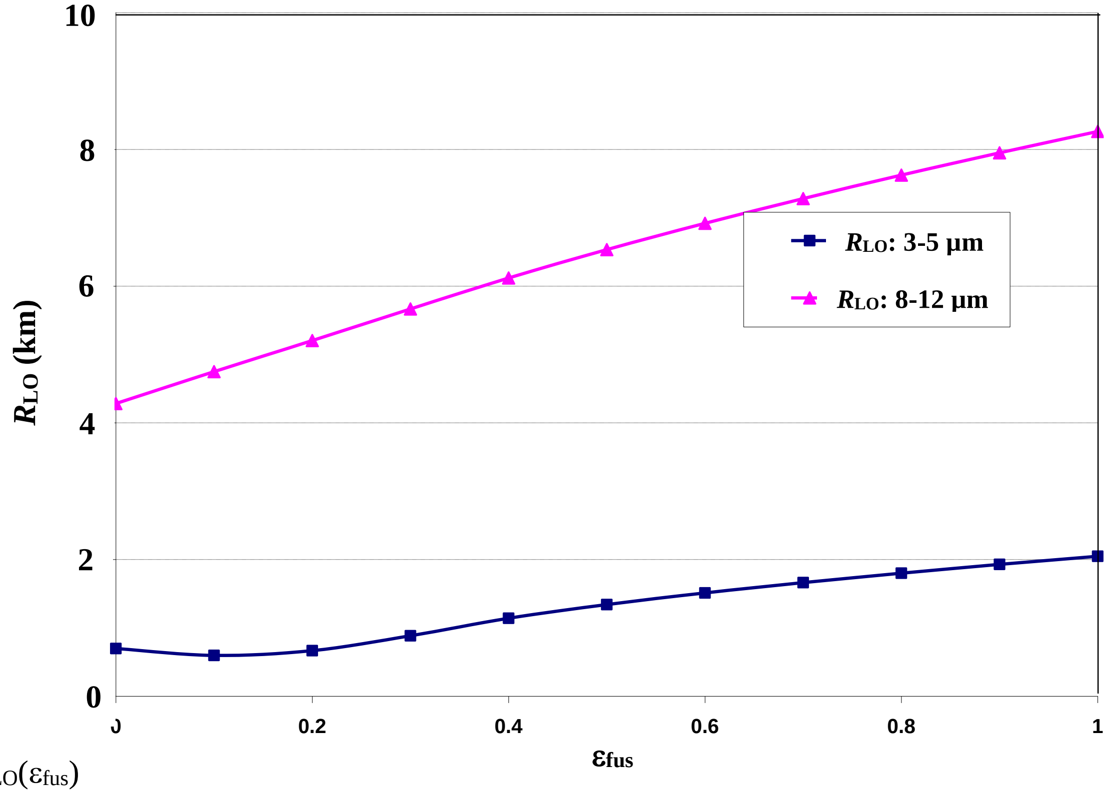


(*a*) Spectral irradiance (H_λ)

