헬기 피탐성 저감설계: RF 스텔스
(1-20P 생존성및스텔스 기본개념, 21-40P 헬기 적용)

2023년 12월 21일 (13:00~13:30)
국기연-KAI 핵심기술과제 2023년 워크샵
(진주시 아시아 레이크사이드)

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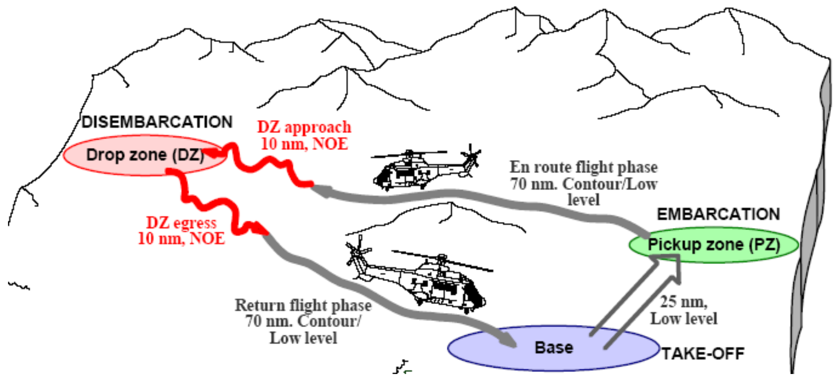
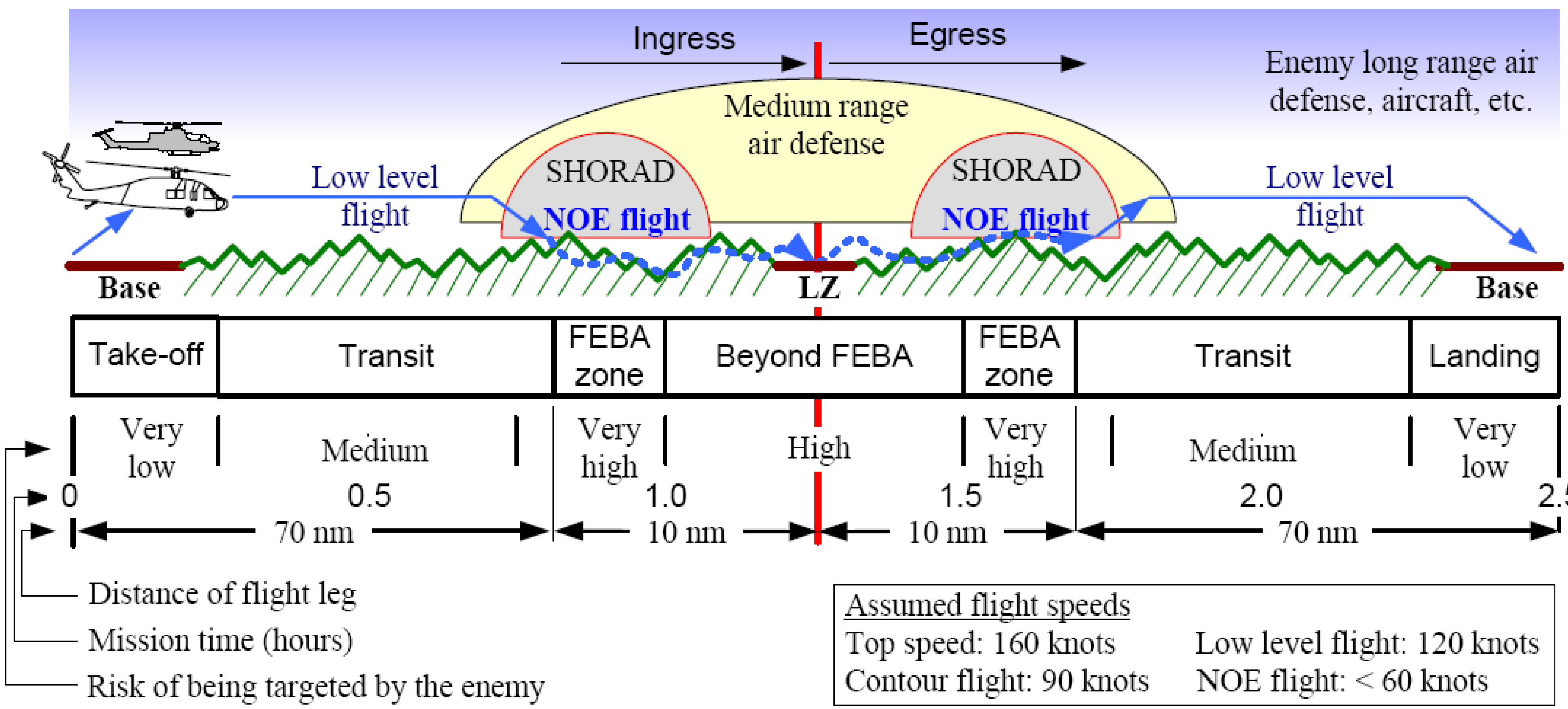
Rotorcraft mission and survivability (susceptibility and vulnerability)



- Survivability = 1 – Susceptibility · Vulnerability
- 회전익기 교전모델

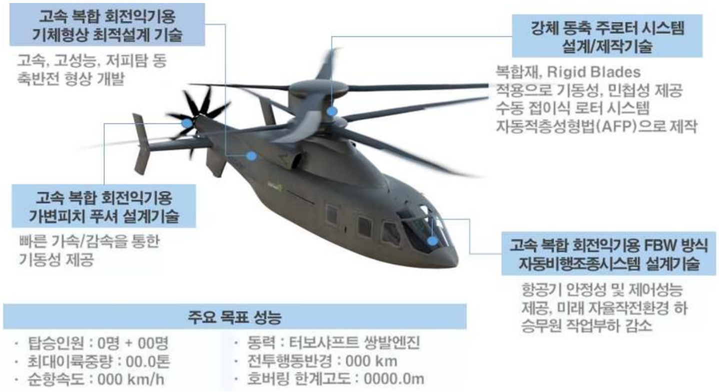
TRACES (Terrain/Rotorcraft Air Combat Evaluation Simulation): 6-DOF 비행운동 모델과 연계하여 비행경로, 타격, 탐지 및 Firing Event, 생존성 추이 등 교전결과 산출



Rotorcraft mission analysis

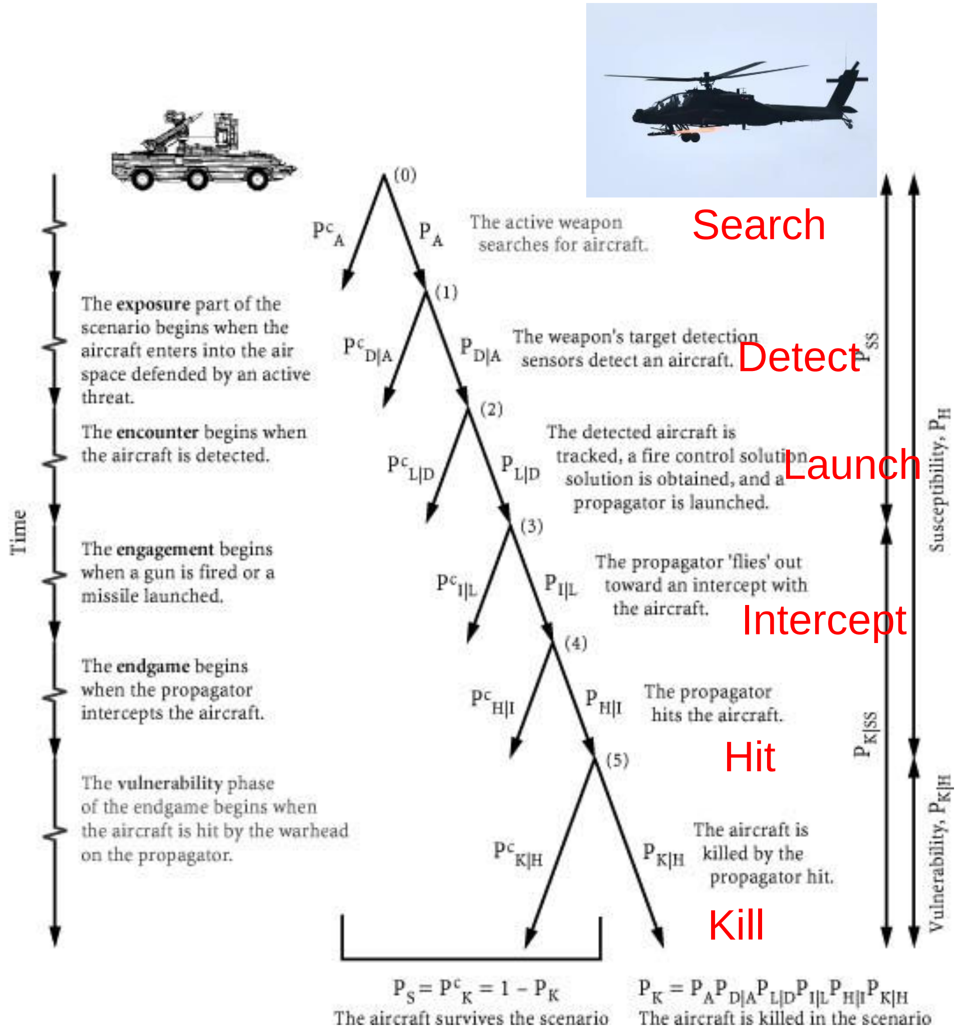
전투효과분석 모델 사례 (임무효과분석 기법 연구 (06-08; KAI))

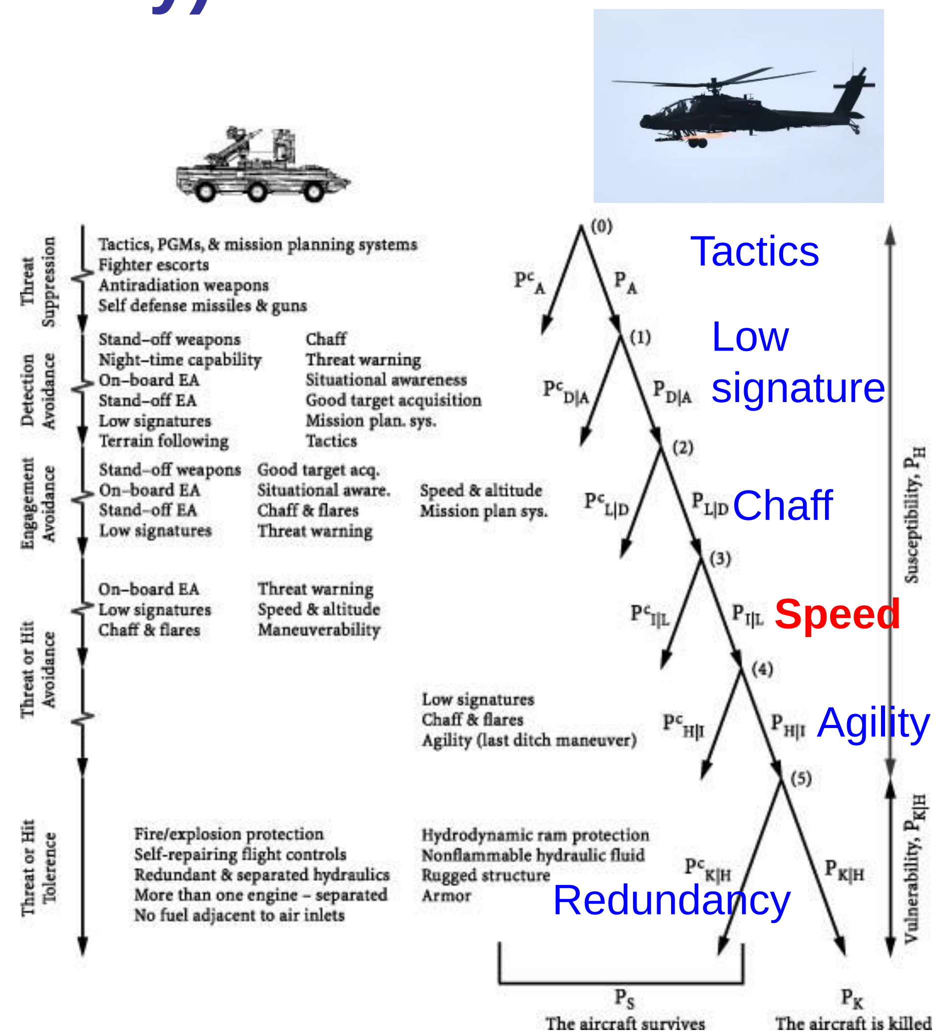
1. 데이터 입력 (항공기, 지상위협)
2. 비행경로 분석
3. 항공기 취약면적 분석
4. 위협에 대한 생존성 분석
5. 전자전 장비 효과 분석
6. 다중위협 종합 분석
7. 임무효과 분석



