IR aspect of aircraft propulsion system and IR-RF interplay in design

November 29th Thursday, 2018 (10:00~10:45)

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ACT
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Aircraft Core Technology

Outline

Background and introduction of aircraft survivability

IR fundamentals

IR aspect of UCAV propulsion system (nozzle and exhaust system)

Interplay of IR-RF

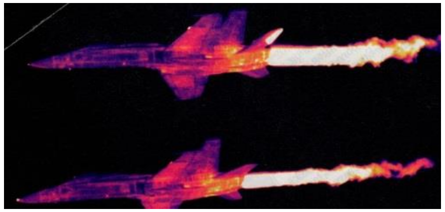
Aircraft signatures and stealth

- **Definition of stealth**

The act of moving, proceeding, or acting in a ***covert*** way

The ability to ***blend*** in with the background

Reducing the aircraft signatures and observables, thus providing the aircraft with the capability of evading the enemy's air defence



- **Aircraft signatures**

  Active

    radar : airframe, engine inlet, weapons, radome, canopy

  Passive

    infrared : engine casing, airframe, exhaust plume, sun glint

    acoustic : engine parts, engine exhaust, airframe

    visual : airframe, engine exhaust and glow, canopy glint

    misc. : navigation radar, communication, countermeasures

Status of stealth technology and driving factors

- **Technology gap**

  "It's been a quarter of a century since we developed the B-2, and the basic tenets of how U.S. goes about designing **a LO airplane have been known for at least 20 years**. But when you look at foreign systems designed to stealth principles, **they're still not even remotely close to what we did**. … So, the U.S. still needs to **protect those things that really make a difference**," A. F. Myers, Northrop then-vice president, 2006

- **Driving factors**

  Effectiveness : **precision weapon**

  Technology : modeling, RAM, avionics, navigation

  Diverse applications : air, sea, land

Aircraft combat survivability

- It is about the **effectiveness** of military aircraft contending with an enemy.
- **ACS**: The capability of an aircraft to ***avoid (susceptibility)*** or ***withstand (vulnerability)*** a ***man-made*** hostile environment (enemy air defenses or terrorist weapons).

  Survivability = 1 – Susceptibility x Vulnerability
- **Assessment**:

  1) establishing the requirements for survivability,

  2) selecting and designing the specific survivability enhancement features that will meet the requirements,

  3) supporting the evaluation that the final product meets the requirements, and

  4) providing survivability and vulnerability data to mission and campaign models.

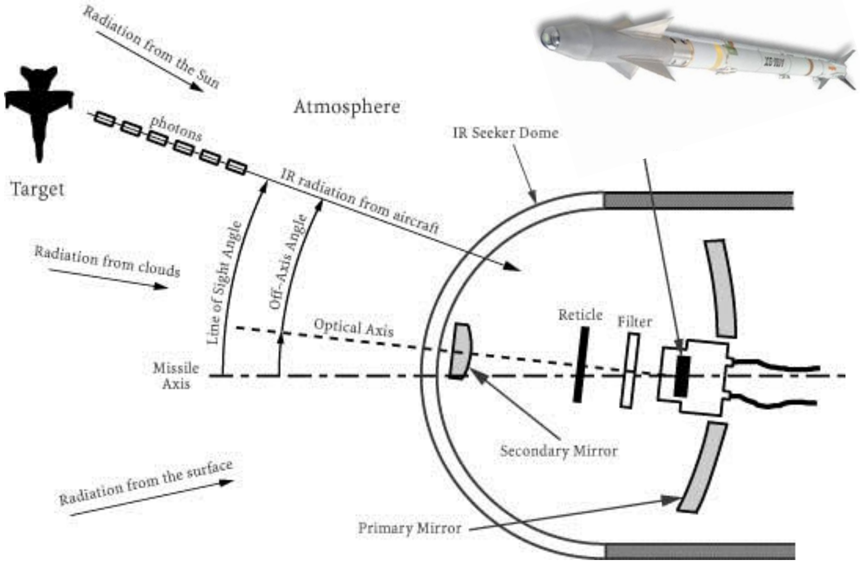
Ball, R. E., The Fundamentals of Aircraft Combat Survivability Analysis and Design, AIAA Education Series, 2003.

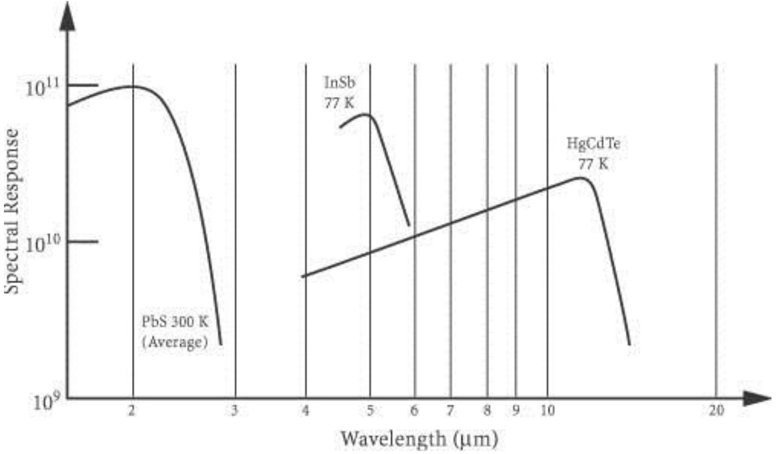
Proliferation of IR seeker missiles

IR detector MANPADS

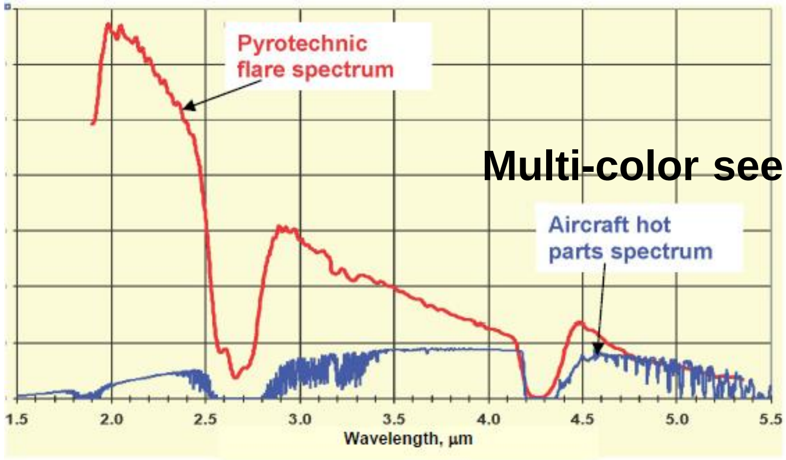
	Mistral 1	Strela-2M	Igla	FIM-92B/C
Country	Europe	Russia	Russia	USA
Range	300-6,000m	800-4,200m	500-5,200m	200-4,800m
Altitude	5-3,000m	15-2,300m	10-3,000m	0-3,800m
Band µm	2-4/3.5-5	1.7-2.8	1.5-2.5/3-5	0.3-0.4/3.5
Mach	Max 2.5	Max 1.3	> 2.0	Max 2.2

IR missile seeker





Multi-color seeker



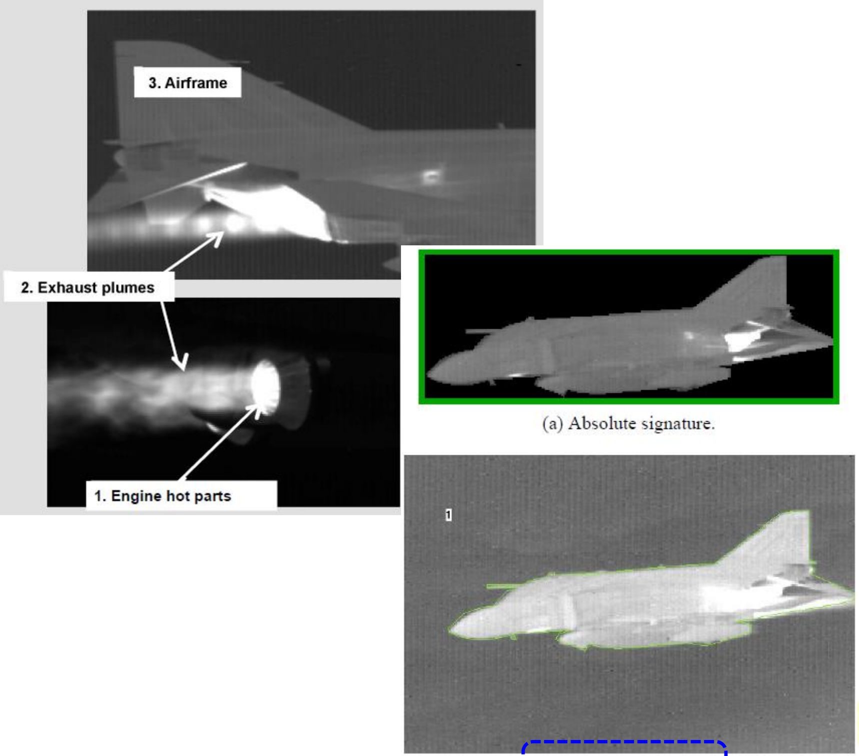
Ball, R. E., 2003 & White, J. R., Aircraft Infrared Principles, Signatures, Threats, and Countermeasures, Naval Air Warfare Center, 2012.

