Infrared Signature Studies of Aerospace Vehicles

(Aero–Optics)

- **Mission Attainment Measure (Offensive)**
  ⇒ Survivability of Aircraft / Helicopters (Carriers of Offense): Foremost in Design
- **Parallel devpts. in sensitive detection & tracking systems**
  ⇒ Dynamic nature of ‘Stealth’
- **Passive** detection tactically superior / anti-radiation missiles
  ⇒ Effectiveness of RADAR is challenged
- **Low flying mission (RADAR horizon)** ⇒ **IRSS, IRCMs mandatory**
- **MANPADS**: Most serious threats to aviation in future
  - Bolkcom *et al.* (2005) *CRS Report for Congress, RL31741*
Sources of IR Signature in Aircraft

- **Principle**: Discriminate ‘Aircraft IR’ with ‘Background IR’

- **Grey Surface Emission Characteristics**
  - Planck’s Law: \( e_{\nu}(\nu, T) \) [W/m²]
  - Wien’s Law: \( \lambda_m \cdot T_{peak} = 2897.6 \text{ µm·K} \)
  - 1\textsuperscript{st} generation – 1.9–2.9 µm: \( T_{peak} = 934°C \) (only for rear aspect)
  - 2\textsuperscript{nd} generation – 3–5 µm: \( T_{peak} = 450°C \) (for – hot spots)
  - Latest – 8–12 µm: \( T_{peak} = 17°C \) (for – higher sensitivity)

Directional Dependence of Aircraft IR Signature

$\lambda (\mu m)$: 1st & 2nd Generation Detectors

IR Signature of Helicopter

- Engine Exh. Duct & Hot Parts (e.g. turbine blades)
- Tail-Boom Heated by Plume
  - > Plume
- Plume

Thompson et al. (1999) 7th CASI Propulsion Symp.
IR Detectors & their Constraint on Flight Envelope

- Cooled GaAs / AlGaAs (Aluminum Gallium Arsenide) & HgCdTe (Mercury Cadmium Telluride)
- Mid-Wave (3-5 µm) & Long-Wave (8-12 µm)
- Multi-Colour
  - Thermal-Imaging Systems
  - QWIP Technology
    - IR-detection in wider spectrum
    - all aspect
    - spatial map of scene
- A/c $H \uparrow$
  - (IR-Det. Sensitivity, $M_\infty$) $\uparrow$
  - $H \uparrow$ w.r.t. Radar-det.

Mahulikar et al. (2001) Aeronaut. J.

![Graph showing IR signal, NEI, and IRSL as functions of $H$ and $M_\infty$.]
Comparison of NEIs for TJE & TFE on Flight Envelope

Mahulikar et al. (2001) Aeronaut. J.
Atmosphere Role: IR-Transmission & IR-Radiance

- CO2, H2O (vap.), O3, & CH4: \( p, T, \) & Conc.

- \( \tau_{\lambda, (\lambda+d\lambda)} \): Spectral Distribution of Source IR Radiation & Intensity
  - LOWTRAN (empirical-based program)
  - 8–14 \( \mu \)m: widest window


Spectral Distribution of Atmospheric IR Radiance

- thermal emission by gases & sunlight scattering
- Berger’s model:
  - Empirical-based
  - Measurement of skies
Berger’s Model for Atmospheric Radiance

- **Input**: Surface Temperature & Humidity
- Ε_λ & E'_λ: \( f(\text{Ground & Dew Pt. Temperatures}) \)
- \( \varepsilon_{\Delta \lambda} = 1 - \exp(-k_{\Delta \lambda} \cdot w) \)
  - \( k_{\Delta \lambda} = C_1 + C_2 \cdot t_{\text{dew}} \):
    - absorption coefficient
  - \( w \): equivalent absorber
    - \( w_{1, \text{night}} = 2.020 \exp(0.0243 \cdot t_{\text{dew}}) \)
    - \( w_{1, \text{day}} = 1.621 \exp(0.0193 \cdot t_{\text{dew}}) \)
    - With \( O_3 \) in 9.3–9.6 μm
    - \( w_{2, \text{night}} = 4.050 \exp(-0.0212 \cdot t_{\text{dew}}) \)
    - \( w_{2, \text{day}} = 3.317 \exp(-0.0182 \cdot t_{\text{dew}}) \)