임무효과 분석 목적: 1) 핵심요소기술 파악, 2) 최대개선요소 파악, 3) 최적 임무효과 방안 도출

Aircraft survivability (susceptibility and vulnerability)





헬기의 고속화와 생존성(저피탐)과의 관련 기초연구는 전무한 상태

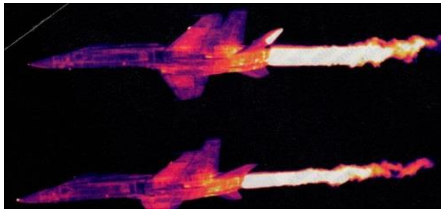
Definition of stealth

- **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

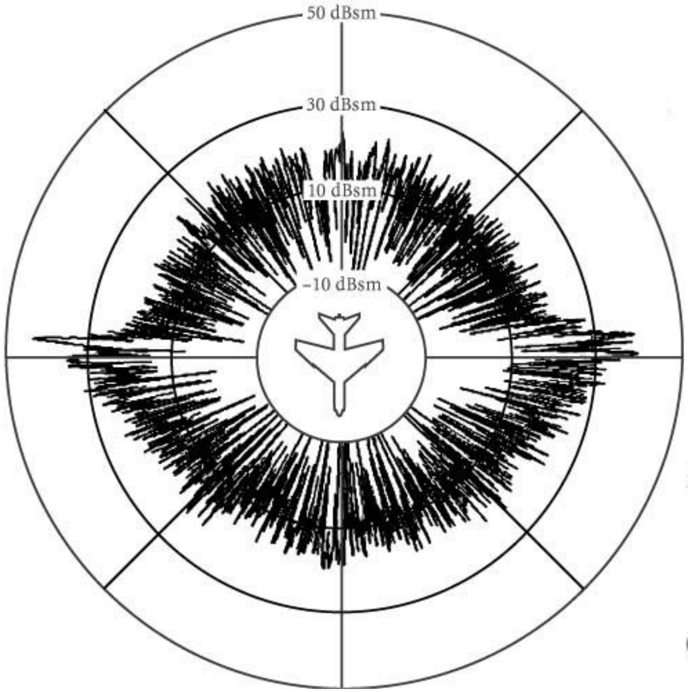
infrared : engine casing, airframe, exhaust plume, sun glint

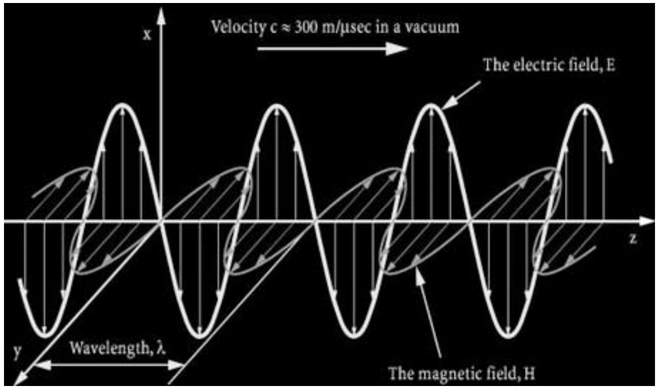
acoustic : engine parts, engine exhaust, rotor blade, airframe

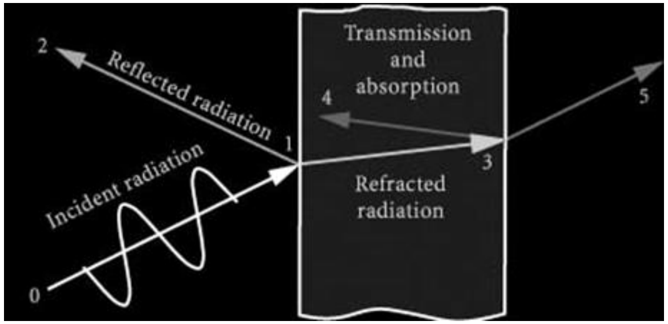
visual : airframe, engine exhaust and glow, canopy glint

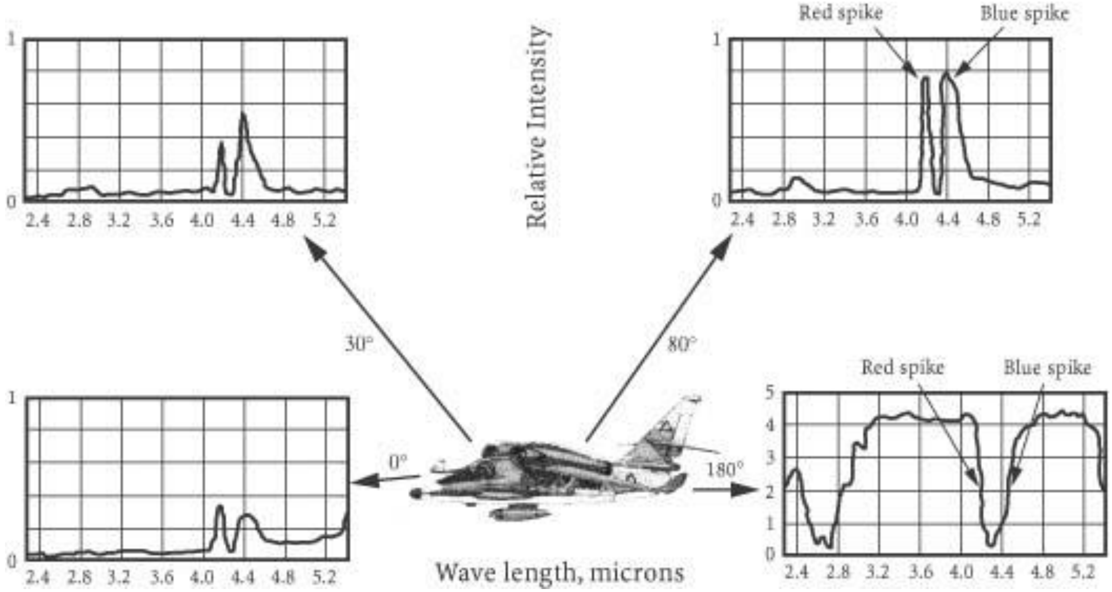
misc. : navigation radar, communication, countermeasures

RF & IR signatures



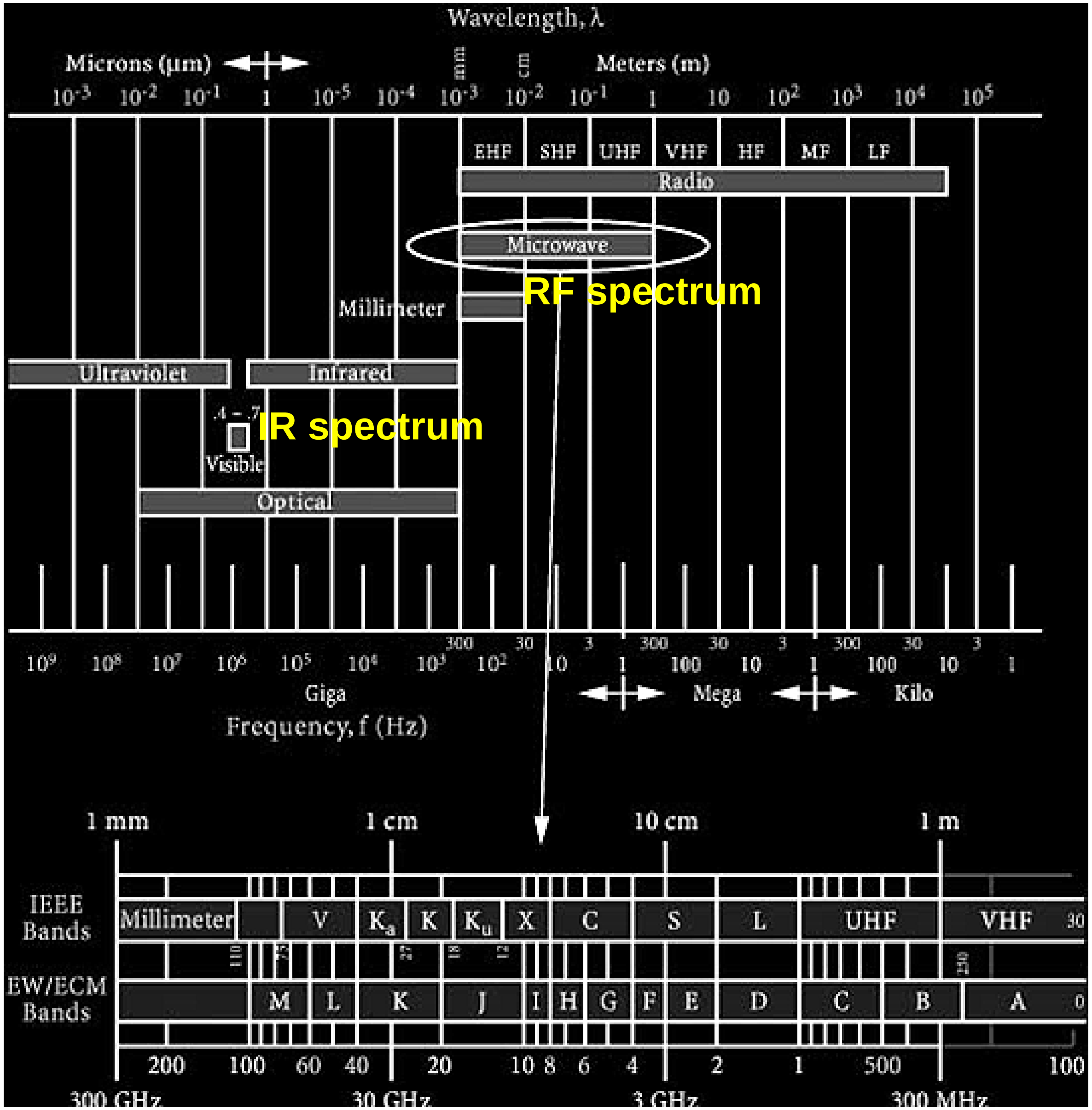






Correction: blue and red, not red and blue

Radar fundamentals I

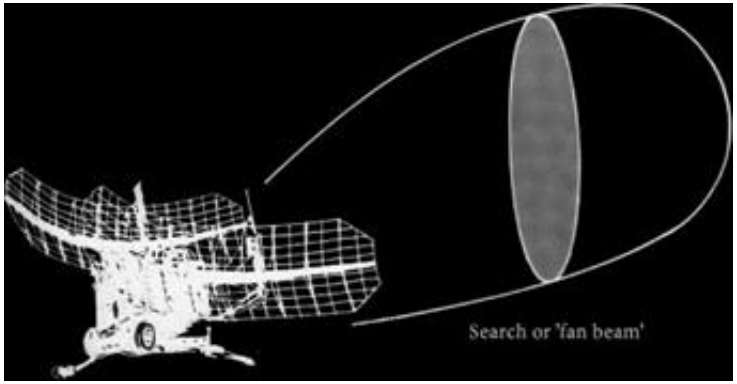


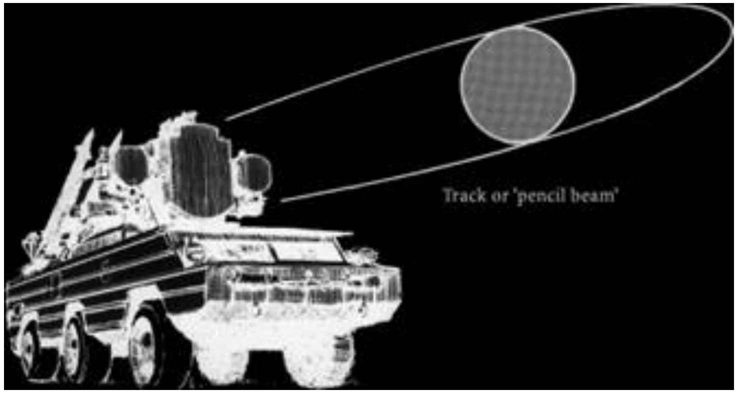
Electromagnetic radiation is emitted by accelerating or decelerating charged particles, such as **harmonically oscillating electrons**.