IR requirement in JSSG (Joint Service Specification Guide)

Azimuth angles	0°, 10°, 20°, 30°, … , 160°, 170°, 180°
Elevation angles	± 0°, 5°, 10°, 20°, 30°, 45°, 90°
IR spectrum	High flying vehicle : 3-12 microns (3-5, 8-12)
	Low flying vehicle : 1-15 microns (1-3, 3-5, 8-12)
Atmosphere model	Standard atmosphere, humidity, aerosol, Sun position, cloud cover etc.
Engine power settings	Maximum, intermediate, maximum continuous

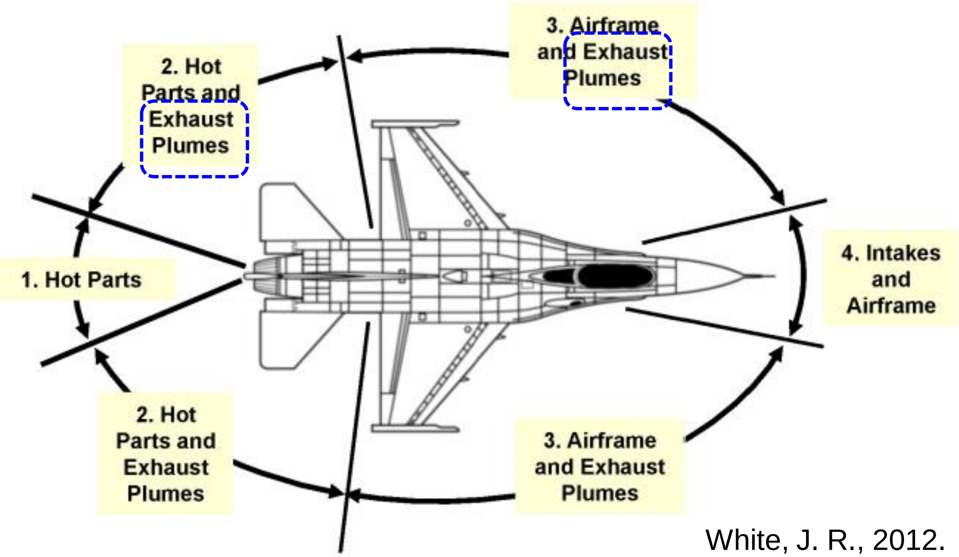
IR fundamentals: sources

Sources of IR in aircraft **(passive)**



(a) Absolute signature.

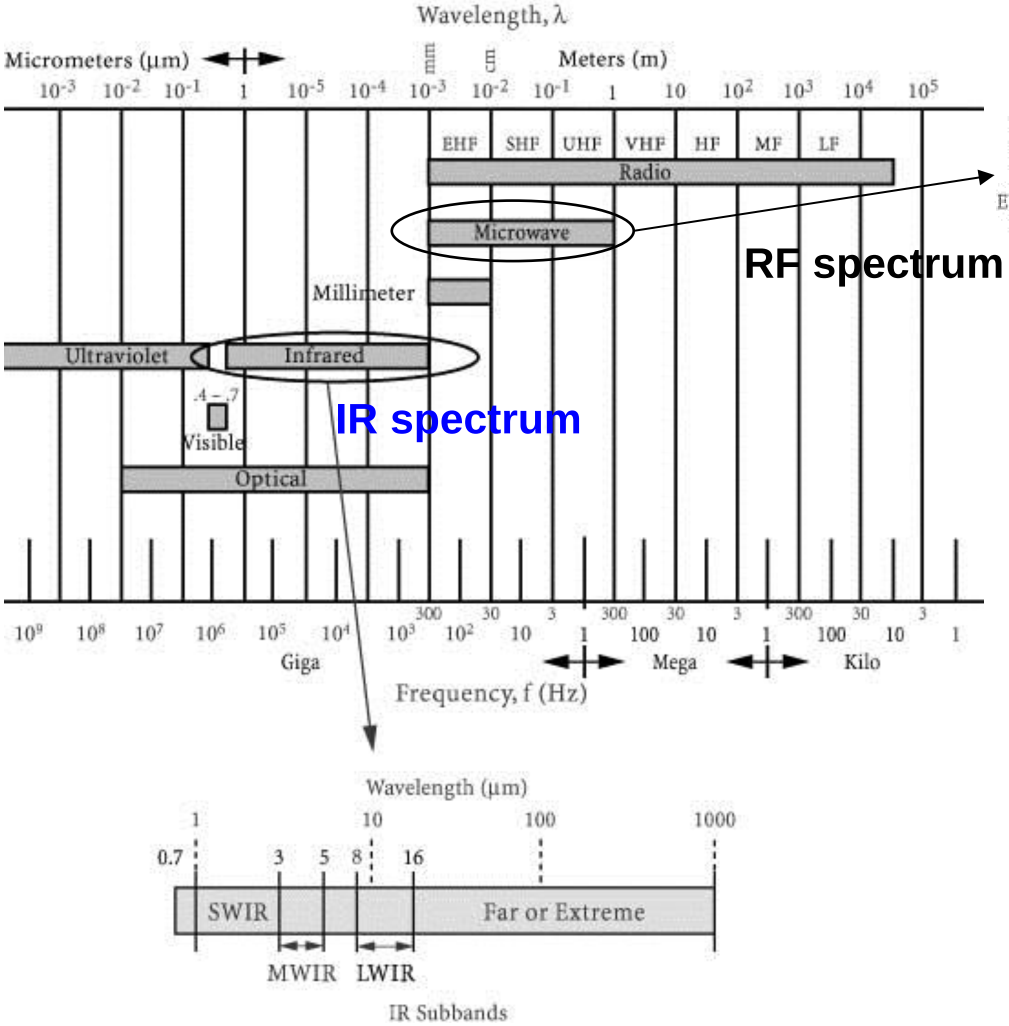
(b) Contrast signature.



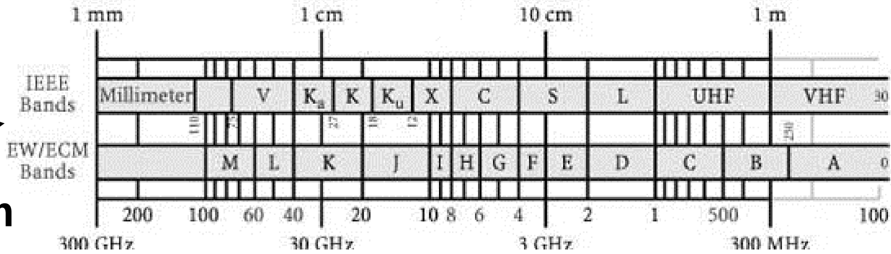
White, J. R., 2012.

