Development & Validation of Mathematical Model for Aircraft Susceptibility Analysis for Infrared Signature Studies

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Abstract

This study focuses on development of mathematical model of Infrared Signature from the first principles using MATLAB environment. The model is used for IR Signature studies and further adopted for aircraft susceptibility analysis with its computed Infrared Signature level (IRSL). The model is validated with the existing literature data of the IRSL from the engine parts of an Aircraft and thus finding the lock-on range from an Air to air missile. This paper reviews the steps to find the lock-on range, with particular focus on IR signature prediction for aerial platforms. In this investigation, the lock-on envelope is estimated in 1.9-2.9μm, 3-5μm and 8-12μm bands, considering various sources of IR signature from aircraft engine surfaces for aerial platforms. The developed model is important for further susceptibity studies of aerial platforms for survivability improvements related studies for any new design configurations and are an important factor of stealth technology.

Keywords: IRSL, Lock-on range, Atmospheric window

1. Introduction

The stealth or non detectable features are very important in combat aircrafts for deceiving and escaping from threats of tracking, and thus to increase the survivability of aircraft [1]. Radar Cross Section (RCS), Infrared signature level (IRSL), Acoustic signature, Visual signature are extremely important aspects of stealth. Among these, passive tracking is caused by Infrared radiation detectors. Helicopters and Aircraft were detected in tactical warfare, have been destroyed by heat seeking missiles like MANPADS shown in Fig.1 and other enemy defence systems. When comparing to active, passive detection is more dangerous and highly lethal. The heat source from aircraft is automatically followed by missiles as shown in Fig.2.

With increasing and improving technologies of IR detectors, analysis and study of IRSL has emerged as an important factor of stealth technology. Thus IRSL analysis and lock-on range estimation are important for assessing aircraft/helicopter susceptibility [2].
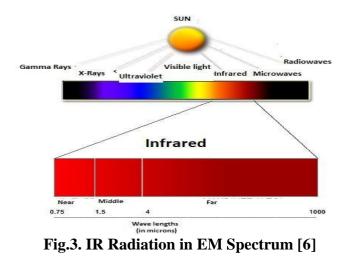
Fig.1. MANPADS [3]

Fig.2. Heat seeking missile chasing A/C [4]

2. Infrared Signature Level

Fig.3. IR Radiation in EM Spectrum [6]

Infrared (IR) radiation is a type of electromagnetic radiation. And in electromagnetic spectrum, it lies in between visible light and radio waves as shown in Fig.3. IR radiation has wavelength range from 0.74μm to about 100μm. That is from red edge of the visible light to origin of the shortwave radio band.

An aircraft's or helicopter's IRSL evaluation is important for its susceptibility analysis, planning of mission, and the design of proper IR signature suppression systems [5]. IRSL is the contrast between IR emissions from the target and the surrounding background which leads to target detection. As the contrast decreases, the IRSL value also decreases; hence the lock-on range decreases.

2.1 Sources of IR signature

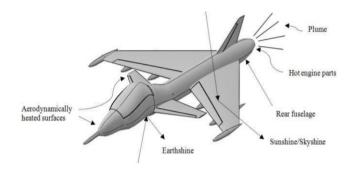The major sources of IR radiation from an aircraft are shown in Fig.4.

Fig.4. Sources of IR signature from A/C

Exhaust plume, Rear side of fuselage, engine parts, and heated skin of aircraft are some of the major sources of IR emission in an aircraft. Due to the anisotropic behaviour of emission from various IR sources, IR emission from a vehicle is non uniform in every direction. For the IRSL calculation, wing leading edges and aircraft nose will contribute when viewing from front of aircraft; plume and airframe from side aspect; and from rear aspect, engine hot parts will contribute [2].