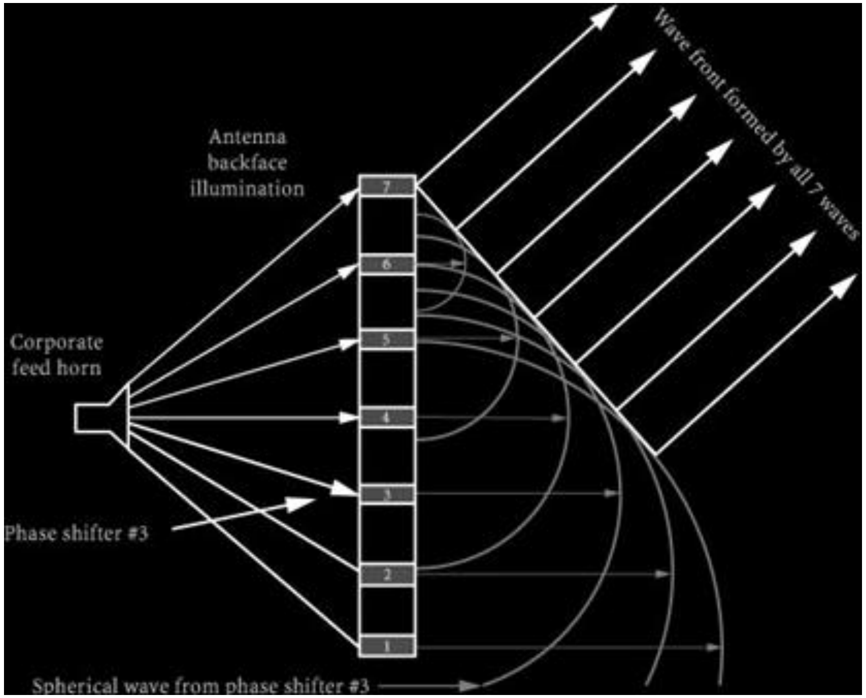
Radar fundamentals II

Radar types

Surveillance radar antennas (VHF, UHF, L and S bands; 1–10 deg. Beamwidth)
Weapon control radars (S, C, X,K u , K bands; less than 1 to 2 deg. Beamwidth)
Phased-array antennas (AESA; active electronically scanned array)







Bi-static radar

Mono-static radar

Radar horizon

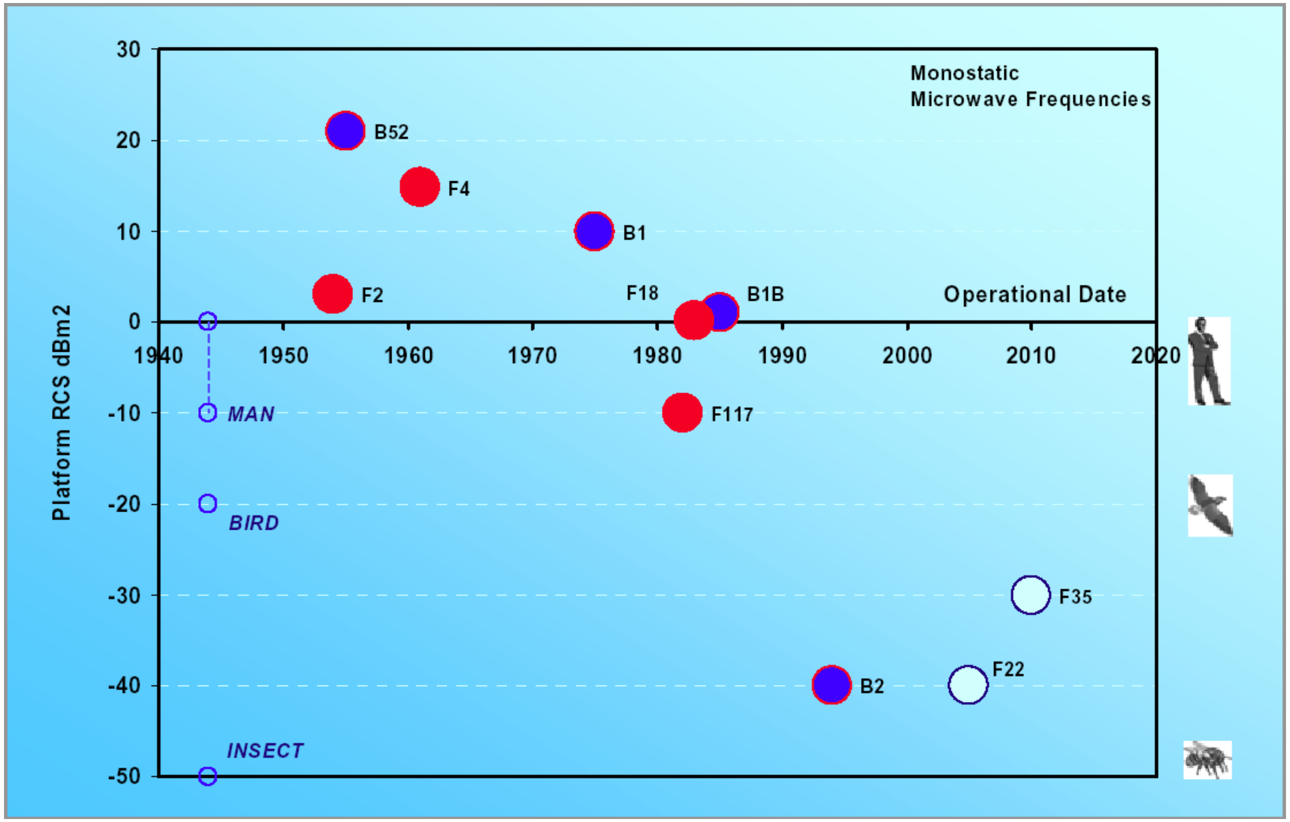
Radar fundamentals III

- **Definition of radar cross section (RCS)**

  σ=Power reflected to receiver per unit solid angle * 4 π /Incident power density

  σ in dBsm = 10 $\log_{10}$ (σ,m^2)

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{\left|E_{scattering}\right|^2}{\left|E_{incident}\right|^2} \quad \text{(dBsm)}$$



Pollard, R., Detection of low RCS air targets, Stealth Conference 2004, U.K.

Radar range equations

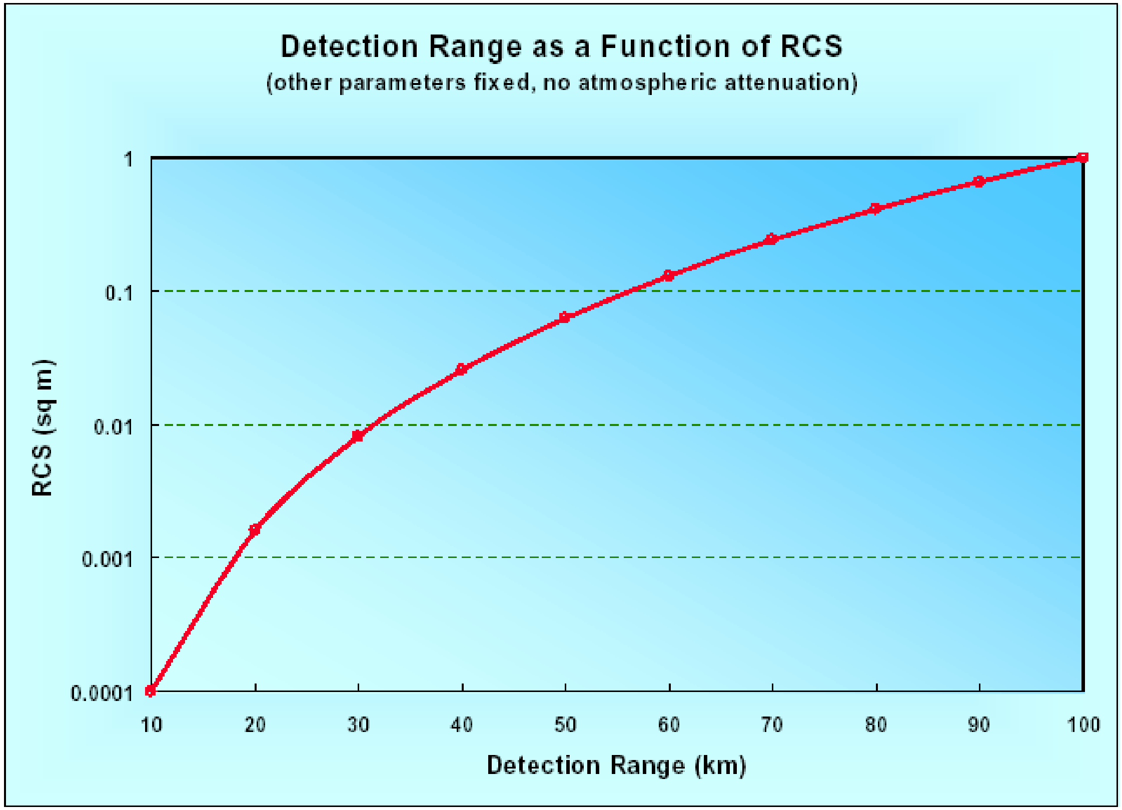
The **radar range equation** defines the maximum range at which a given radar can detect a given target in free space.

12 dB reduction to halve the range

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

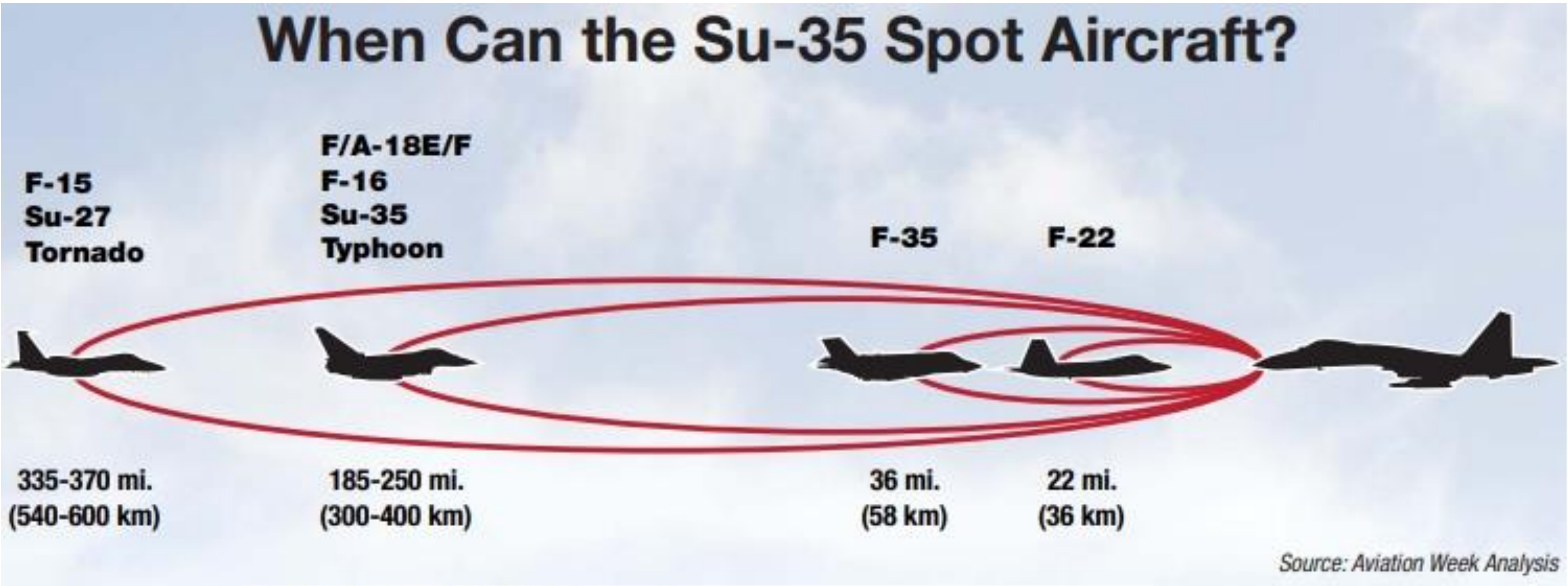
$$P_{receive} = \frac{P_{trans} G^2 \lambda^2 L_{H/W} G_{process} \sigma}{(4\pi)^3 R^4}$$

$$SNR_{\min} = \frac{P_{receive_{\min}}}{k_B T_{eff} W_{bandwidth}}$$



Pollard, R., Detection of low RCS air targets, Stealth Conference 2004, U.K.