Band (μm)	2~3	4~5
IR level (W/sr) (Jet fighter)	O(5~100)	O(100~1000)

IR fundamentals: spectrum



IR spectrum



RF spectrum

Wavelength: 0.7 ~ 1000 micron

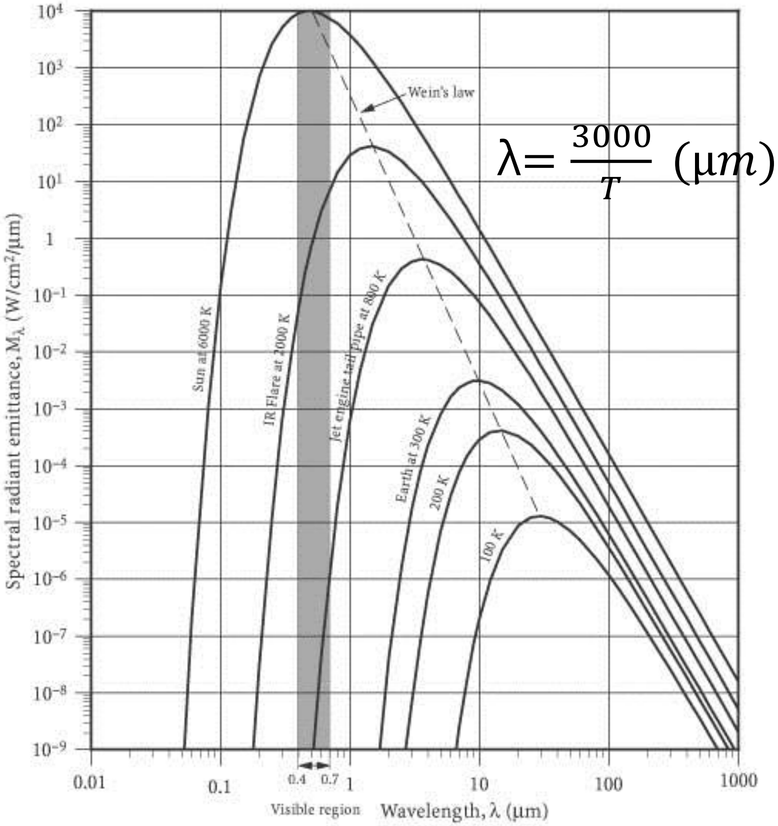
continuum radiator (solid; grey bodies)

line radiator (gas): water vapor (1.4, 1.9, 2.7, 3.2, 5.5, 7.5 micron), carbon dioxide (2.7, 4.3, 14, 16 micron)

IR fundamentals: continuum & discrete sources

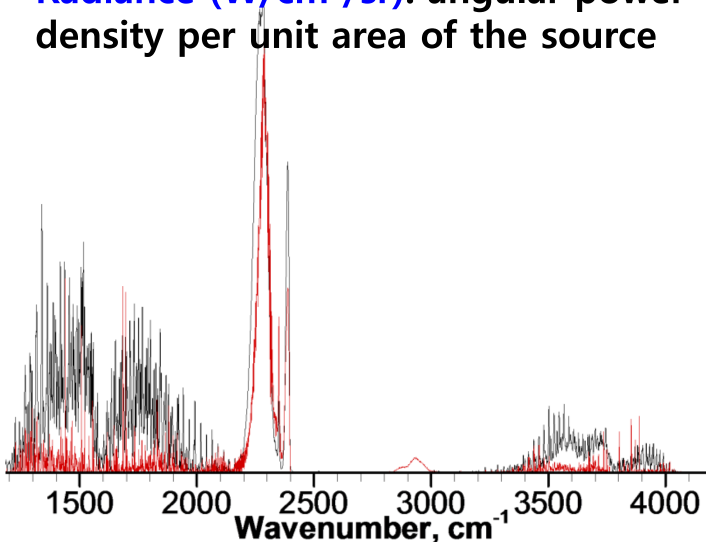
EM radiation caused by the accelerations and decelerations of electrons
Continuum (solid) radiation governed by Planck's law

Wein's law of the wavelength associated with the peak spectral radiant exitance



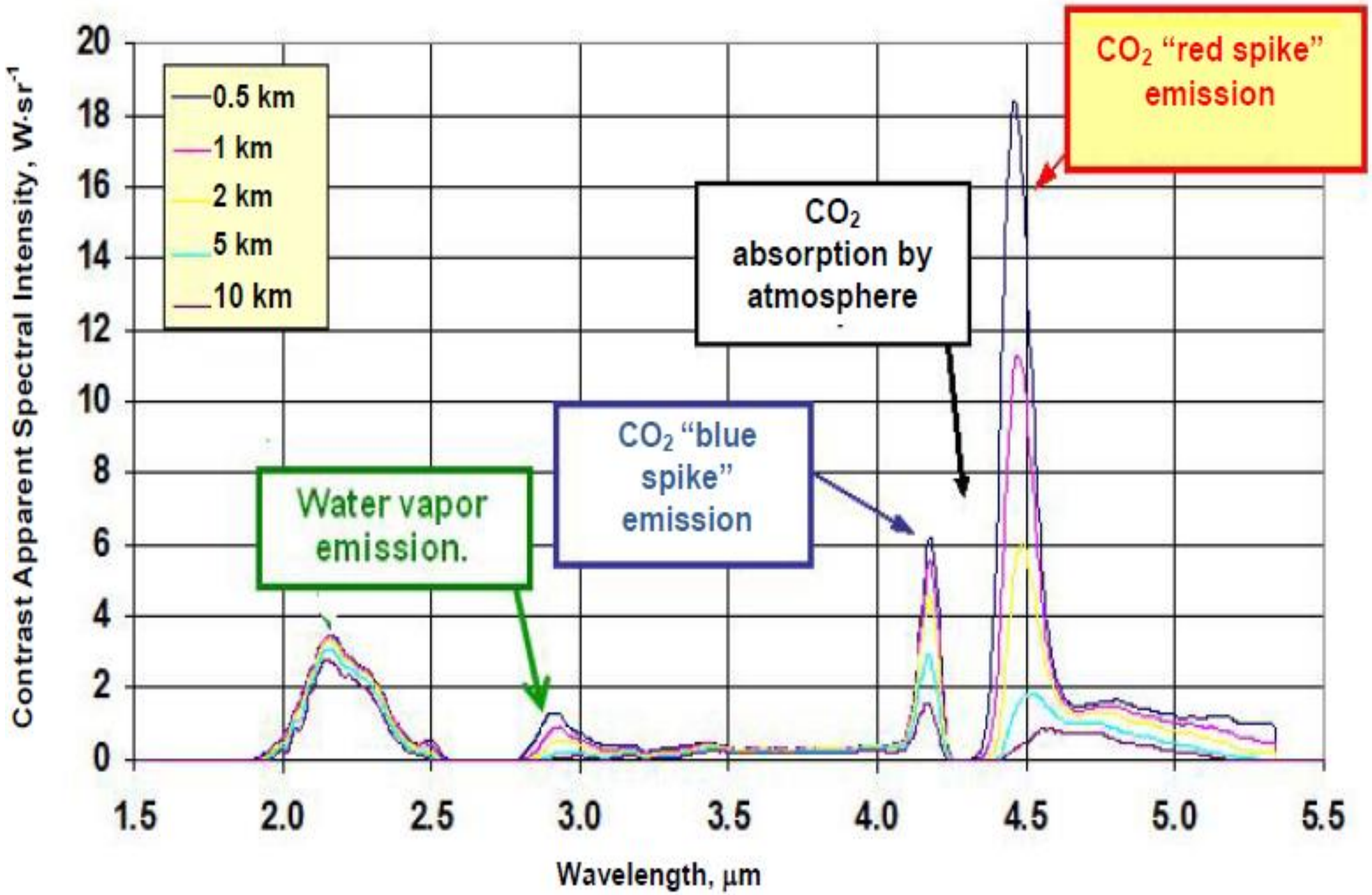
$$\lambda = \frac{3000}{T}\ (\mu m)$$

Cf. Intensity (W/sr): angular density of the power emitted from a source
Radiance (W/cm²/sr): angular power density per unit area of the source



Discrete (line) gaseous radiation: emitted and absorbed only at discrete wavelengths associated with specific rotation and vibration frequencies
CO_2 at 2.7 and 4.3 μm; H_2O at 2.7 μm.