2.2 Atmospheric windows

The wavelength of radiation, temperature and composition of radiation participating gases are the factors affecting the absorption and scattering

process of IR radiation. There are three wavelength bands (1.9-2.9μm, 3–5μm and 8-12μm) which is using for surveillance and tracking because of the high atmospheric transmittance as shown in Fig.5.
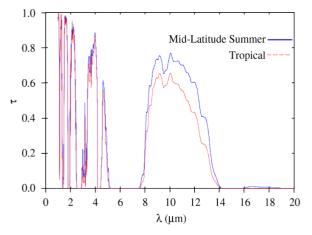

Fig.5. Atmospheric Transmission [2]

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Outside of these windows, amount of CO_2 and H_2O (vapor) for absorption and scattering is higher, so that attenuation of IR radiation will be high. At higher altitudes or in sunny or dry weather conditions, atmospheric IR transmittance is very high. At lower altitudes, where H_2O and CO_2 concentration is higher, IR transmission is low. 1.9-2.9μm window is mostly suited for detecting radiation from high temperature surfaces like engine parts. In 3–5μm window, the temperature emission will be high and is recommended for detecting hotspots like plume from exhaust. In 8–12μm band window has lowest emission temperature and is generally used for detecting emissions from larger surfaces areas at lower temperature [2].

3. IR Signature Level Prediction

IRSL is the factor of IR radiance and projected area of the target. Radiance is the radiant flux emitted, reflected, transmitted or received by a given surface, per unit solid angle per unit projected area.

3.1. Estimation radiance from various parts of target

Spectral radiance is the radiance of a surface per unit wavelength. The spectral radiance from a blackbody (E_B) is the function of wavelength, λ, and temperature, T, according to *Planck's law* as

$$E_B = \frac{C_1}{\lambda^5} * \frac{1}{e^{C_2/_{\lambda T}} - 1} \qquad \text{unit- Wm}^{-2}\mu\text{m}^{-1} \qquad (1)$$

Where,
T=Temperature (^{0}K)
λ=Wavelength(μm)
C1=3.7418×10^{-12} Wcm^2
C2=1.43×10^{-2}cm K

Stephan-Boltzmann law provides a standard comparison; it describes an ideal radiator, i.e. blackbody which can be used to compare the radiation of any other sources. A factor can, be added, so it can be applied to sources that are non-blackbodies. This factor is called emissivity, ε [8].

Spectral Radiance from any sources is
$$E_{source} = \varepsilon * E_B \qquad (2)$$
Radiance from black body is
$$I_B = \left(\int_{\lambda_1}^{\lambda_2} \frac{C_1}{\lambda^5} * \frac{1}{e^{C_2/_{\lambda T}} - 1} \, d\lambda \right) / \pi \quad \text{unit- Wm}^{-2}\text{Sr}^{-1} (3)$$

3.2. Estimation of background IR-Radiance

Not only the target (aircraft), the atmosphere will also emit some radiation. The atmospheric IR radiance is based on the property of atmospheric gases. The contrast of radiance from atmosphere and target will make the IRSL value. The radiance from the atmosphere is mainly depends on temperature and humidity. But the atmospheric radiance is only considering for the 8-12μm band. Because 8-12μm band detector is used for finding sources with less temperature. Berger's model is a method based on measurement directly from clear skies, using temperature and humidity. The model evaluates spectral emissivity and spectral radiance as a function of ground-level temperature and dew-point temperature (t_{dew}) [2].

In day and night condition, (except in 9.3–9.6μm)

$$W_{1,\,night} = 2.020e^{(0.0243t_{dew})}$$

$$W_{1,\,day} = 1.621e^{(0.0193t_{dew})} \qquad (4)$$

When additional emission from O_3 in 9.3–9.6μm band is considered, w is given as

$$W_{2,\,day} = 3.317e^{(-0.0182t_{dew})}$$

$$W_{2,\,night} = 4.050e^{(-0.0212t_{dew})} \qquad (5)$$

The C_1 and C_2 (Coefficients of absorption)are predefined and shown in Table.1.

$$k_{\Delta\lambda} = C_1 + C_2 t_{dew} \qquad (6)$$

The spectral sky emissivity in wavelength band $\Delta\lambda$ is obtained by an extension of Beer's Law as

$$\varepsilon_{\Delta\lambda} = 1 - e^{(-K_{\Delta\lambda}W)} \qquad (7)$$

Where,

$k_{\Delta\lambda}$- Coefficient of absorption
W_{night} − Equivalent absorber at night
W_{day} − Equivalent absorber at day