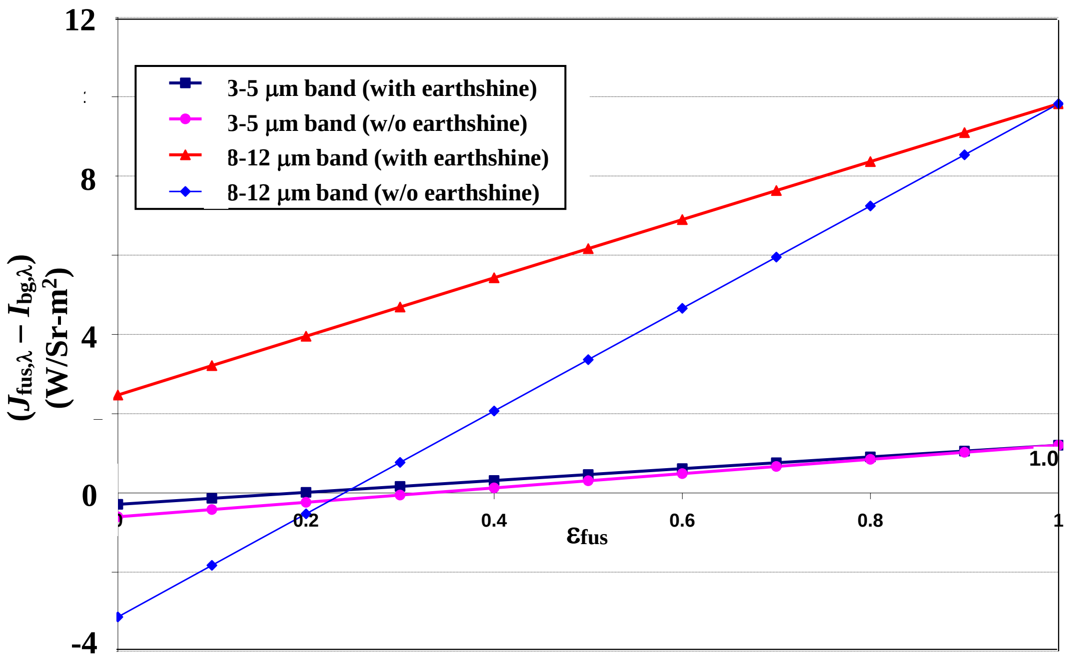


(*b*) Spectral lock-on range ($R_{LO,\lambda}$)

Fig. 3. Variation of rear fuselage skin's IR-signature parameters with ε_{fus}, with respect to SAM



(*a*) $R_{LO}(\varepsilon_{fus})$



(*b*) $J_{fus,\lambda} - I_{bg,\lambda}$

Fig. 4. Variation of IR-signature parameters with ε_{fus}

For lock-on by SAM, IRSL of the aircraft is highest for the case when the flight-paths of aircraft and SAM are in the same vertical plane. The variation of R_{LO} in 3-5 µm and 8-12 µm bands for the case when the aircraft is overhead of the SAM, is in Fig. 4(*a*). For given ε_{fus}, R_{LO} in 8-12 µm band is larger than in 3-5 µm band by a factor of about 4, which highlights the importance of Long Wavelength Infrared (LWIR) seekers. The R_{LO} in 8-12 µm band increases with increase in ε_{fus} and the least value is for ε_{fus} = 0 due to the exclusive role of earthshine, which highlights its importance for LWIR seekers. The R_{LO} in 3-5 μm band initially decreases with increase in ε_{fus}, reaches a minima, and then increases; hence there exists $\varepsilon_{fus} \in (0, 1)$, for which, R_{LO} in 3-5 μm band is minimum. At low ε_{fus}, H_λ is lower than the background radiance in 3-5 μm band; and the resulting negative contrast is responsible for R_{LO} [ref. Fig. 4(*a*)]. This technique of ε_{fus} optimization is effective especially in reducing aircraft susceptibility from the frontal aspect and in the dry mode, e.g. in super-cruise [14]. The LWIR sensors using 8-12 μm band enhance the military utility of low emissivity paints. The threat from advances in LWIR sensors and their incorporation in SAM (e.g. MANPADS) necessitates the consideration of earthshine reflection [15]. The variation of average contrast between aircraft IR-radiance and background IR-radiance in 3-5 and 8-12 μm bands with ε_{fus} for the two cases: with and without earthshine, are in Fig. 4(*b*). It shows that the effect of earthshine is less significant in 3-5 μm band relative to 8-12 μm band. Also, the effect of earthshine decreases with increase in ε_{fus} in both the bands, due to decrease in surface reflectivity (= 1−ε_{fus}).