Impact of low RF signal

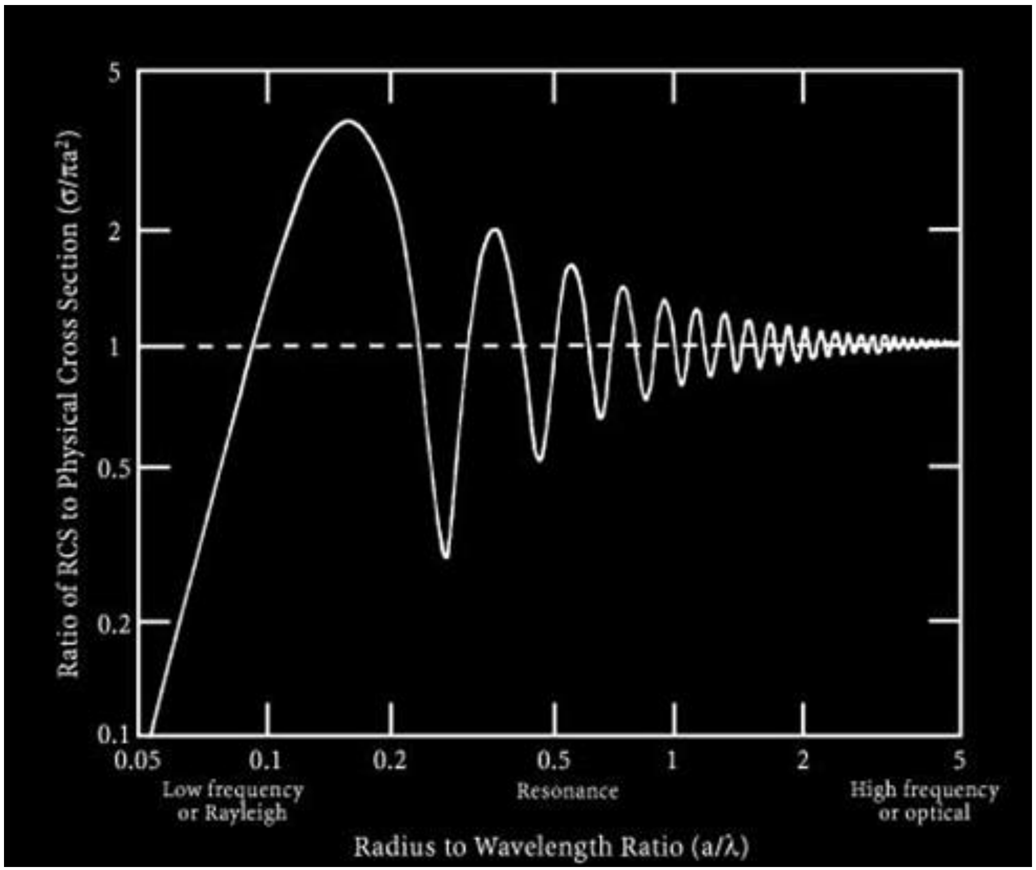


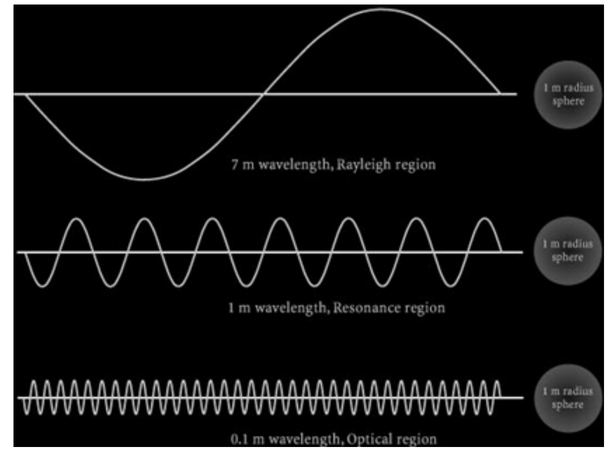
- To halve the detection range:-
  - *Radar*
    - 12dB RCS reduction.
  - *Acoustic*
    - 6dB noise reduction.
  - *Infrared*
    - 25% temperature reduction.
  - *Visual*
    - Dependant on background (Paints and or Camouflage netting).

RCS characteristics

σ=function of frequency, polarization, angles (azimuth & elevation)

Rayleigh (low freq.), resonance (Mie intermediate freq.), optical (high freq.) regimes





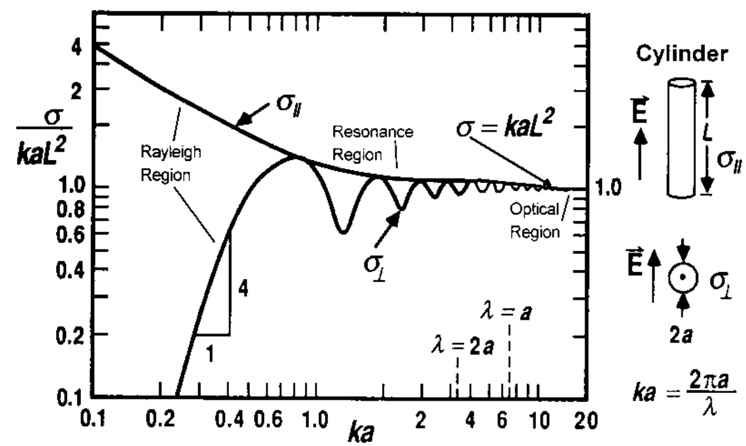
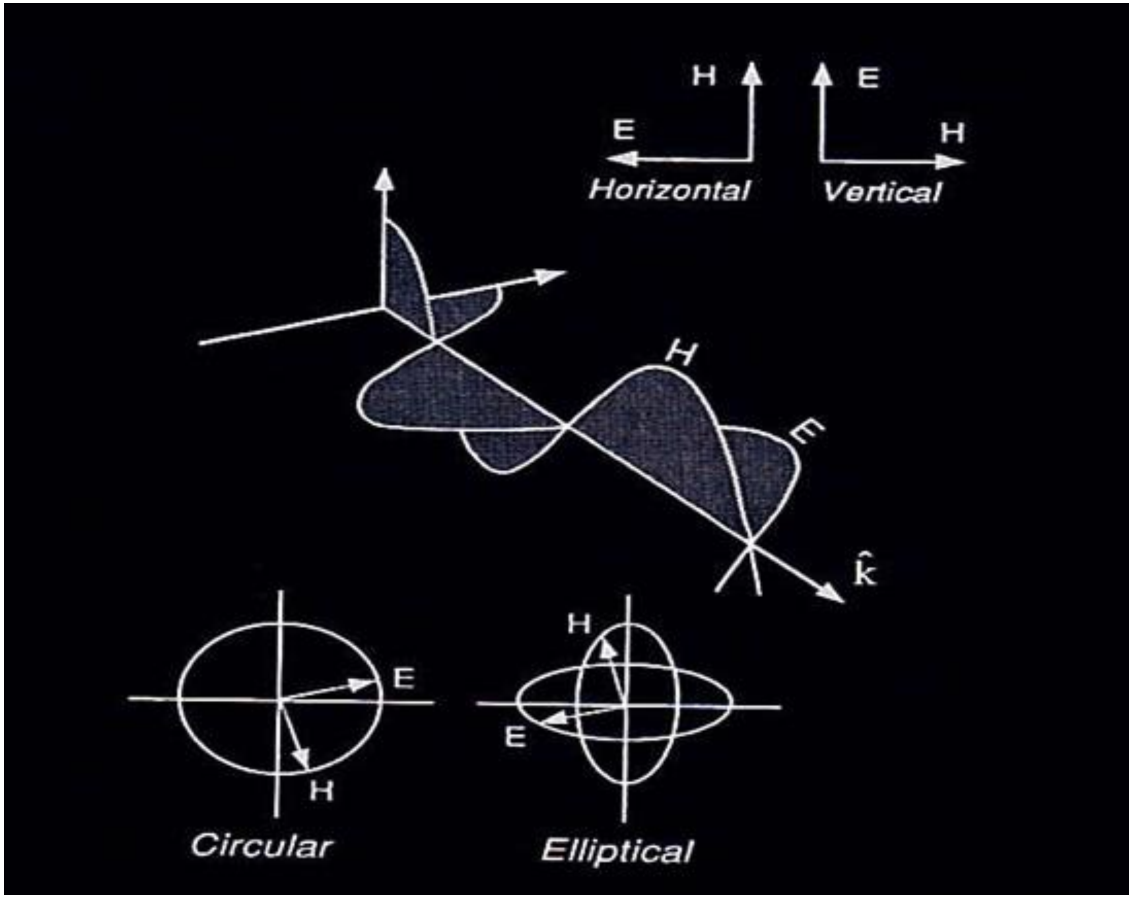
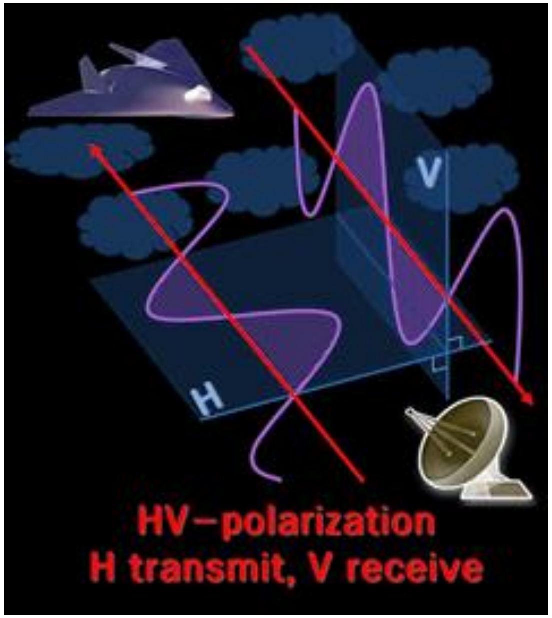
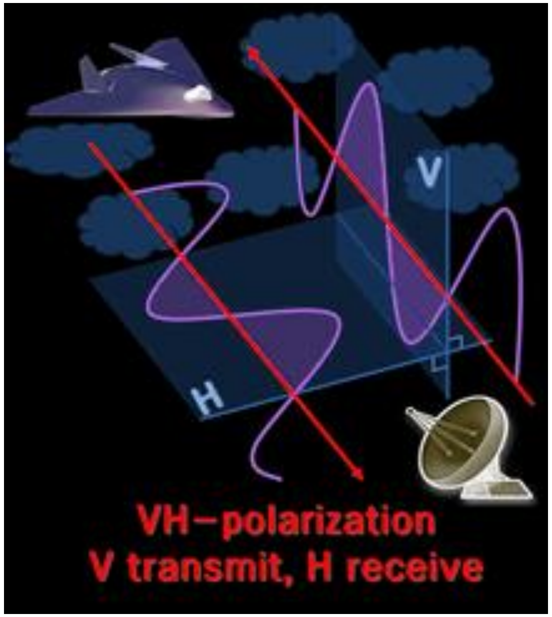


Figure RCS of a cylinder relative to wavelength

RCS characteristics (polarization)