Table.1. Coefficient C1, C2

W_1/W_2	λ	C_1	C_2
	7.9375	1.000	0.0000
W_1	8.6375	0.085	0.0028
	9.0000	0.102	0.0031
	9.2000	0.092	0.0027
W_2	9.5000	0.124	0.0058
	9.8000	0.116	0.0058
	10.1500	0.104	0.0027
	10.8500	0.084	0.0044
	11.8000	0.134	0.0066
	12.1000	0.124	0.0071
W_1	12.5000	0.252	0.0086
	12.9500	0.274	0.0082
	13.3750	1.137	-0.0116
	13.8000	2.147	-0.0391
	16.9250	1.455	0.0113
	18.0000	1.265	0.0299
	18.8000	1.431	0.0268
W_2	19.5000	1.909	0.0208
	20.5000	1.885	0.0162
	21.1750	2.281	-0.0065
	22.0000	2.671	-0.0202

3.3. Estimation of atmospheric transmissivity

Temperature, pressure, and concentration of water vapor, CO_2, and ozone (O_3) is the factors affecting the radiative properties of the atmosphere. As height increases, the concentration of vapor decreases and is completely absent above 11 Km. The O_3 concentration present only at an altitude of 20–30 Km. Other gases like CH_4 and nitrogen oxides affect atmospheric IR properties in very negligible way when compared to water vapor and carbon dioxide. So for predicting the infrared signature level of an aircraft, it is important to evaluate the atmospheric transmissivity in which radiation is passing through. To calculate the transmissivity for a given volume of the atmosphere, one have to study the fundamental principles in quantum physics and it is too complicated. Another problem arising here is for vertical and slanting beams of radiations. The concentration and density of gases participating in radiation varies along the path. But Fortunately, data is available for the transmissivity, for **a** given length of horizontal beam, for various wavelength bands, at various altitudes, for ISA [9] is shown in Table.2.

The transmissivity follows the Beer's Law. The value of transmissivity (τ) for various wavelength bands, for an l km horizontal beam, for ISA, is available

Transmissivity at 6Km for vertical beam is,

$$\tau_{0-6} = \tau_{0-1}.\ \tau_{1-2}.\ \tau_{2-3}.\ \tau_{3-4}.\ \tau_{4-5}.\ \tau_{5-6} \qquad (8)$$

If it is a slanting beam

$$\tau_{slant} = (\tau_{vert})^{1/\cos\beta} \qquad (9)$$

β, is the angle made by slant beam with the vertical.

Table.2 Horizontal transmissivity

Altitude (Km)	Transitivity
0.5	0.64
0.6	0.66
0.7	0.68
0.8	0.7
0.9	0.71
1	0.72
2	0.82
3	0.9
4	0.95
5	0.96
6	0.97
7	0.974
8	0.9777
9	0.979
10	0.982
11	0.985
12	0.987

4. Lock-On Range

Lock-on range is one of the factors affecting susceptibility of the Aircraft. The IR-detection systems itself generate some noise in addition to the external noises. When IR radiation from the aircraft that falls on the detector is more than the net noise from the detection system, the IR-detector is able to detect the target aircraft. If the irradiance exceeds a certain value (ε_{min}) as compared to the noise level of the detection system, the probability of the missile to track the target aircraft autonomously will increase. This distance at which the missile is able to track the target is the lock-on range, and the locus of all such points around the aircraft as shown in Fig.6 is the lock-on envelop for the aircraft [10].

$$R_{LO} = \sqrt{\left(\frac{\left\{ \begin{array}{c} \sum_{i=1}^{N_{pl}}\left[I_{i.pl} - I_{bg,pl}\left(1 - \tau_{pl}\right)\right]A_{i,pl} + \\ \sum_{i=1}^{N_{fuse}}\left[I_{i.fuse} - I_{bg,fuse}\right]A_{i,fuse} + \\ \sum_{i=1}^{N_{tp}}\left[I_{i.tp} - I_{bg,tp}\right]A_{i,tp} \end{array} \right\}}{NEI * \varepsilon_{min}} \tau_{atm} \right)} \tag{10}$$

$$R_{LO} = \left(\frac{IRSL_{ac}}{NEI * \varepsilon_{min}} \tau_{atm} \right)^{1/2} \tag{11}$$

Where,
I_{pl} Intensity of the radiation from plume
I_{fuse} Intensity of the radiation from fuselage
I_{tp} Intensity of the radiation from tailpipe
$I_{bg,pl}$ Intensity of the radiation from background of plume
$I_{bg,fuse}$ Intensity of the radiation from background of fuselage
$I_{bg,tp}$ Intensity of the radiation from background of tailpipe
τ_{pl} Transmissivity of plume
N   Number of discretized volumes.
τ_{atm} Transitivity of atmosphere