Spectral Radiance (W/m²·Sr·μm) vs. λ (μm)

- 0°: Horizon (Black-Body)
- 15°
- 30°
- 90°: Zenith

Spectral clear sky radiance on ground for mid-latitude summer

Berger (1988) *Solar Energy*
Path-Lengths of Horizontal & Vertical Beams

Horizontal path-length: Horizon
\[ [H_{atm} \cdot (H_{atm} + 2R_e)]^{0.5} \]

Horizontal / Vertical
\[ = [1 + 2(R_e/H_{atm})]^{0.5} \]

Mahulikar et al. (2007)
*Prog. Aerospace Sci.*
Spectral Contrast between Aircraft & Background

Rear-Fuselage Skin / Atm. Radiance

Mid-Latitude Summer: +ve Contrast ↑

Tropical: −ve Contrast ↑


- Tail-pipe Invisible, IRSL 3.24–4.18, 4.50–4.93, 8.20–11.80 μm
- Tail-pipe Visible, also: 1.95–2.50, 2.92–3.20 μm

- Earthshine $\uparrow \iff \varepsilon_{a/c} \downarrow$ (w.r.t. temp. based), 8–12 $\mu$m band
  - IR radiance from earth reflected off aircraft & collected by detector
- $\varepsilon_{\text{earth}}$ (soil type & temp. water body, vegetation, humidity) $\sim$ 0.93
- Non-Lambertian:
  - Vegetation
  - B.R.D.F.
    - Nicodemus (1965) Appl. Optics

![Graph showing IR contrast against $\varepsilon$ for 3-5 and 8-12 $\mu$m bands with and without earthshine]
Analysis & Modeling of IR Signature Sources

- **Re-entry Vehicle**
  - Sources: Shock heated air, Heated surface, Ablation products, Wake
  - Prediction: Trajectory i.e. variation of $H, M_\infty, \rho, \alpha$; Shock structure & B.L.
  - Prediction of surface temps. by multimode thermal model

- **Aircraft (A/c) Engine: Exptl. Measurements**
  - Static engine testing – Engine is instrumented in outdoor test facility
  - Wind tunnel testing – Scaled a/c model (prob. stray radiation)

- **A/c Sources: Power-Plant, Jet-Nozzle, Exhaust Plume, Airframe**
  - Plume – visible from all aspects – 2–5 μm, A/c surfaces – 3–5 & 8–12 μm
  - Amount & specific wavelength bands?

- **Aircraft Rear Fuselage: Large area at lower temp.**
  - Sources – internal power-plant & external free-stream aerodynamic heating
  - Earthshine & Skyshine reflections: $\varepsilon_{\downarrow}$ & 8–12 μm

- **Rear Fuselage Temp. Pred. Multimode Thermal Model**
  - Variations in: 
    - a) transport & flow properties with temp.
    - b) cross-sectional area,
    - c) heat transfer (Rayleigh flow),
    - d) skin friction (Fanno flow)
### Afterburning Mode:

- Jet-pipe temp. doubles (Rear-View)
- Skin temp. increases by 70 K (All Aspects)
Role of Free-stream in Rear Fuselage Skin’s IRSL

- Free-stream as Heat Source
  - IRSL from rear fuselage skin
  - IRSL from airframe / wings


Free-stream as heat-source:

\[ M_\infty \uparrow (> M_{\infty,\text{trans}}) \& H \downarrow (< H_{\infty,\text{trans}}) \]