IR fundamentals: atmospheric effect



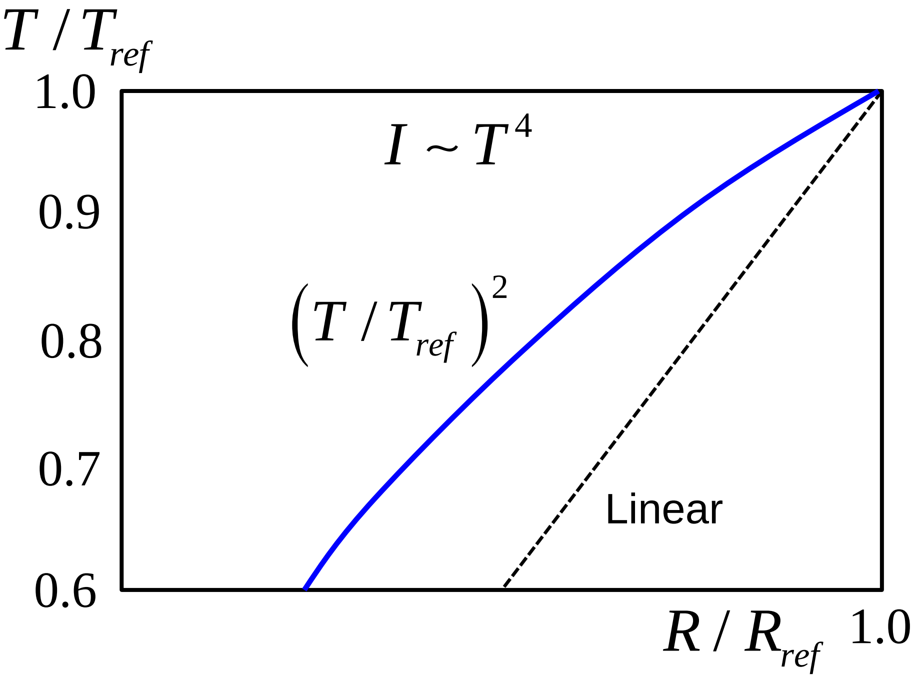
Contribution of CO_2 and H_2O to Plume IR Signature

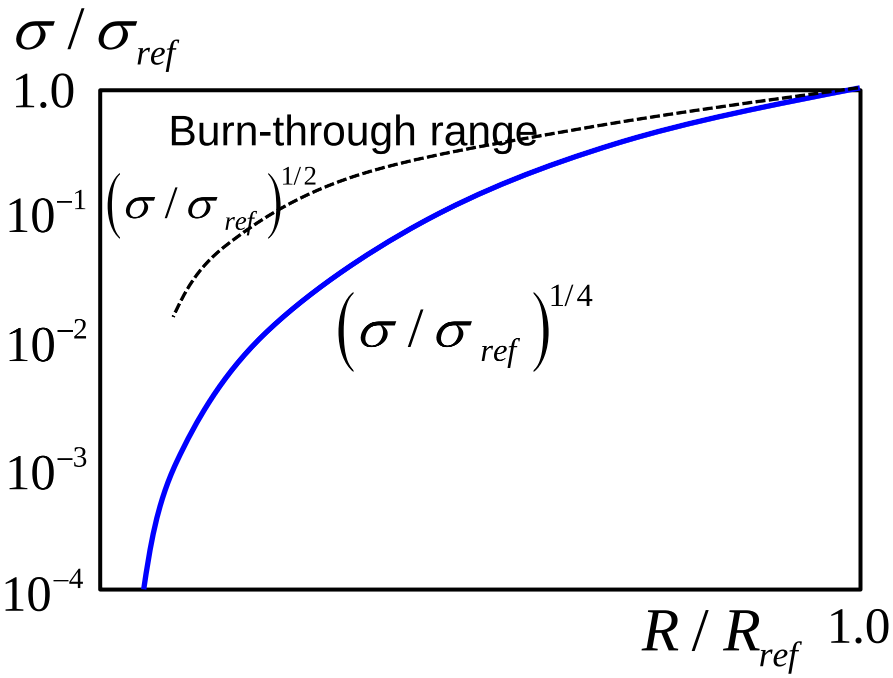
White, J. R., 2012.

Detection range relations: IR (passive) vs RF (active)

$$R_{IR\ Lock-on} = \left[\frac{I_{contranst}\eta_{atmos}}{I_{noise\ equiv\ irrad} \cdot SNR_{\min}} \right]^{1/2}$$

$$R_{RF} = \left[\frac{\sigma P_{trans} G^2 \lambda^2 L_{H/W} G_{process}}{(4\pi)^3 k_B T_{eff} W_{bandwidth} SNR_{\min}} \right]^{1/4}$$

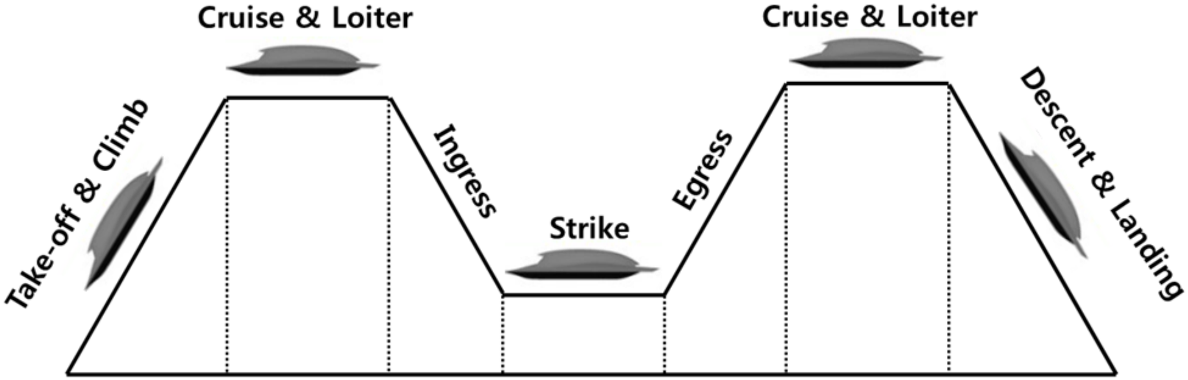




Spectrum, view angles
Contrast, atmospheric effect
Surface condition

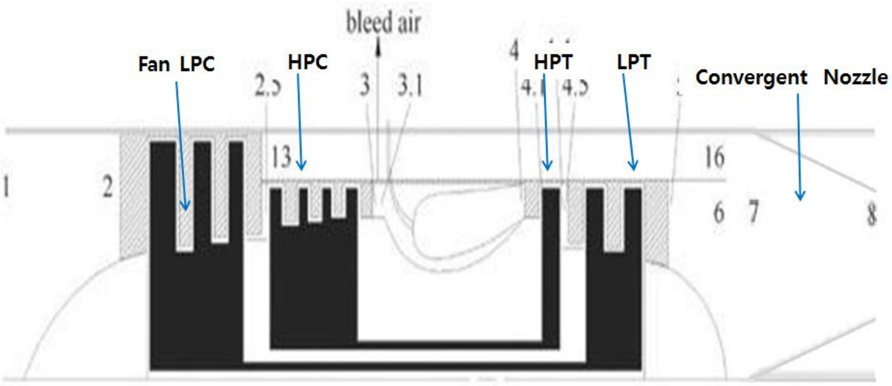
Frequency, angles, polarization
Monostatic vs bistatic radar
RAM, RAS

IR aspect of UCAV propulsion system

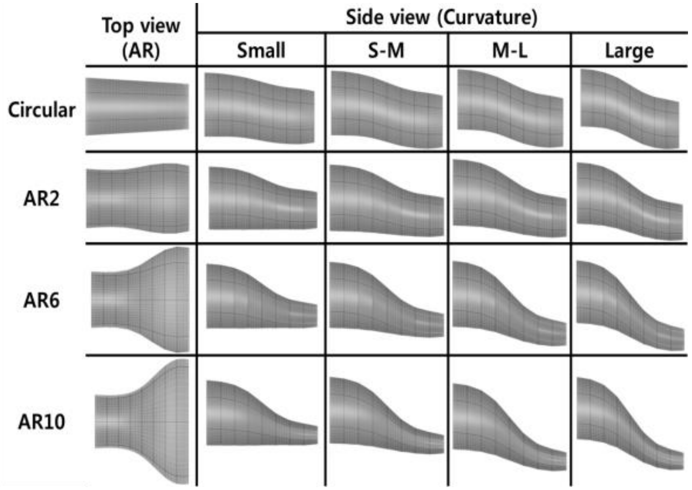


Payload	725.7kg
Max. Mach Number	0.8 at 12,192m
Acceleration	Mach 0→0.8 at sea level
Mission Radius	1,852 Km