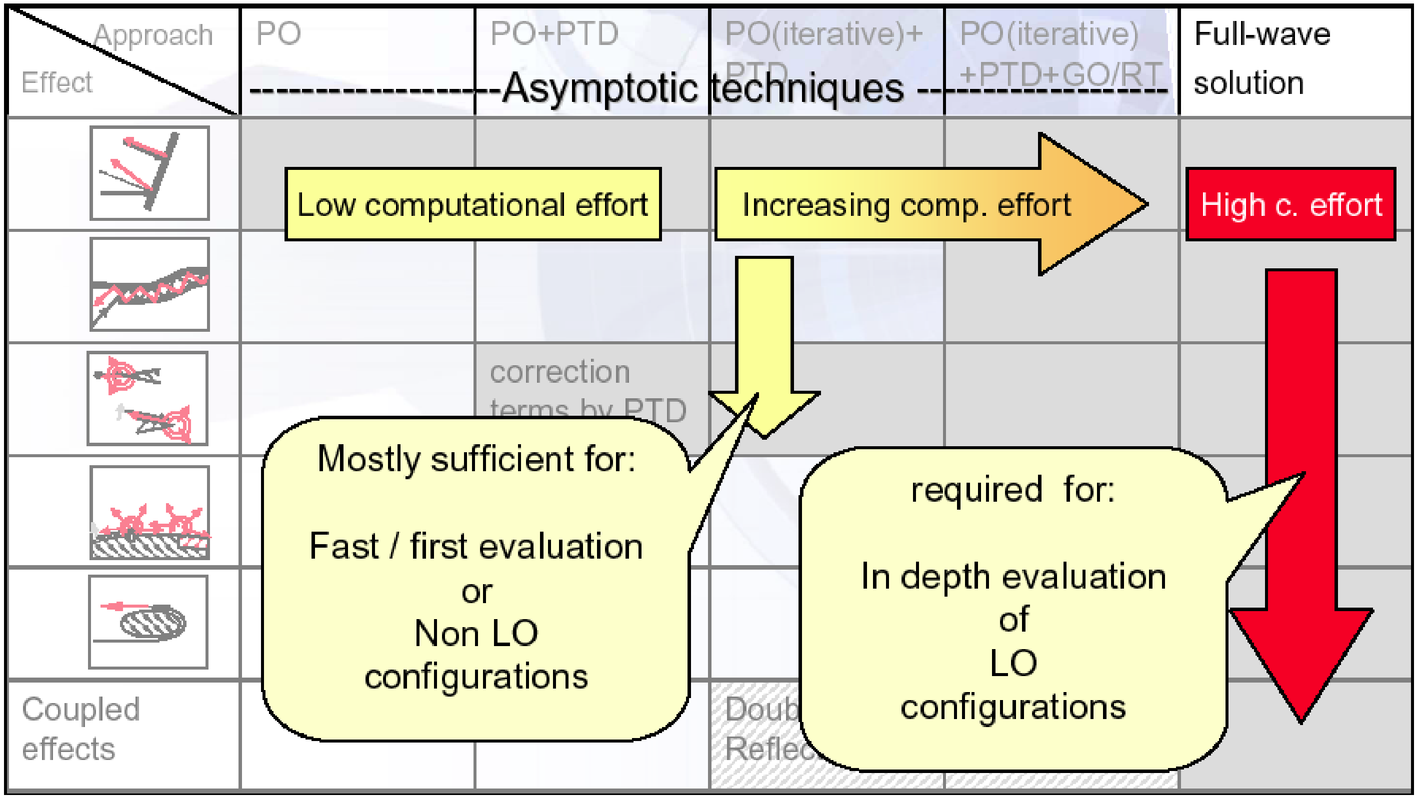






RCS calculations

Component buildup method, high-frequency asymptotic methods, full wave methods



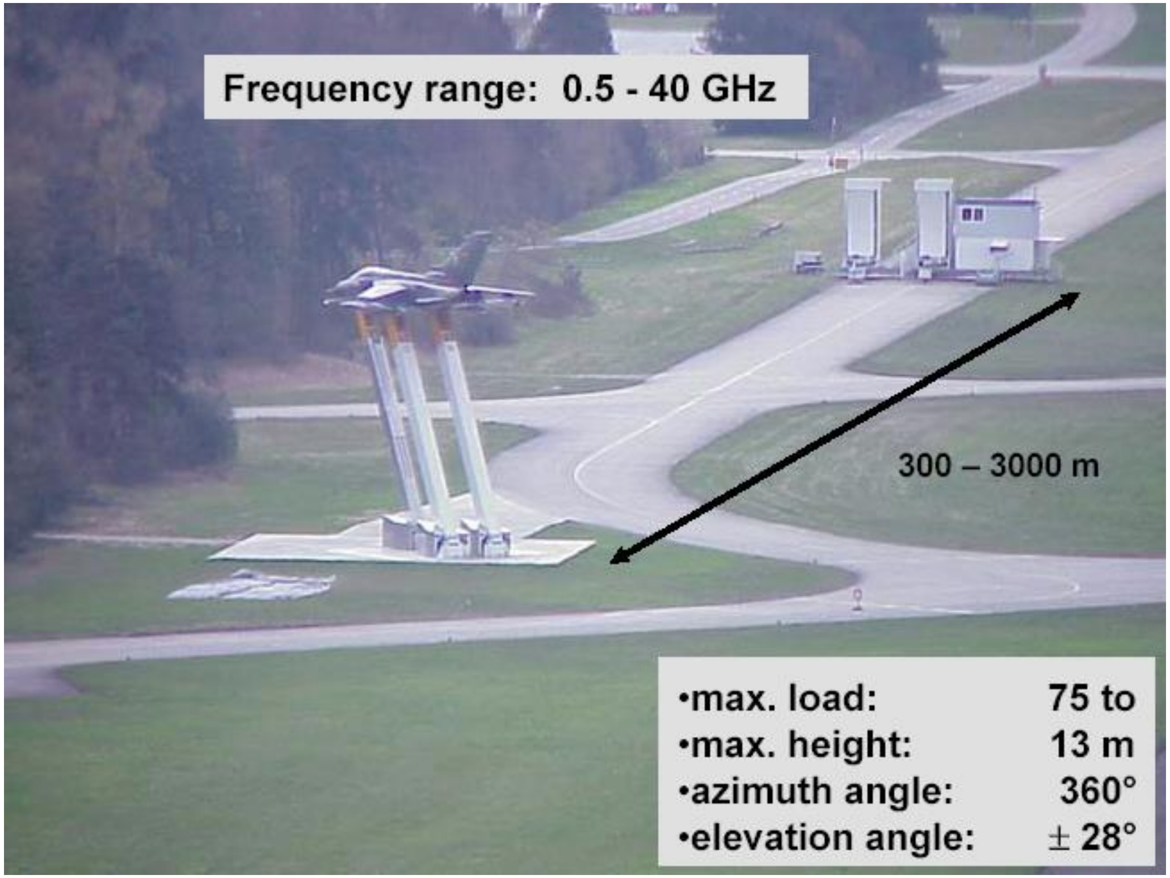
PO (physical optics)

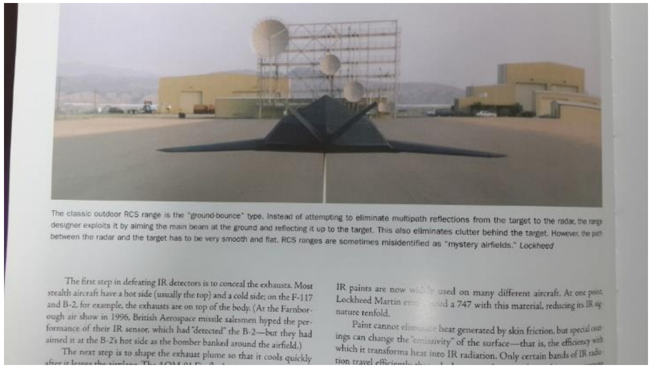
PTD (physical theory of diffraction)

GO/RT (geometrical optics / ray tracing)

Ritter, J., The Role of CEM in the Realization of RCS Reduction of Aircraft, Stealth Conference 2005, U.K.

Outdoor RCS measurement





Kruse, J., Applying Stealth Technology to Non-Stealthy Platforms, Stealth Conference 2005, U.K.

Indoor RCS measurement and scaling laws

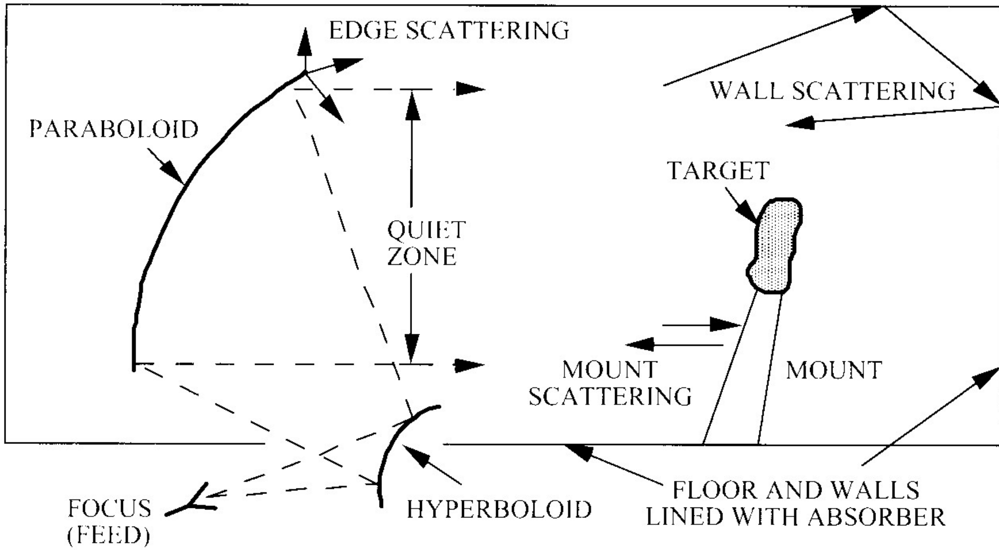


Fig. 8.7 Some sources of RCS measurement error.

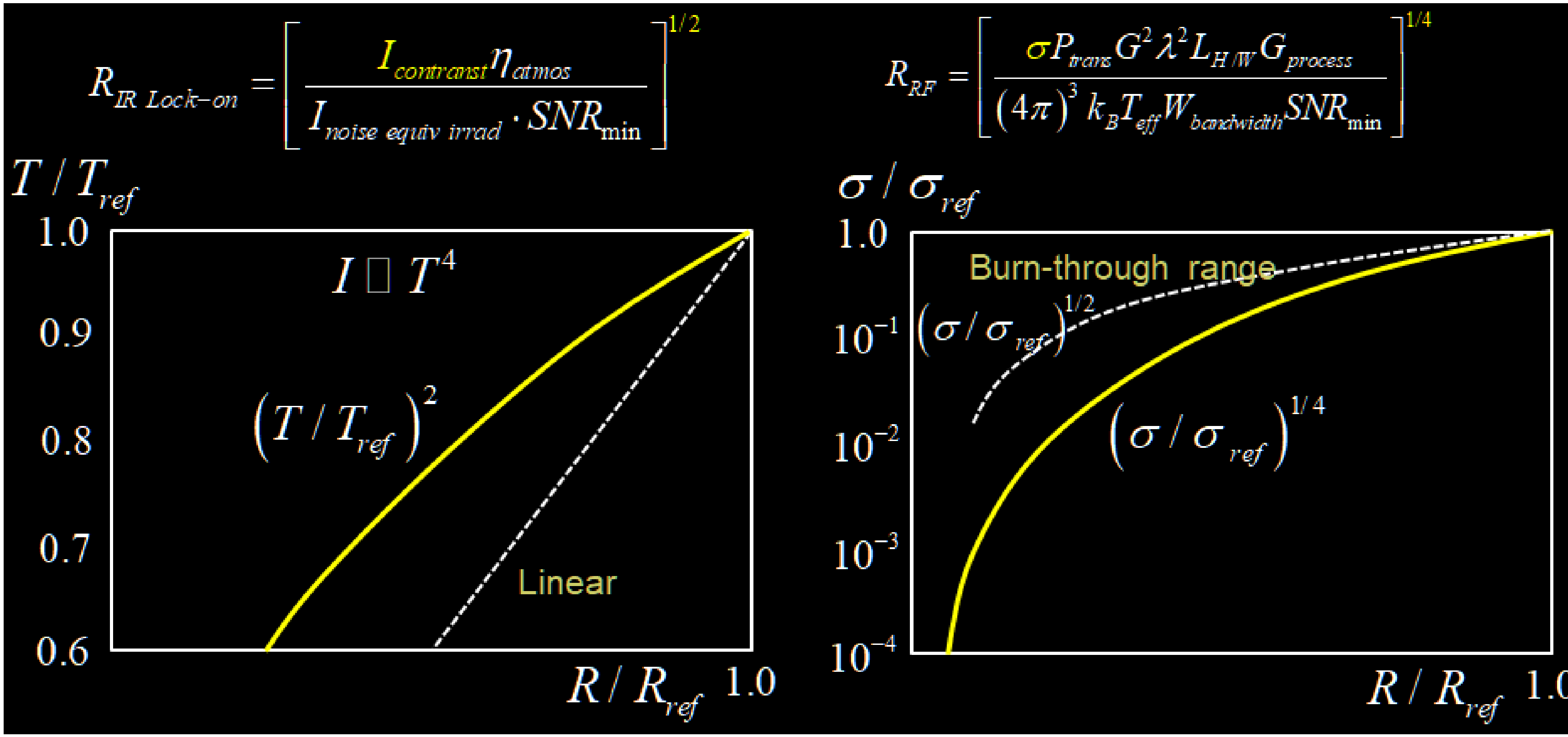
This small scale model of Have Blue is undergoing RCS tests in Lockheed's anechoic chamber at Rye Canyon. *Lockheed Martin*

Figure of merit of an RCS chamber: The quiet zone and the operating frequency range

Scaling laws for scale-model testing:

- For p scaling factor, $f_m = pf, \ \sigma_m = p\sigma$
- The complex index of refraction and impedances should be duplicated.