Free-stream as heat-sink:

\[ M_\infty \downarrow (< M_{\infty,\text{trans}}) \& H \uparrow (> H_{\infty,\text{trans}}) \]
Estimation of $\omega(\phi)$-subtended: *Parallel Rays Projection*

- Engine Layout (Well-Resolved)
  - turbine exit disc
  - jet-nozzle
  - rear fuselage skin

Mahulikar *et al.* (2007) *Applied Optics*

$D_{gt. \ sect.} \omega \uparrow \& \omega > 0 \ \forall \phi \in [0,90^\circ]$
A/c Plume IRSL

- Visible from $\phi \uparrow$; Rad. H$_2$O (vap.), CO$_2$, CO; TJE (IRSL $\uparrow$) $>$ TFE
- AR $\uparrow \Rightarrow$ (Pot. Core) $\downarrow \Rightarrow$ IRSL $\downarrow$ (Decher 1981 *J. Aircraft*)

Spectral Plume IRSL Emitted

- A/c at zenith over SAM site
- $I_{pl,\lambda}$ recd. by SAM: 4.15-4.45 μm band

Dry Mode: Plume IRSL $<<$ tail-pipe & rear fuselage IRSL
8–12 μm band: No Gaseous Plume IRSL

Mahulikar et al. (2005)
*J. Thermophys. & Heat Transf.*
Parameters Affecting IRSL of Rocket Plume

- **Vehicle** – No. of Nozzles, Nozzle Spacing, Base Dia.
- **Ambient** – Solar Azimuth / Elevation; Flight – $M_\infty$, $H$, $\alpha$
- **Engine** *(Nelson 1987 J. Spacecraft & Rockets)*
  - Mass flow rate, Propellant type, Oxidizer-to-fuel ratio, Area ratio, Nozzle contour, Chamber pressure

Standard Models for Prediction of IRSL

- **Models** for IRSL from plume, power-plant, & complete aircraft
  - SIRUS, SIRRM, NIRATAM, SPIRITS, IRSTORM, MIRSAT, OPTASM
- **Models** for atmospheric IR transmission & radiance
  - LOWTRAN, MODTRAN, & HITRAN
- **Models** for processing & generating spatial scene map, wire model
  - SPIRITS, IRST, IIR, EOSAS
- **Models** for IRSL prediction from ships & ground vehicles
  - SHIPIR, GTSIG, PRISM
NIRATAM (NATO InfraRed Air Target Model, 1991)

- Based on Field Measurements, Theor. Studies, & Data Analysis
- Considers IRSL by Internally & Aerodynamically Heated Surfaces, Hot Engine Parts, Combustion Gases, Plume Particles
- Skyshine (Radiance), Atmospheric Trans., Sunshine, Earthshine

SIRUS (Spectral Signature Analysis Code)

- For: Air Breathing & Rocket Motor Propelled Vehicles
- Models (Based on B.R.D.F.):
  - surface temperature, surface reflectance, cavity physics, plume gas radiative transfer, atmospheric effects (including solar contribution), background & imaging sensor effects (imaging & threshold detection)
- Capability to Assess IR Characteristics of Paints on Airframes
IRST (IR Search & Track) 1989

- Simulates Air-to-Air Detection & Tracking Engagements; Integrates:
  - LOWTRAN; SPIRITS (aircraft IR signatures imaging module)
  - CLOUD (sky background imaging module)
  - TRACKER (signal processing & tracking module)
  - IPAS (optical sensor & spatial processing module)
  - MISSION (dynamic trajectory module)
  - HIGH LEVEL SCENARIO SPECIFIER (user interface module)

Models

- Empirical-Based Models:
  - IR measurements obtained on operating a/c for multiple aspects & operating conditions, data analyzed to fill prediction-gaps

- Physics-Based Models (I/Ps):
  - a/c geometry, surface emissivity, temp. profile, surface reflections
Lock-On vs. Lethal Envelope & Target A/c Susceptibility ($P_H$)