Conceptual design of turbofan engine



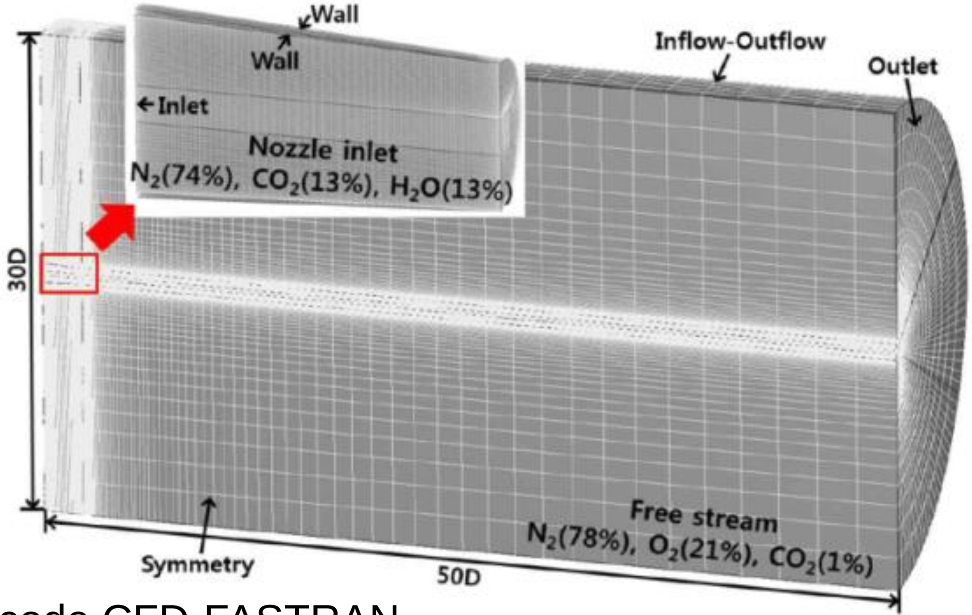
Definition of Jet Engine Stations



Analysis of plume infrared signatures of S-shaped nozzle configurations of aerial vehicle, *Journal of Aircraft*, Vol. 53, No. 6, pp. 1768-1778, 2016

IR aspect of UCAV propulsion system

Nozzle geometry	**Inlet (m^2)**	**0.18232**
	Outlet (m^2)	**0.12617**
	Length (m)	**0.964**
Inlet condition	**Mass flow (kg/sec)**	**17.19**
	Specific heat ratio	**1.3477**
	Static pressure (Pa)	**104,740**
	Static temperature (K)	**629.86**
	Mach number	**0.4454**



- Compressible Navier–Stokes–Fourier code CFD-FASTRAN
- Complete combustion of a jet fuel ($C_{11}H_{22}$)
- Narrowband model (Grosshandler, 1993)
- LOWTRAN 7 model for atmospheric transmissions

Average spectral intensity: $\overline{i_\lambda(l)} = \dfrac{1}{4\pi}\int i'_\lambda(l)\,d\omega$

where $i'_\lambda(l) = i'_{\lambda,w}e^{-\kappa_\lambda(l)} + \int_0^{\kappa_\lambda(l)} i_{b,\lambda}(l^*)\exp[-\kappa_\lambda(l)+\kappa_\lambda(l^*)]\,d\kappa_\lambda(l^*)$, $\kappa_\lambda \equiv \int_0^l a_\lambda(l^*)\,dl^*$

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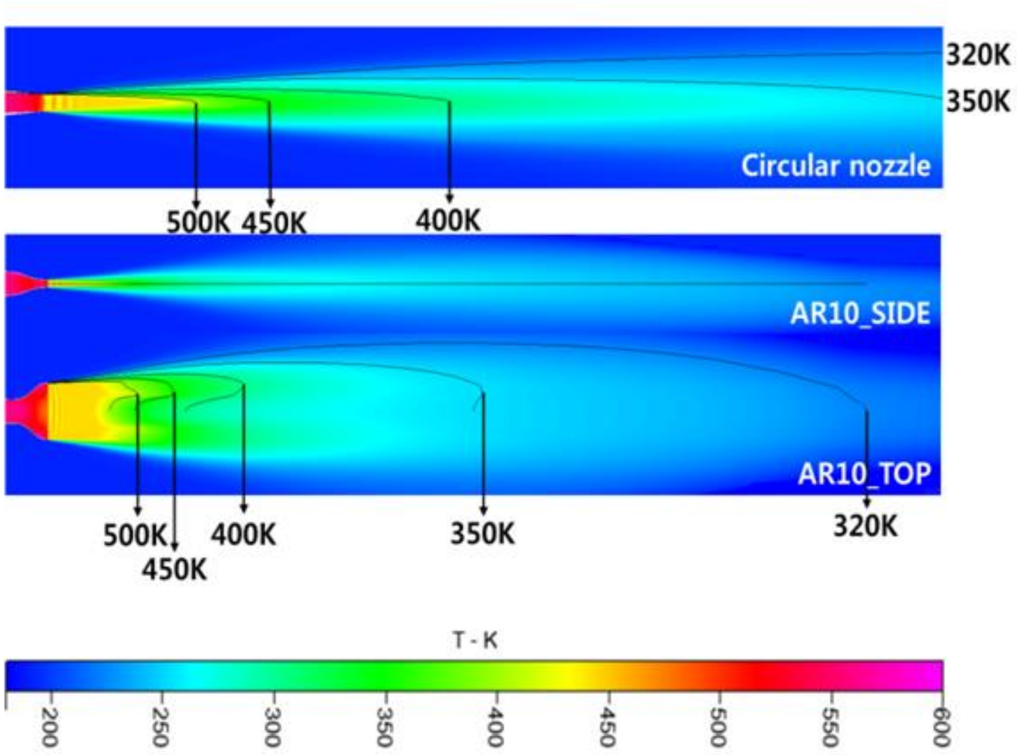

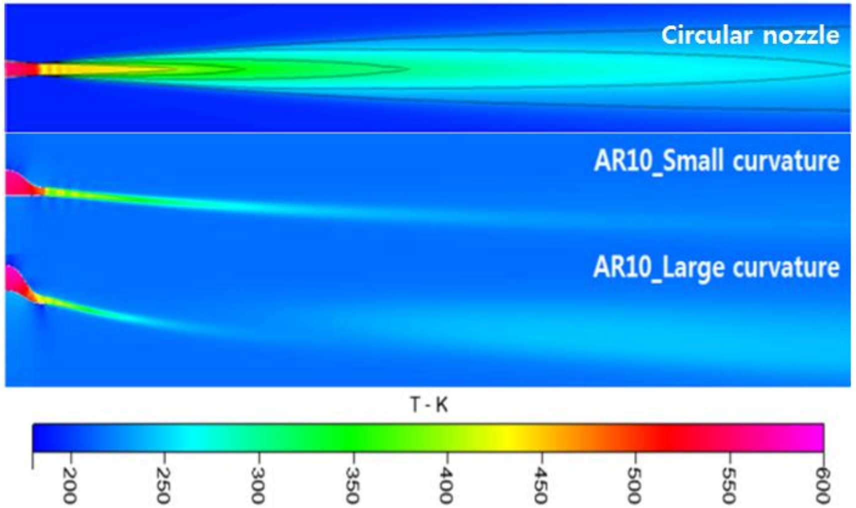

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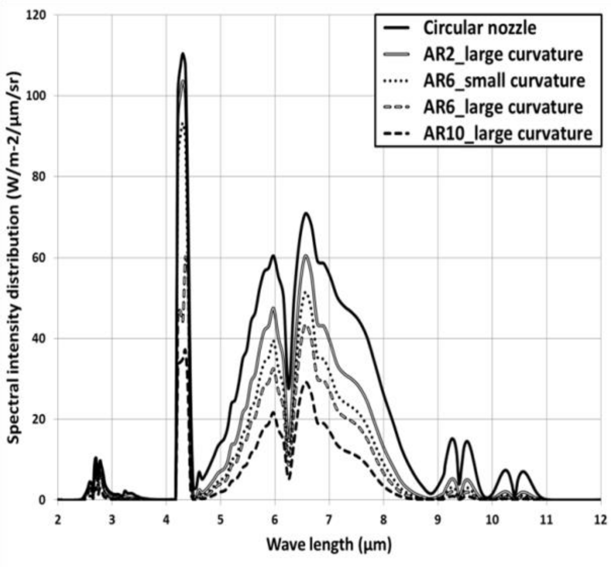
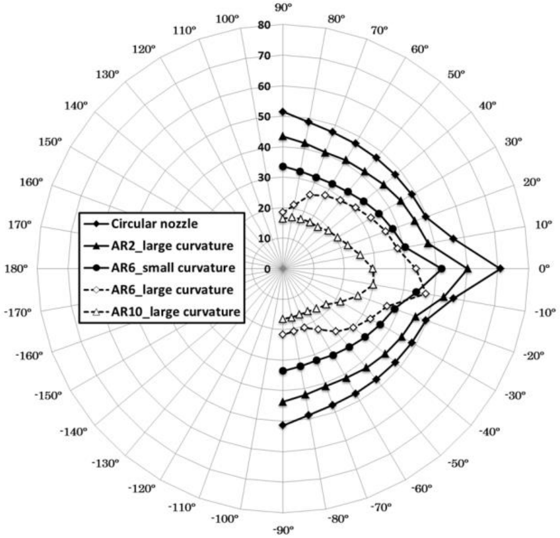
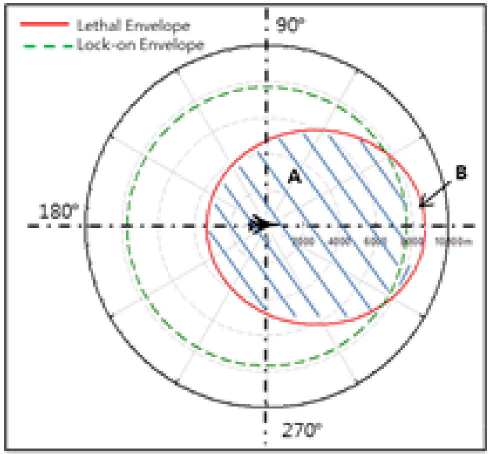