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



Spectrum, view angles
Contrast, atmospheric effect
Surface condition

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

Complicated game: IR counter-measures

Past

CM

CCM

After-burner IR 저감 Radiation Shield; Decoys & Jammers

⇕

Two-color Detector; Conical Scan

⇕

Present

C-CCM

CC-CCM

형상변형/표면처리 IR 감소; Multiple & Pyrophoric Flare; DIRCM; Early Warning

⇕

Multi-color & Imaging Detector with Digital Signal Processing

⇕

Future

C-CC-CCM

Temporal Active IR 저감 및 조절

[**능동성**, **미사일 작동원리**(추적시간, Direct Hit Near-miss, 2nd Lock-on 불가능 약점 등) 최대 활용, **4차산업혁명 기술과 연계** 가능]

※ **Counter-Measure 기본원리**: Spectral, Temporal, Spatial & Tactics

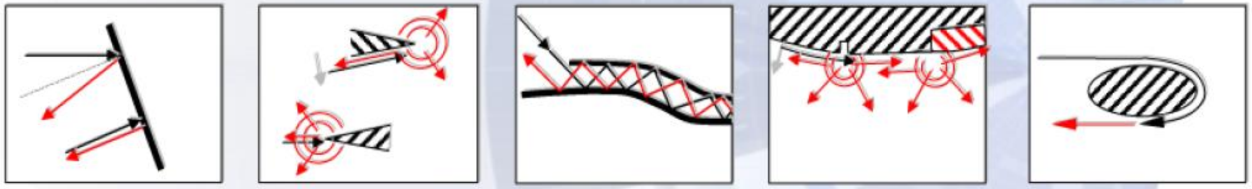
RCS Reduction: Components

Influence of components RCS / accuracy requirements

-30..-20dBsm ← **RCS** → >+10dBsm

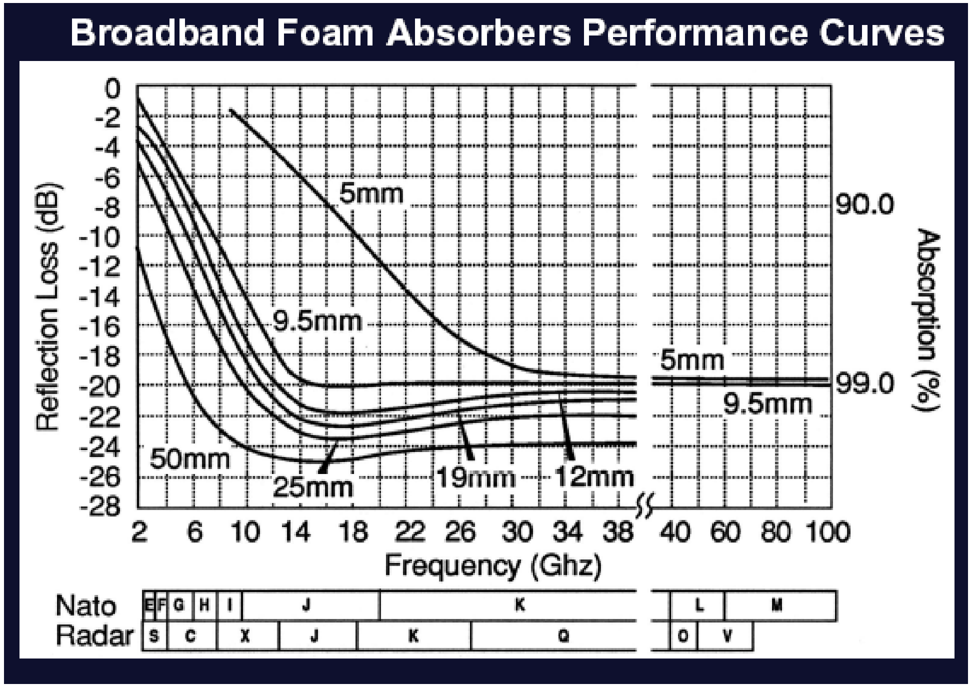
Stealth-A/C | Conventional A/C

Configuration	X	X	X	X	X	X	X	X	X
Stores	X	X	X	X	X	X	X	X	X
Engine inlets	X	X	X	X	X	X	X	X	
Front radar / radome	X	X	X	X	X	X	X		
Auxiliary inlets	X	X	X	X	X	X			
Trailing edges	X	X	X	X	X	X			
Gaps	X	X	X	X	X				
CNI+ECM antennas/rad.	X	X	X	X	X				
Access doors	X	X	X	X					
Material Transitions	X	X	X						
Sensors (air data, etc.)	X	X							
ESM antennas	X								



Ritter, J., The Role of CEM in the Realization of RCS Reduction of Aircraft, Stealth Conference 2005, U.K.

RCS reduction: radar absorbing material



Summary of Graded Deposit Absorbers

From the Design Parameters (wish-list)

Frequency	=	Good
Reflection Loss	=	Good
Polarisation (x2)	=	Good
Angle of incidence	=	Good
Weight	=	Low
Thickness	=	Medium
Mechanical	=	Fragile
Environment	=	Benign

Broadband (attenuating) RAM

Small change in impedance

Absorbing lossy layered material

Resonant (interference) RAM

BAE Systems, Microwave Materials Technology, Stealth Conference 2004, U.K.

RCS reduction examples in helicopter

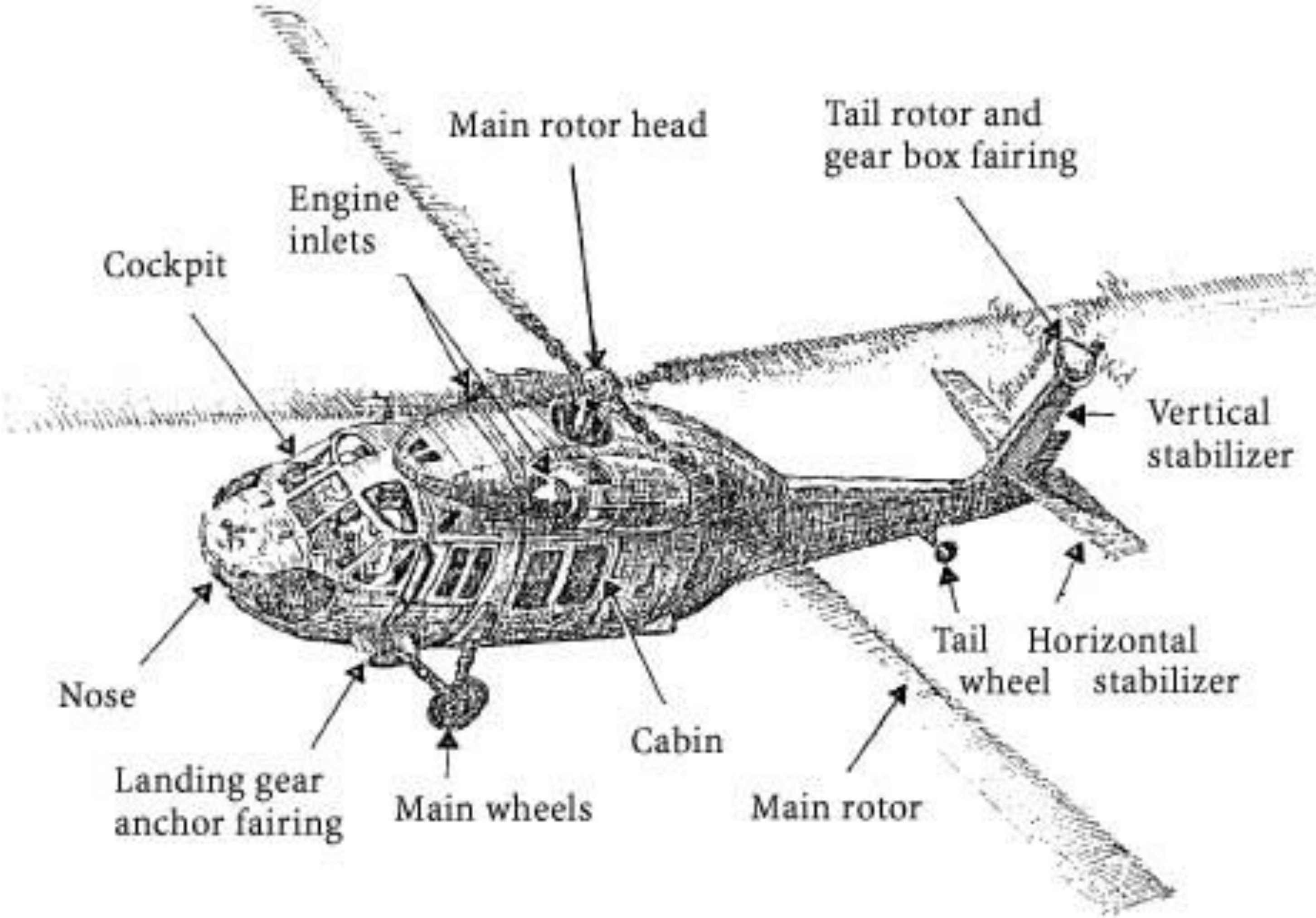
HAL Light Combat Helicopter	**Some design features that will reduce its RCS: narrow fuselage and flat panels.**
Stealth Black Hawk	**Shape of tail boom has been altered and possibly enlarged to evade radar. Pan-like cover or hubcap over the rear rotor head conceals exposed machinery which is more easily picked up on radar. Smaller five tail rotor blades were used. Rotor blades in composite material, radar absorbing fairing on main rotor hub. Radar absorbing coating on the airframe, tail boom, and engine pods.**
WZ-10	**The fuselage has a sloped side and have a stealthy diamond cross section to reduce its radar cross section (RCS).**

Indian HAL Light Combat Helicopter

US Stealth Black Hawk (Version 1)

Chinese WZ-10

RF scattering sources in helicopter

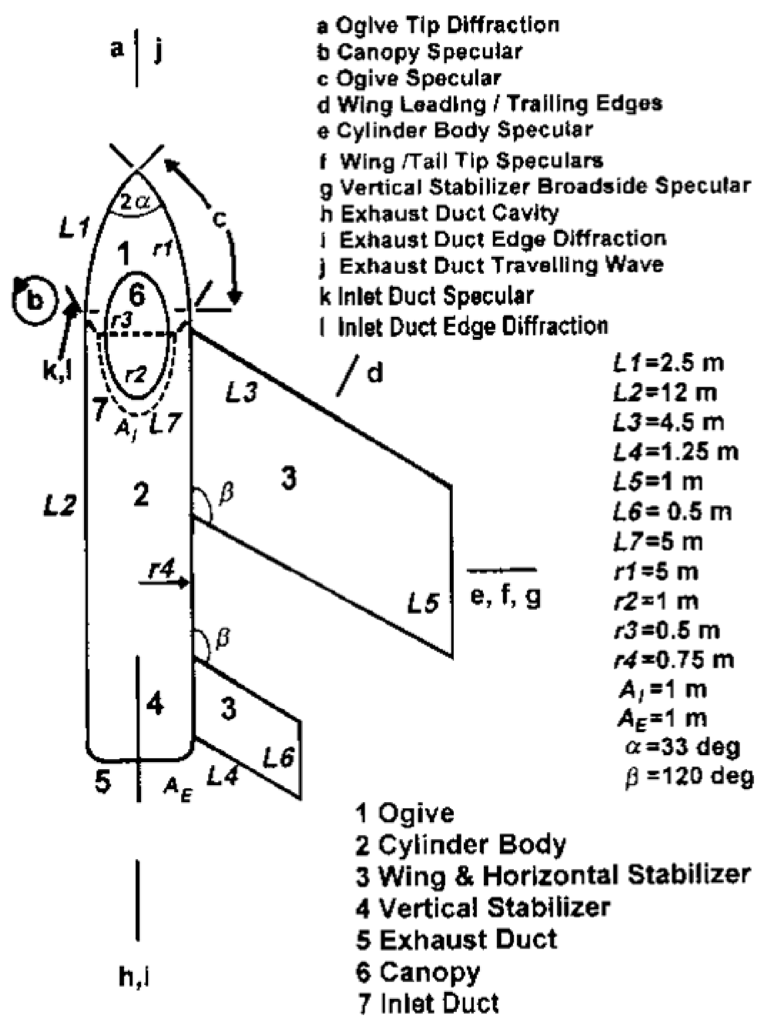


Calculations for RCS reduction (component build methods; RCS budget distribution)