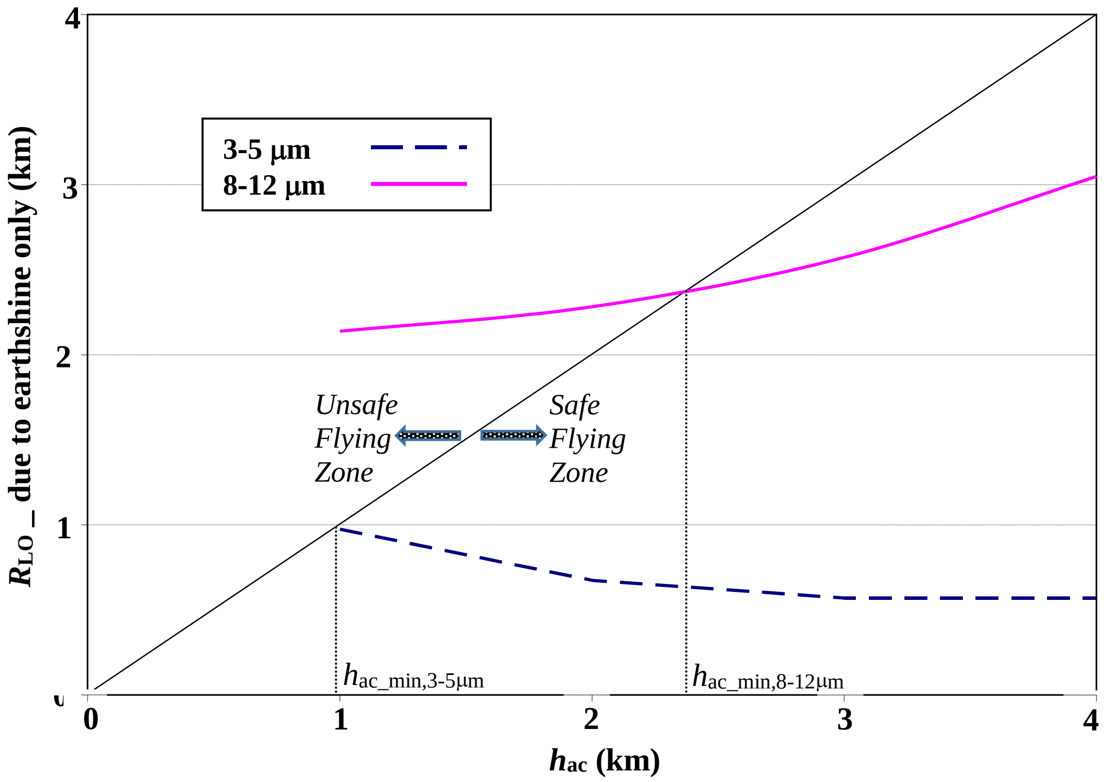


Fig. 5. Variation of "R_{LO} due to earthshine only" with h_{ac}, in 3-5 μm and 8-12 μm bands

Figure 5 shows the variation with h_{ac} of "R_{LO} due to earthshine only" (ε_{fus} = 0), in 3-5 and 8-12 μm bands. A 45°-line divides the figure in two parts: safe ($R_{LO} < h_{ac}$) and unsafe ($R_{LO} > h_{ac}$) flying zones. The $h_{ac\_min,3\text{-}5\mu m}$ (~ 1-km) and $h_{ac\_min,8\text{-}12\mu m}$ (~ 2.3 km) are the lowest flight altitudes in the two bands up to which, there is no IR lock-on with "earthshine only". The inequality, $h_{ac\_min,3\text{-}5\mu m} < h_{ac\_min,8\text{-}12\mu m}$, is because earthshine is more important for LWIR seekers.

Summary and Conclusions

(i) Low altitude missions pose a threat with respect to the aircraft's Infrared (IR) Signature Level (IRSL) as perceived by ground-based IR-seeker.

(ii) If IR lock-on does not occur for θ = 90° (aircraft in zenith position relative to SAM) then lock-on will also not occur for θ < 90° during approach in ingress mode.

(iii) For given rear fuselage skin emissivity (ε_{fus}), IR lock-on range (R_{LO}) in 8-12 μm band is larger than in 3-5 μm band by a factor of about 4.

(iv) The rear fuselage skin contributes substantially to the overall aircraft IRSL especially in 8-12 μm band. Optimization of ε_{fus} is effective in reducing aircraft susceptibility against IR guided missiles.

(v) Aircraft on low flying missions can be locked-on by ground based IR-seekers only based on the reflection of earthshine. The role of earthshine reflection in IRSL is prominent in 8-12 μm band relative to 3-5 μm band.

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