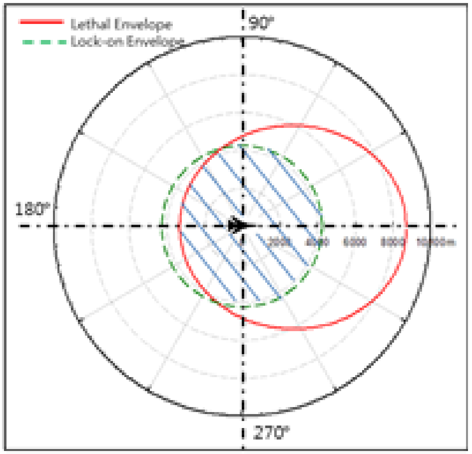
5-7μm



Lethal Envelope

vs

Lock-on Envelope



3-5μm

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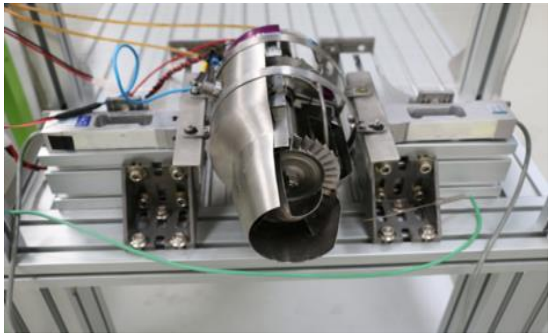
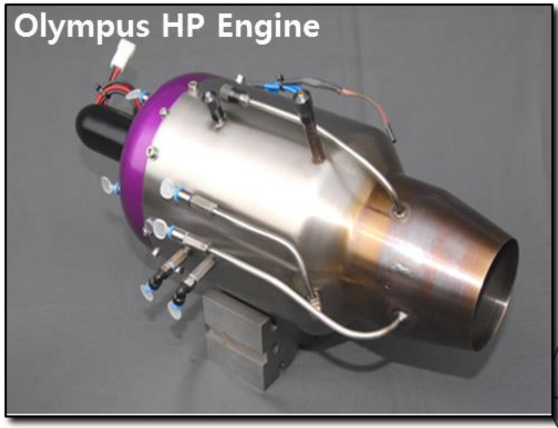
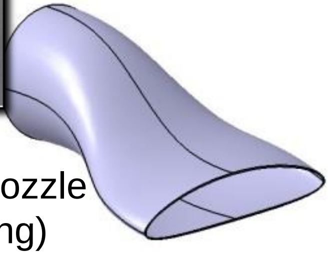
Experimental study of plume IR: a microturbojet engine

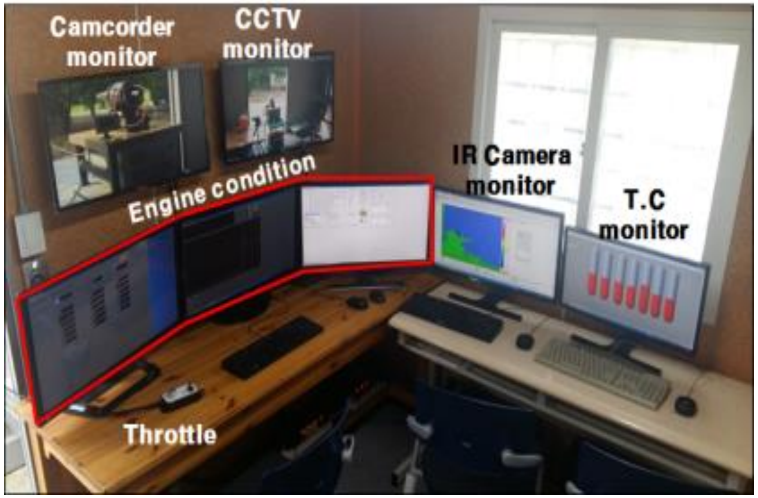


Olympus HP Engine Specification	
Max Thrust	230N
Pressure ratio	3.8
Max RPM	108,500
Max EGT	750°C
Fuel	JP-4





S-shape nozzle
(3-D printing)



Experimental investigation of infrared signal characteristics in a micro turbojet engine, *To Appear in the Aeronautical Journal, 2019*

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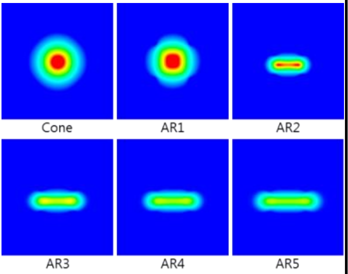
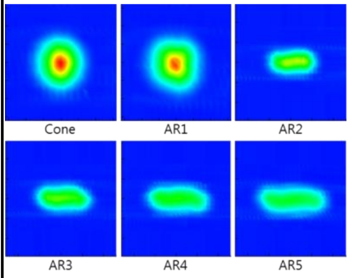
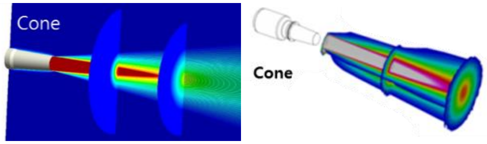
<tr><td>300 mm</td><td> </td><td> </td><td rowspan="2">
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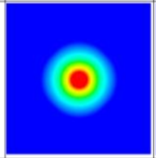
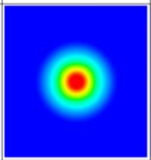
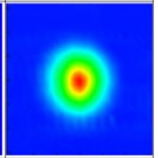
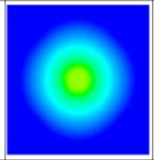
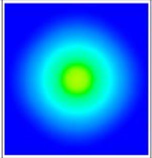
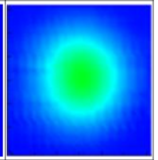
<tr><td>300 mm</td><td></td><td></td><td></td></tr>
<tr><td>T_{Max}</td><td>825.3 K</td><td>707.5 K</td><td>698.6 K</td></tr>
<tr><td>600 mm</td><td></td><td></td><td></td></tr>
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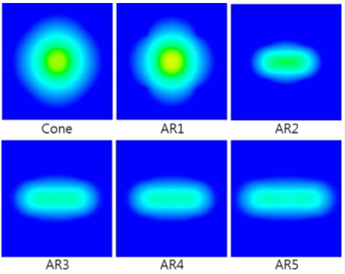
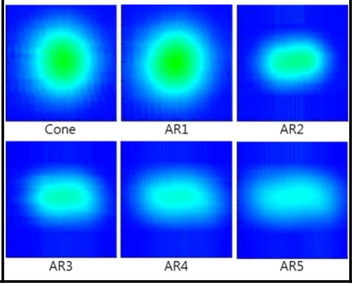
<tr><td>600 mm</td><td> </td><td> </td></tr>
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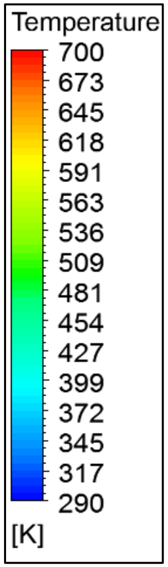
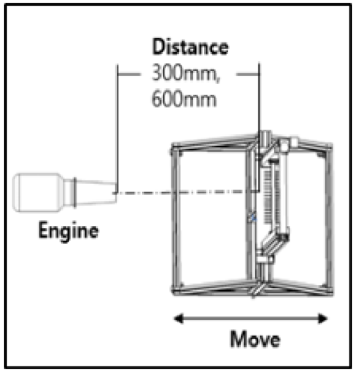
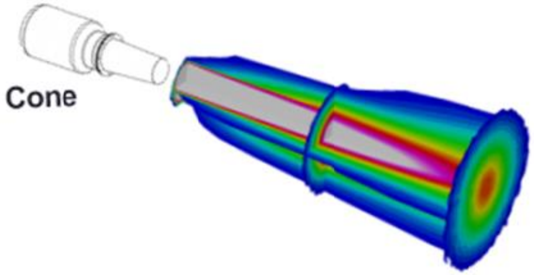