A   Planar area
i   Discretized volume
NEI   Noise Equivalent Irradiance of the detector
ε_{min} Min. Signal to noise ratio of the detector
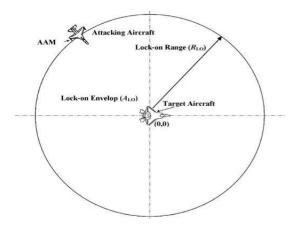

Fig.6. Typical air to air battle of target and adversary [10]

5. Results and Discussion

For validation the current approach, infrared signature of aircraft engine with choked converging nozzle used by author B Nidhi [11] is utilized for current validations. As per the literature, an aircraft is flying at an altitude of 2km height. An air to air missile is in the rear portion of the aircraft in the same horizontal plane at a line of sight of 500m. The sketch of rear side of the engine layout is given in Fig. 7. The evaluation of a Lock-on Range is composed of the following three important steps:

- Prediction of axial temperature of the exhaust geometry of engine.

- Estimation of solid angle (ω) of the turbine-exit disk and the hot jet pipe and nozzle using parallel ray projection method for different viewing angles (0 deg ≤ ϕ ≤ 90 deg) and thus find the projected area on the detector plane

- Prediction of transmissivity of atmosphere and background radiance.

Temperature distribution for the chocked

convergent divergent nozzle used in the reference paper [11] is further reproduced here as shown in Fig. 8. The 0% area reduction shows the design point of view temperature distribution along the inner portion of inlet disc, jet-pipe and converging nozzle.

And the emissivity of the surface is taken as 0.9. The solid angle subtended by the inner portion of the engine from rear aspect (0^0 to 90^0) is plotted in Fig. 9. The visibility of turbine inlet disc is higher at direct rear view (0^0). As the viewing angle changes from 0^0 to 90^0, the visibility range changes from jet pipe to converging nozzle. At side view (90^0), the only part visible is converging nozzle. The projected area of the same is calculated from the equation and is shown in Fig.10.

$$A_{pl} = \omega * LOS^2 \tag{12}$$

Where,

A_{pl}= projected area (cm^2)

ω= solid angle subtended (sr)

LOS= Line of sight (cm)

Fig.7. Sketch of the rear side of the aircraft engine layout. [11]

IRSL value for 1.9-2.9µm and 3-5µm band is found out by using the Eq .11 for rear aspect from 0^0 to 90^0 and the same is compared with the literature as shown in Fig. 11. A good matching is found between the literature data and calculated data. The IRSL value for 3-5µm band is much more than 1.9-2.9µm band. Because the surfaces with high power radiation; predominantly in 1.9-2.9µm band. From Fig. 13, it is observed that the value of IRSL is maximum at 0^0 solid angle. This is because at

this angle the projected area for the hot parts are maximum.

The background IR-radiance plays a major role in estimation of IRSL in the 8-12µm band. For day time the dew temperature is taken as 20^0C and ground temperature is taken as 30^0C. Then radiance from the atmosphere is calculated using burgers' model. Then IRSL is found out by taking the contrast of atmospheric radiance and radiance from engine. The IRSL value for 8-12µm band is estimated with and without the consideration of atmosphere is shown in Fig. 12. The calculated data without background consideration seemed to over predict the IRSL value. For this, it is absolute necessary that in the IRSL calculation for low temperature surfaces, background radiance should be taken into consideration. The atmospheric attenuation (absorption and scattering) reduces IRSL value to a significant level.
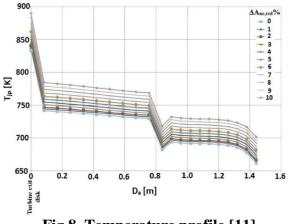

Fig.8. Temperature profile [11]

The IRSL values of three bands are compared and shown in Fig. 13. The IRSL value is very much higher for 3-5µm band when comparing to other two bands. The typical value for 3-5µm band at rear view is 600 W/sr. But for 1.9-2.9µm band, it is only 210 W/sr. At 8-12µm band, the IRSL value is very low at direct rear aspect because it radiates only low temperature and due to its contrast with atmospheric IR-radiance.