A hypothetical aircraft with dimensions comparable to an F-16 (wavelength 6 cm of SAM threats): Accurate within 3 dB

$$\sigma = \sum_{m=1}^{M} \sigma_m$$

Figure feature	Equation	RCS @ 0° (dBsm)	RCS @ 10° (dBsm)	RCS @ 20° (dBsm)	RCS @ 30° (dBsm)	RC @ 4 (dB
a	$\lambda^2 \tan^4 \alpha/(16\pi)$	−40	−40	−40	−40	−4
b	$\pi r_3 r_2^*$	−7	−5	−2	1	2
c	$\pi r_1^2 (1 - \cos\alpha/\sin\theta)$	−60	−60	−60	−60	−6
d	$2(L3^2 + L4^2)/\pi$	−60	−60	−60		−6
e	$2\pi r4 \cdot L2^2/\lambda$	−60	−60	−60	−60	−6
f	$(L5^2 + L6^2)/\pi$	−60	−60	−60	−60	−6
g	$4\pi(L4 \cdot L6 \sin\beta)^2/\lambda$	−60	−60	−60	−60	−6
h	$2A_E$	−60	−60	−60	−60	−6
i	$(2\lambda)^2/\pi$	−23	−23	−23	−23	−2
j	$\pi\lambda(r4)^2/(L1 + L2)$	−21	−60	−60	−60	−6
k	$2A_I \cos^2\theta$	3			1.8	−0.
l	$(L7)^2/\pi^{**}$, $(2\lambda)^2/\pi$	9	−23	−23	−23	−2
Total	Noncoherent Sum	10				3.



Example first-order RCS estimate from specular segments.

RCS reduction numbers game

Concentrate on the dominant scatterers because a reduction there yields the greatest payoff. However, when there are many echo sources, all of about the same magnitude, treatments must be devised for many scatterers instead of just a few.

Effect of a Dominant Scatterer

	Untreated	Reduce σ_1 by 10 dB	Reduce σ_1, σ_2 by 10 dB	Reduce σ_1, σ_2, σ_3 by 10 dB
σ_1	200	20	20	20
σ_2	20	20	2	2
σ_3	20	20	20	2
Total	240	60	42	24
dB reduction	0	6	7.6	10

Effect of Working Harder on the Dominant Scatterer

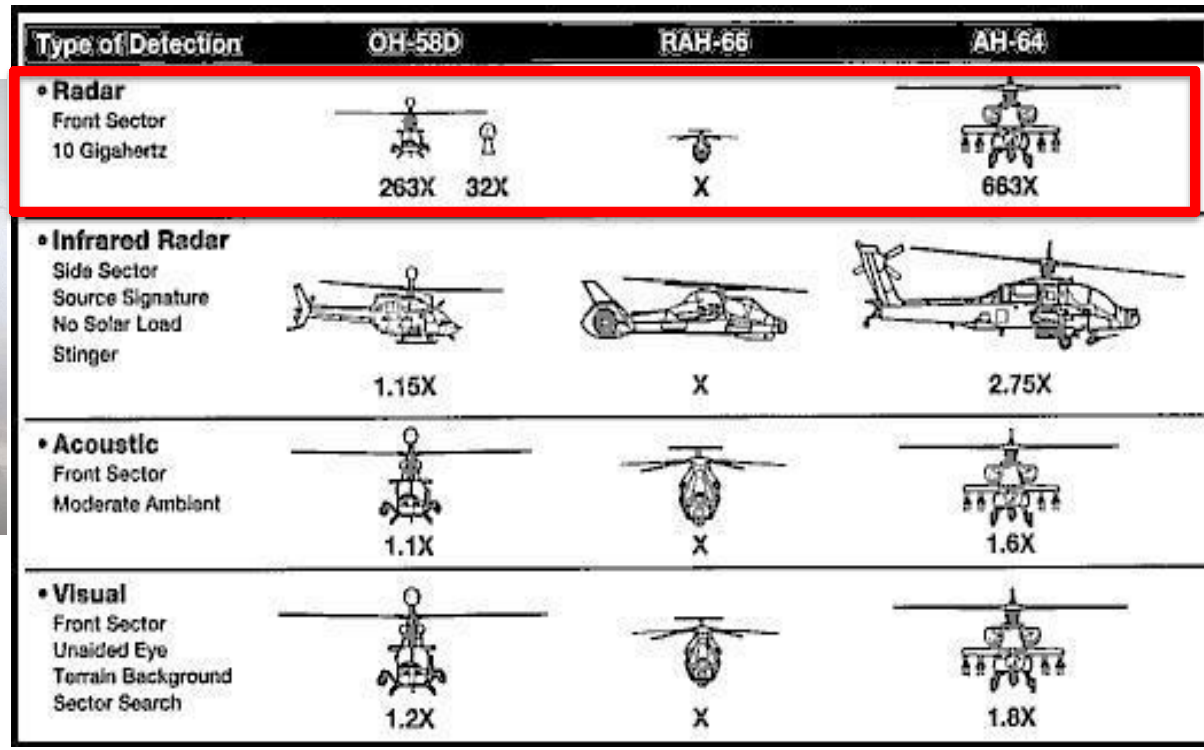
	Untreated	Reduce σ_1 by 15 dB	Reduce σ_1 by 15 dB, σ_2 by 10 dB	Reduce σ_1 by 15 dB, σ_2 by 10 dB σ_3 by 10 dB
σ_1	200	6.3	6.3	6.3
σ_2	20	20.0	2.0	2.0
σ_3	20	20.0	20.0	2.0
Total	240	46.3	28.3	10.3
dB reduction	0	7.1	9.3	13.7

RCS reduction examples in helicopter
(RAH-66 Comanche)

The first stealth helicopter and a role model for stealth helicopters

RCS about 1/630 of AH-64 (Boeing) and 1/250 of OH-58D (Bell)

RAH-66 Comanche
(Boeing–Sikorsky)



Type of Detection	OH-58D	RAH-66	AH-64
• Radar Front Sector 10 Gigahertz	263X 32X	X	663X
• Infrared Radar Side Sector Source Signature No Solar Load Stinger	1.15X	X	2.75X
• Acoustic Front Sector Moderate Ambient	1.1X	X	1.6X
• Visual Front Sector Unaided Eye Terrain Background Sector Search	1.2X	X	1.8X

Stealth helicopter RAH-66 Comanche

Stealthy Black Hawk (version 2)
Operation Neptune Spear (Killing of Osama bin Laden)

LAH 헬기 RCS 해석 및 저감 예

무장헬기의 피탐성 저감방안 연구 (2012; KAI-아피아엔지니어링)

RCS 해석 헬기 형상 및 CATIA 모델 (2012)

Some useful results (2012)

고속 헬기의 경우

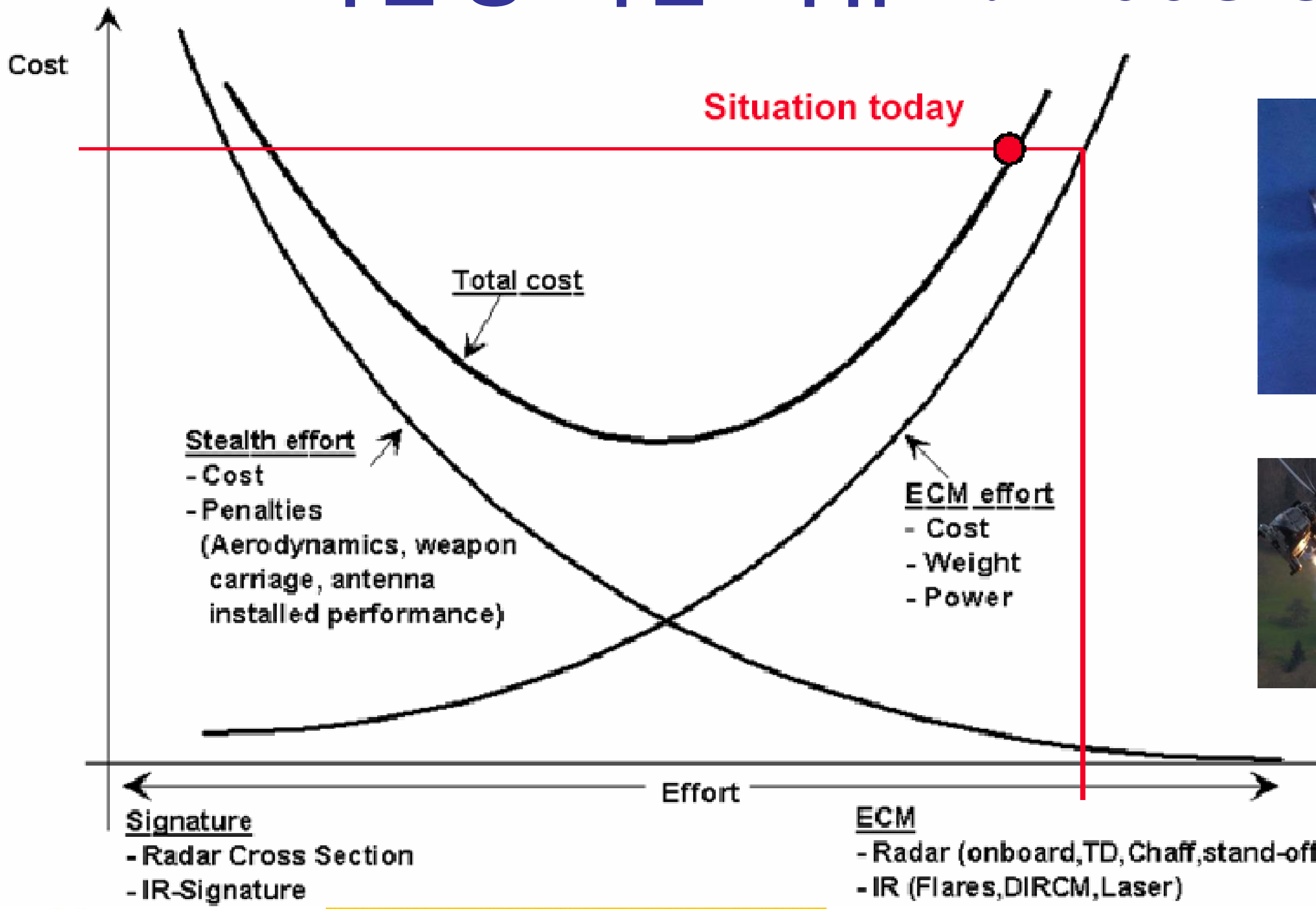
선두부-엔진 Cowling/Intake-Hub-로터 간극의 복합 작용에 의한 항력, 소음/진동, RCS, Ice Shedding 등이 중요할 것으로 예상

저피탐 헬기 RF 위협 요소

RF 신호 추적 미사일	S-125 Neva/Pechora	S-300	Buk Missile System
제작국가	러시아	러시아	러시아
크 기	6.1×0.38m(길이×직경)	7.5×0.5m(길이×직경)	5.55×0.4m(길이×직경)
탄 두	60kg Frag-HE	150kg	70kg Frag-HE
유효사거리	35km	200km	30km
최소사거리	3.5km	6km	4km
최대속도	Mach 3	1700 m/s	Mach 3
최대상승고도	25km	25km	25km
주파장대	D/I Band	I/J Band	D/G/H/I Band
유도방식	RF CLOS	SARH by TELAR	Semi-Active Radar Homing
사용국가	북한, 이집트 등 27개국	북한, 러시아 등 17개국	북한, 시리아 등 11개국