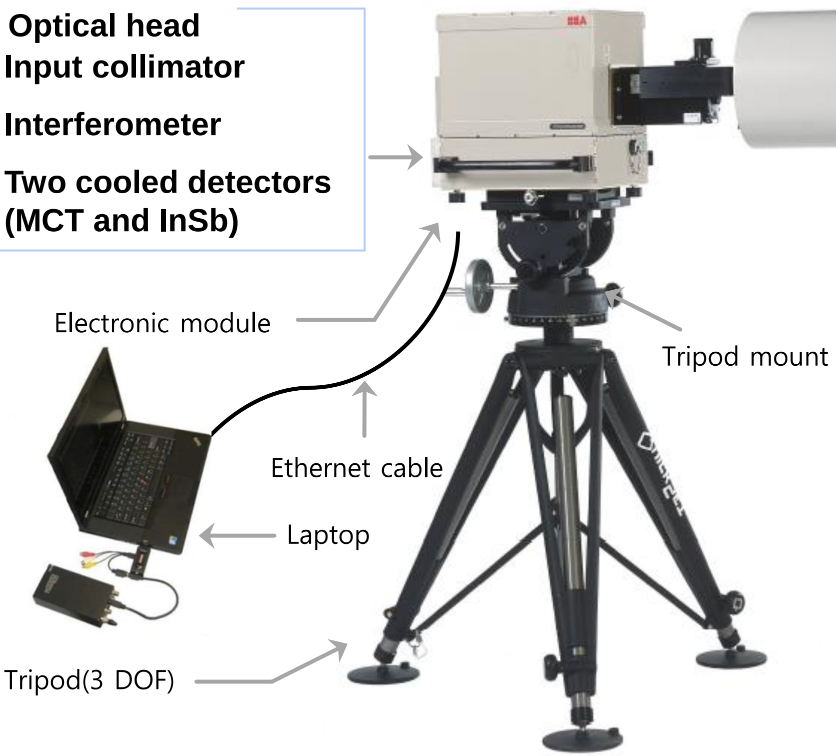


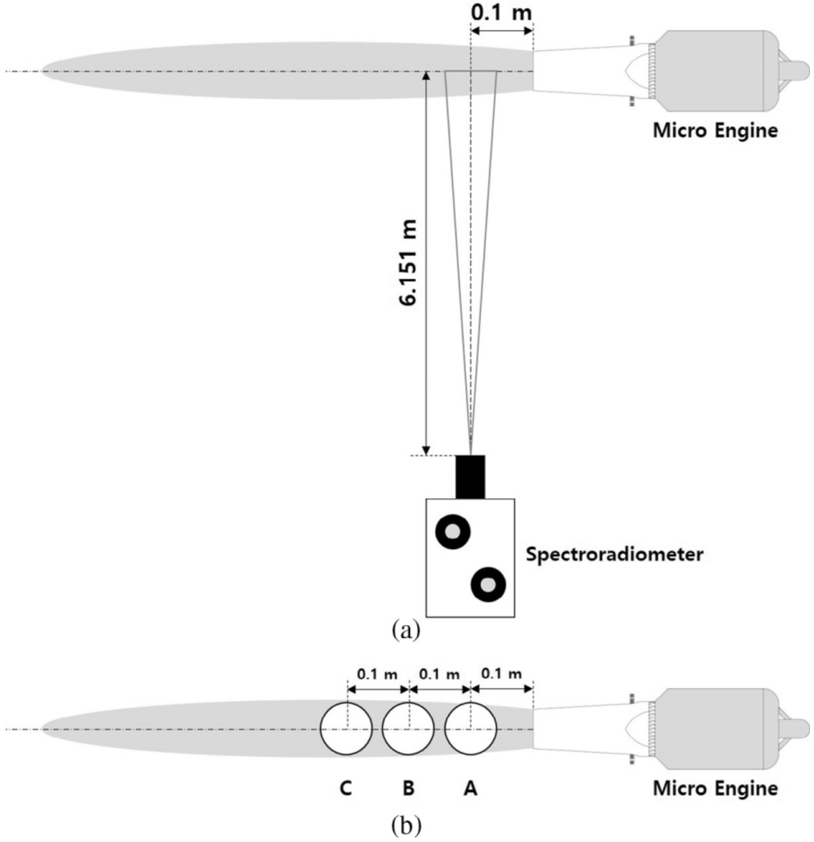
Experimental investigation of infrared signal characteristics in a micro turbojet engine, *To Appear in the Aeronautical Journal, 2019*

Experimental study of plume IR: a microturbojet engine

Optical head

- **Input collimator**
- **Interferometer**
- **Two cooled detectors (MCT and InSb)**





Infrared signature characteristic of a microturbine engine exhaust plume, *Infrared Physics & Technology*, Vol. 86, pp. 11-22, 2017

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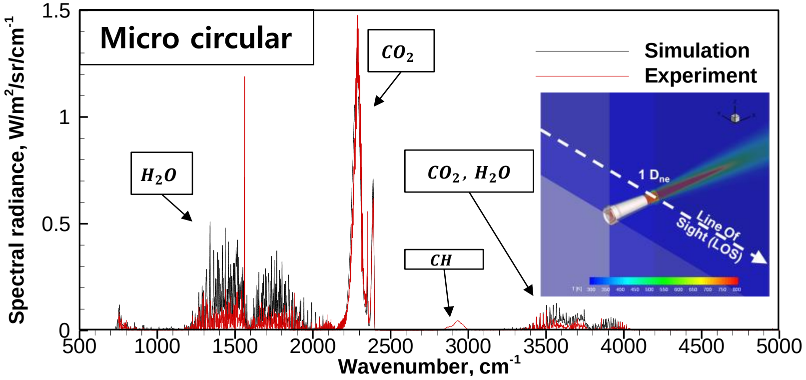
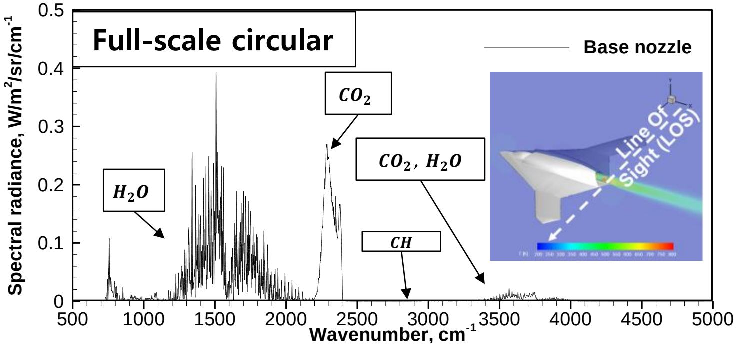




Scaling laws

$$\mathrm{Bo}=\frac{Convetion}{Radiation}=\frac{\rho C_p L}{\sigma T^3}$$

$$N_R=\frac{Conduction}{Radiation}=\frac{\tau Bo}{Pe}=\frac{\tau k}{\sigma T^3 V}$$

(τ optical thickness)

	M	Re	τ	Bo	N_R
nEUROn	**1.30**	**4.64*10^6**	**2.96**	**34.3**	**3.20*10^{-5}**
Micro engine	**1.20**	**9.01*10^5**	**0.67**	**1.85**	**1.99*10^{-6}**

Infrared signature characteristic of a microturbine engine exhaust plume, *Infrared Physics & Technology*, Vol. 86, pp. 11-22, 2017