- Lock-On (L-O) Envelope:
  - Locus of pts. around target a/c where missile’s IR seeker locks-on

- Missiles Constrained by B-O Range ⇒ L-O Inadequate for $P_H$

- $P_H = \mathcal{A}[\text{Lethal Envelope} = \phi(L-O, V_{ac}, B-O, ....)]$:
  - locus of pts. within which, if missile is launched → hitting probability ↑

\[
\frac{V_{ac}}{V_m} = 0.66 \
\frac{V_{ac}}{V_m} = 0.50 \
\frac{V_{ac}}{V_m} = 0.33 \
\frac{V_{ac}}{V_m} = 0.25 \
\frac{V_{ac}}{V_m} = 0.20
\]

\[
R_{bo} = 10 \text{ km}
\]

\[
\frac{V_{ac}}{V_m}\uparrow
\]

\[
A_{\text{lethal}} (\text{km}^2)
\]

\[
R_{LO} (\text{km})
\]

Rao & Mahulikar (2005)

Aerospace Sci. & Tech.
IR Counter-Measures (IRCMs)

Passive

- IR Suppressors / Optimizers
  - Obj. to minimize a/c IRSL

Active

- IR: Flares, Jammers, Pyrotechnic Decoys, Lamp on Sacrificial Structure
  - Obj. to confuse IR seeker by IR jamming / luring away towards false target / sacrificial structure

Passive Countermeasures

- $R_{LO} \propto (IRSL)^{1/2} \Rightarrow IRSL \downarrow$
  - Minimise penalties: back-pressure, wt. cost, complexity, drag

- Techniques:
  - **Conceal** hot engine parts; Peak temp. reduction of exhaust gases
  - **Camouflage** IR by modifying exposed temp.
  - Reducing reflectivity of reflecting surfaces

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IR-Suppressors for Helicopter

Mahulikar et al. (2008) *J. Propulsion Power*
Modification to Exhaust System

- D.R.E.S. Canada: F.C.T. & C.B.T.
- Characteristics of Typical Patented IRSS System:
  - Efficient mixing / pumping of plume with ambient
  - Engine temperature reduction by fuel cooling

**Fuselage IRSS:**
Aircraft skin heating / cooling, Emissivity optimisation

- Penalties of IR Signature Suppressors (IRSS)
  - Wt.
  - Complexity
  - Changes to nozzle geometry
  - Power loss
- Mission Power – Engine Power
  - Power for IRSS Penalties

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[Graph showing the relationship between emissivity and range for IRSS penalties.]

*Mahulikar et al. (2006) J. Aircraft*
Active Countermeasures

- IR jammers, IR flares as decoys
- Smart jammers: non-directional / directional (DIRCM)
- MAWS: Radar, IR Detectors (scanning & staring), UV detectors
- High altitude flight to avoid detection

Counter–Countermeasures ($C^2M$)

- to counter active & passive IRCMs
  - increasingly sensitive IR sensors; imaging seekers
  - high speed temporal processing (to minimise reaction time)
  - multiple attack
Conclusions: IR Signatures → Passive

- Missiles: fire- & forget capability, portable, lethal↑
  - IR-detection / guidance up to terminal phase (unlike mono-static radar)
- Fuselage: Main Source for 8–12 μm; A/c Plume: for 4.15–4.20 μm
- Background IR-Radiance (+ve & –ve contrast)
- Earthshine ↑: Rear Fuselage → (ε & H) ↓
- Divergent-Nozzle: Imprudent → From Rear Aspect
- Nozzle Shape Modification:
  - notching / corrugating; aspect ratio ↑; retrofit devices
- IRSL ↓ with (Performance Penalties) ↓ e.g. Emissivity Optimization
- Next Gen. IR Imaging Sys. → multi-λ spatial detection
  - large area, multi-spectral / multi-colour staring arrays / immune to IRCM