Lock- on envelope is further estimated for the 3-bands from the IRSL value calculated and plotted in Fig.14. For that, atmospheric transmissivity for 2km is taken from the table.2. NEI is taken as

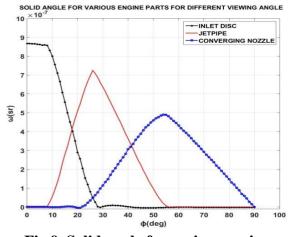$5*10^{-8}$ w/m^2/sr. And the signal to noise ratio is taken as 10.

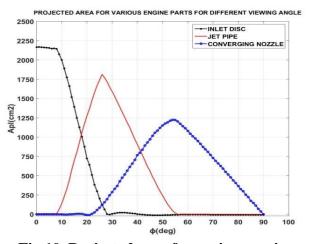**Fig.9. Solid angle for various engine parts**
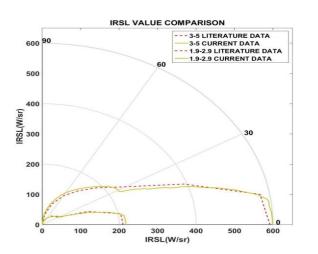

Fig.10. Projected area for various engine parts

Fig.11. IRSL value comparison for 1.9-2.9μm band with literature data
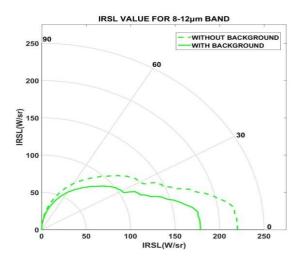

Fig.12. IRSL value for 8-12μm band with and without background

In the plot it is clear that the lock-on envelope is higher for 3-5μm band than the other bands. It is due to the high value of IRSL in that band. The IRSL and lock-on is directly proportional to each other. So, from rear aspect, the 3-5μm band detector can lock-on from a distance of 31Km. In 8-12μm band, the lock-on range will be 17Km. In modern technology, 8-12μm band detectors are using for tracking because of its sensitivity nature. But for tracking from rear   aspect, always 3-5μm band detectors are used.
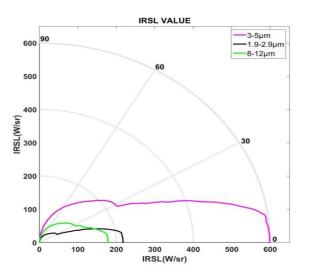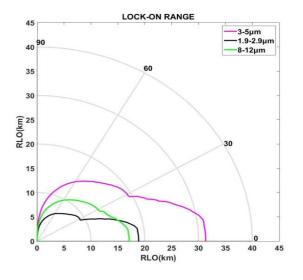

Fig.13. IRSL values of three bands

Conclusions

In conclusion, the susceptibility i.e the probability that the aircraft or target will be detected by the enemy in pursuit of its mission is predicted based on IRSL and Lock-on envelope considerations. A mathematical model based on MATLAB environment is developed. Estimations for IRSL are done for simplified engine configuration in 1.9-2.9μm and 3–5μm band for which data is in open literature. The estimated IRSL values are compared with literature data and found to be promising. The predictions are also done for 8-12μm band and reported in this paper. Lock-On range is further estimated based on these IRSL predictions in all the 3 important atmospheric windows (band). It is found that with altitude increases the lock-on range also increases.

The model is developed with an objective to study the survivability enhancements related studies for any new design configurations which forms an important aspect of stealth technology.

Fig.14. Lock-on range of three bands

Then the Lock-on envelope for different altitudes are found out for all 3 bands and shown in Fig.15. The bottom line in each band indicate the lock-on at 1Km altitude and the top most line is for 12Km altitude. As in the plot, the lock-on distance is low at 1Km altitude and increases gradually with altitude. It is because, H_2O and CO_2 concentration is much lower at higher altitudes . So, higher the IR transmission will be . If, the target is flying in low altitude, the lock-on range will decrease.
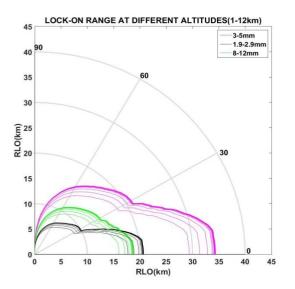
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Fig.15. Lock-on range for different altitudes

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