IR reduction: penalty and tactics

- **Penalties**

  Weight

  Thrust, drag

  Complexity

  Back pressure increase in engine

  RCS change

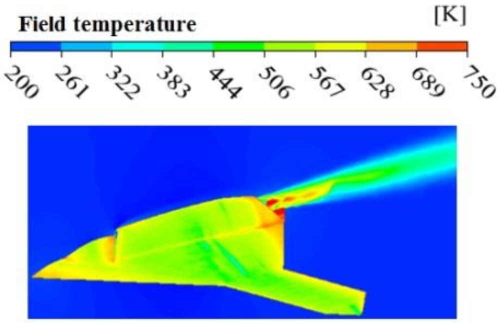
- **Lethal envelope**

  Flight Mach number & altitude

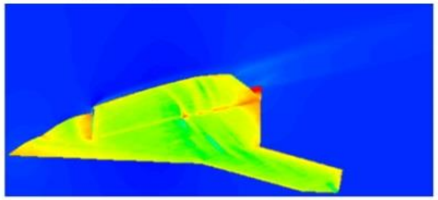
  Burnout time & speed of missile

- **Tactics**

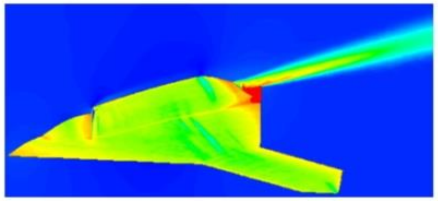
Penalties when integrated in UCAV



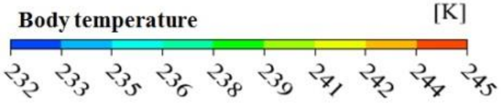
(a) Axisymmetric nozzle jet on

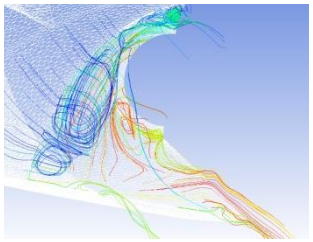


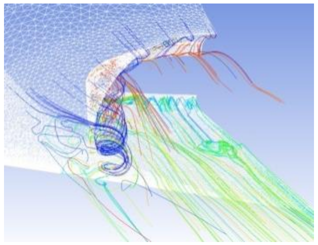
(b) Axisymmetric nozzle jet off

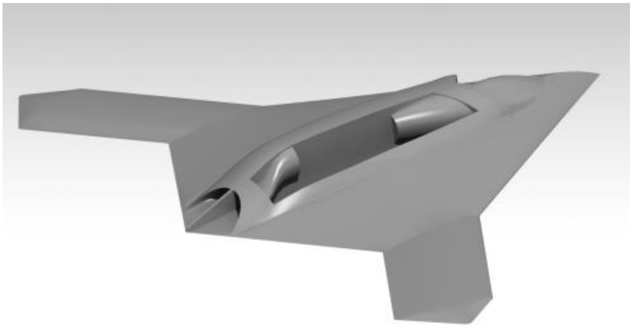


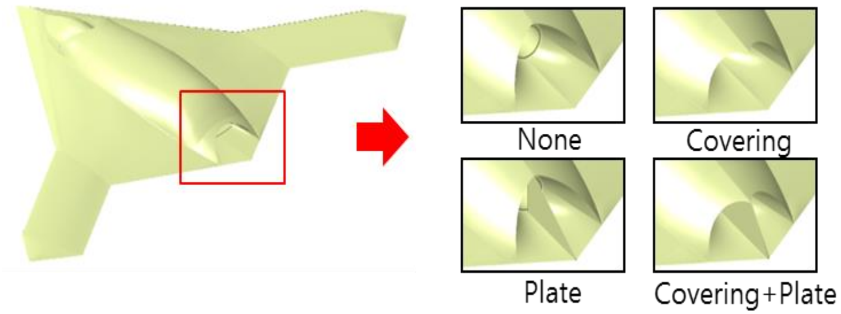
(c) Shape-deformed nozzle









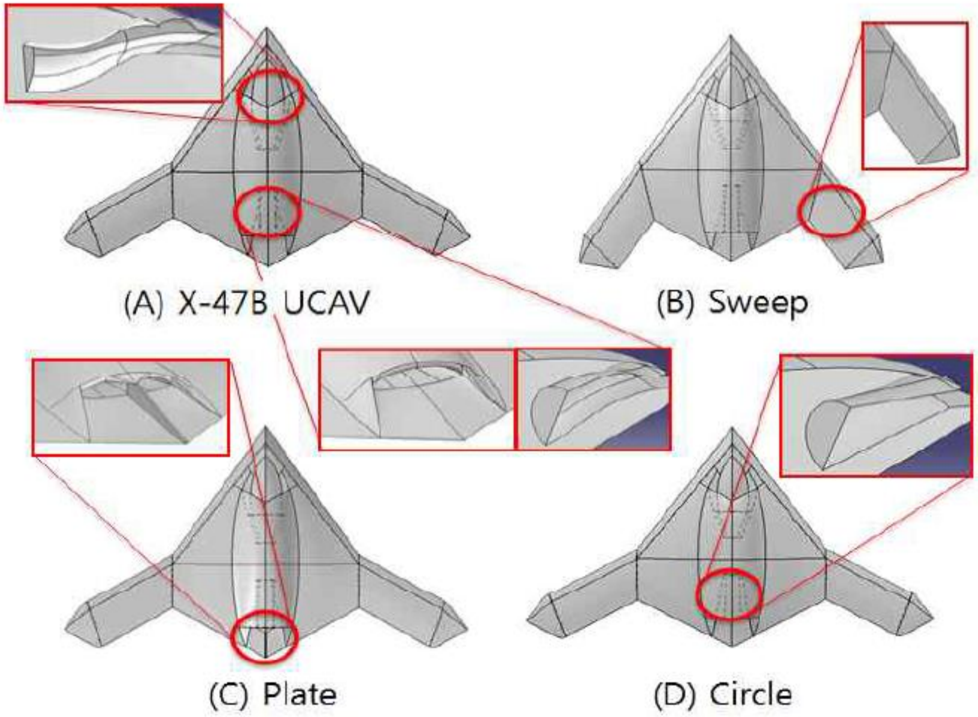


Slight decrease of thrust & drag by S-shaped nozzle

Covering & plate causing thrust decrease and drag increase

Numerical Analysis of Thermal Flow Field According to Shape of Exhaust Nozzle of UCAV and Jet On/Off, *Journal of Computational Fluids Engineering*, Vol. 23, No. 1, pp. 77-85, 2018

Interplay of IR-RF



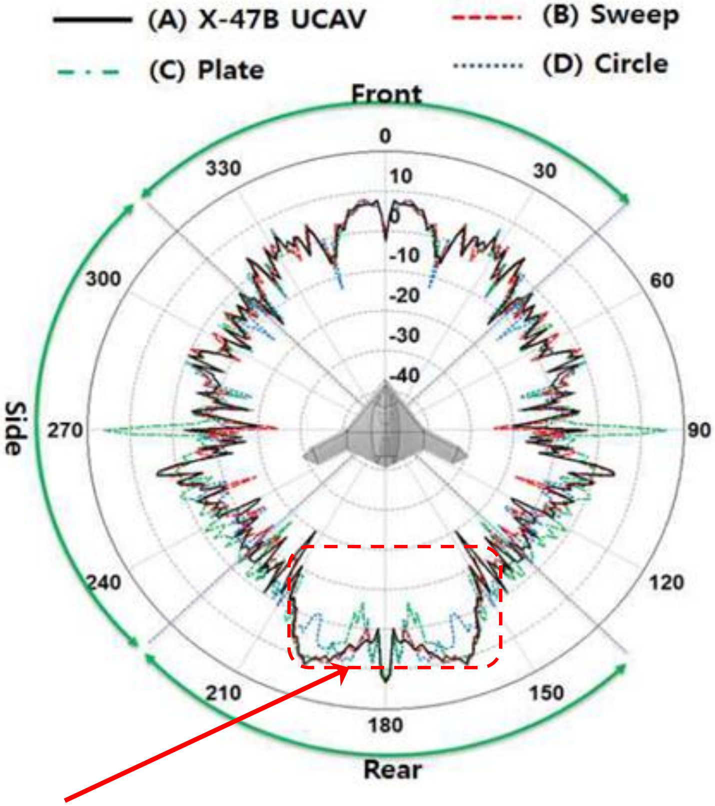
(A) X-47B UCAV

(B) Sweep

(C) Plate

(D) Circle

RCS (RL-GO) (10GHz; HH)



S-shape nozzle increasing RCS for ±30 degree in rear direction
Plate increasing RCS from side

Effects of IR reduction design on RCS of UCAV, *Journal of The Korean Society for Aeronautical and Space Sciences*, Vol. 46, No. 4, pp. 297-305, 2018

Further topics

- Extension from microturbojet to turbofan with higher thrust
- In connection with aircraft thermal management (integrated energy system analysis)
- In combination with TVC nozzle design with active flow control

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