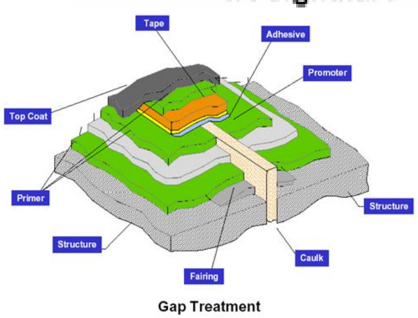
Cf. RF, IR, 소음 탐지거리 고도와 탐지기의 위치에 따라 차이가 남

피탐성 저감 이슈 1: Trade-off



Chaff

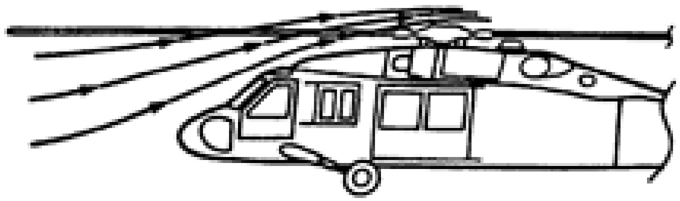
Flare



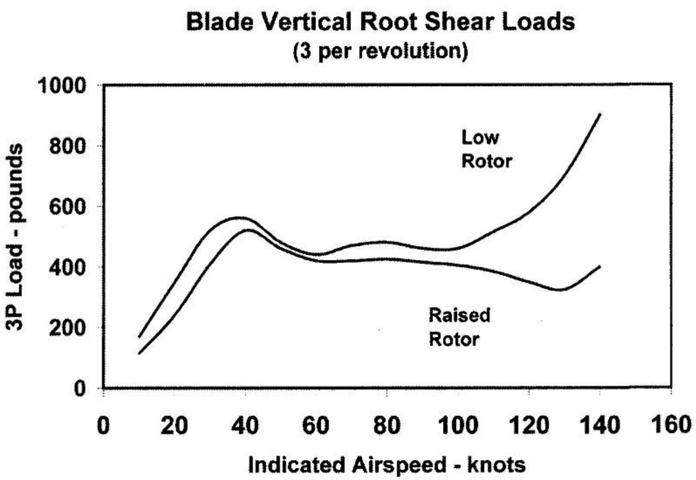
Helicopter-borne jammer against SAM with radar and IR homing heads

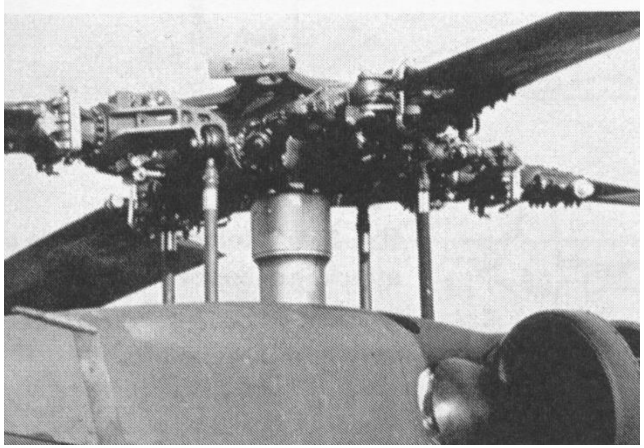
피탐성 저감 이슈 2: 모순적 요구조건

스텔스 기술의 다분야 통합설계 적용기법 연구(07-12; 국과연)



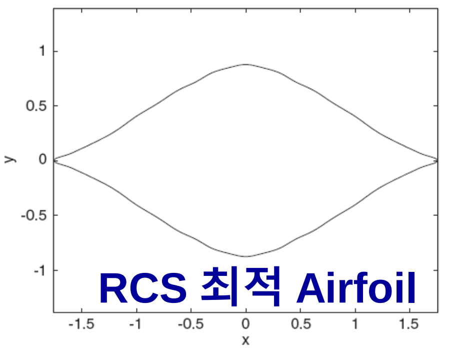
- In case of the Black Hawk (UH-60), the US army's high-priority requirement: **air transport capability (using a C-130 cargo** aircraft) demanding the main rotor close to the fuselage
- However, the **low rotor position created severe interference** flow conditions that could **increase required power in forward flight significantly**.
- To resolve this contradictory requirement, the Sikorsky rotor designers invented **an ingenious solution; a two-position rotor system** based on a removal new part.
- The rotor shaft extender enabled the **rotor location 15 inch higher during flight**, while it permitted **the rotor to be lowered for air transport**.



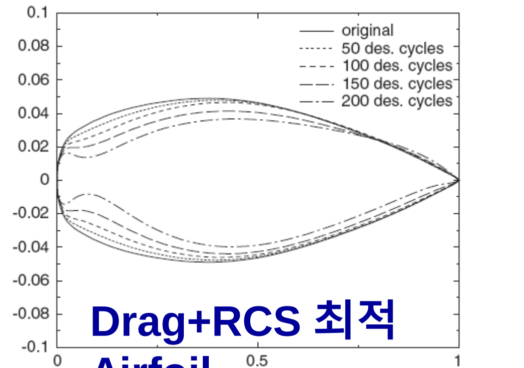


R.D. Leoni, Black Hawk: The Story of a World Class Helicopter, AIAA, 2007.

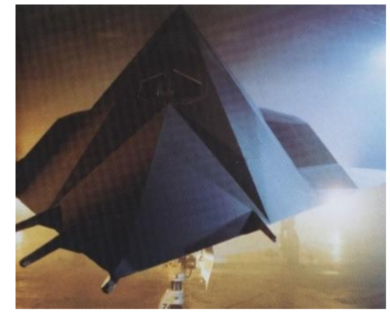
피탐성 저감 이슈 3: MDO vs Hybrid
모순 요구조건 해결 Hybrid 설계



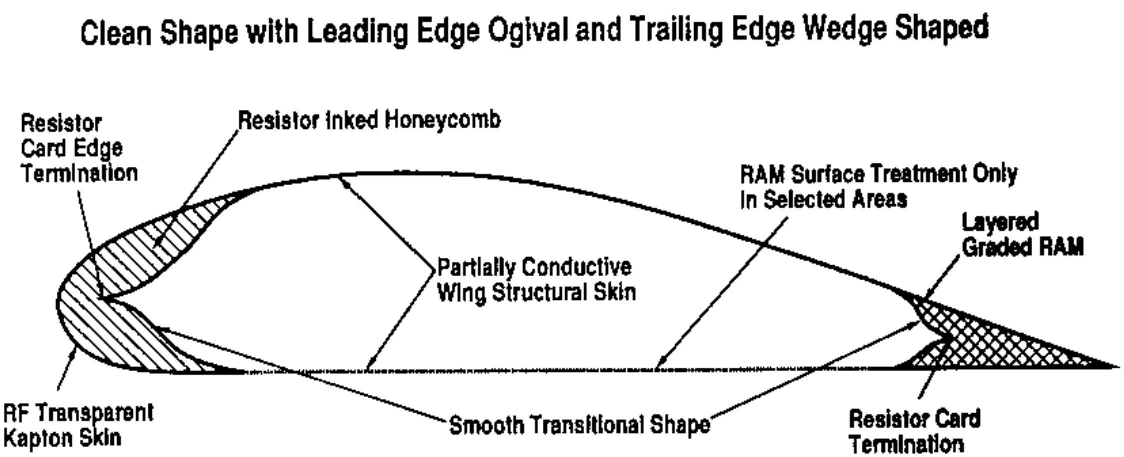
Shape optimized for TE and TM polarization with a penalty



Wing profile from the combined RCS and drag optimization with $\beta = 0.8$



RCS 최적 비행체 형상



Typical RCS edge treatments

공력&소음 MDO 효과적

공력&RCS MDO 비현실적

공력, 추진, 구조, 소음, IR, RCS의 Trade-off는 단순하지 않음

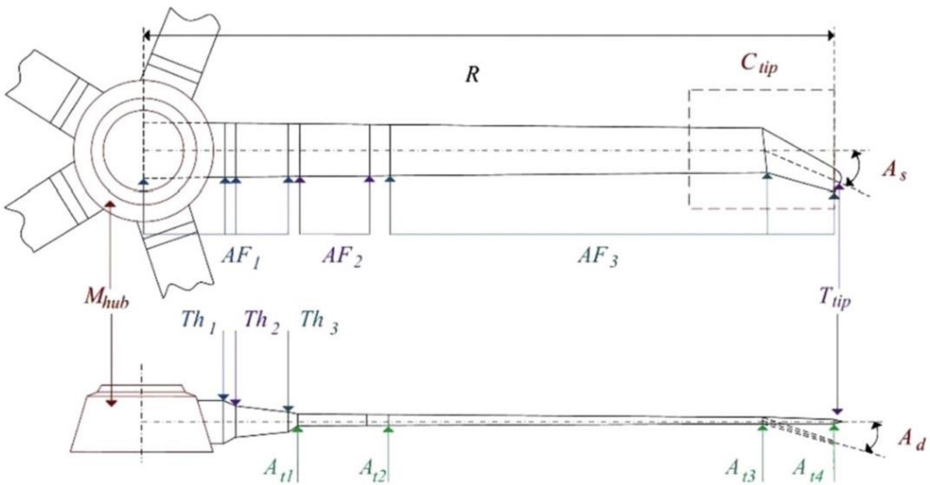
MDO, Hybrid, 그리고 ECS의 적절한 혼용이 핵심

An ingenious (hybrid) solution to meet both requirements for radar stealth and aerodynamics is the radar absorbing structure (RAS).

피탐성 저감 이슈 4: MDO 해외 연구 사례

중국 Beihang 대학 (Z. Zhou et al., Aerosp Sci Technol)

Rotor hub & blades (2018)



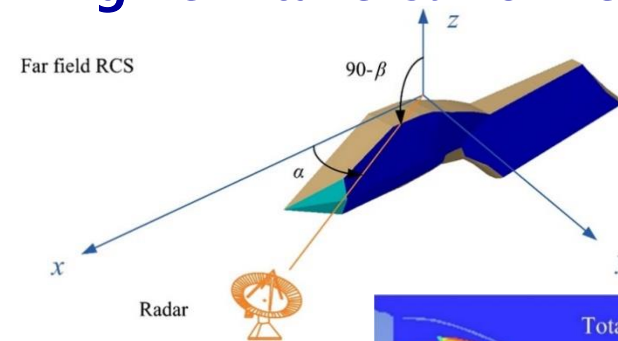
RCS　Noise thickness　Noise loading　Lift

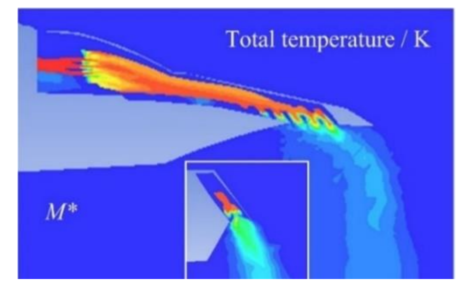
	σ_m (dB·m^2)	σ_t (dB)	σ_l (dB)	L/N
m_0	−2.2946	101.8144	94.5489	20696.971
M^*	−6.7272	100.0612	92.7847	24758.906

Hovering & Tip Mach 0.67

10 GHz & HH (PO+PTD)

Engine intake & nozzle (2019)





RCS　IR_n　IR_h　Temp

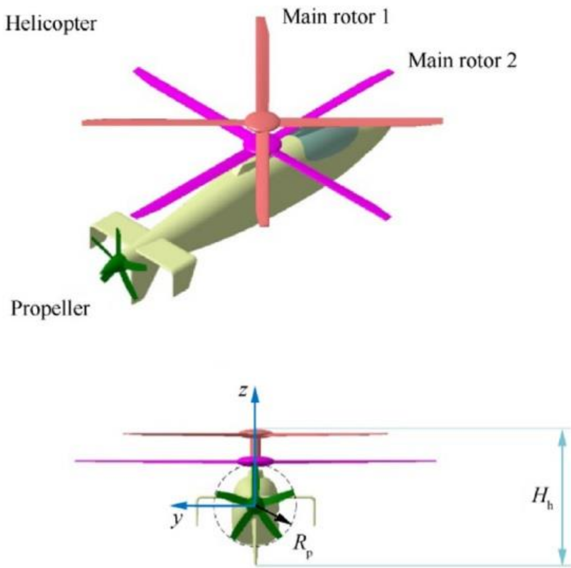
	σ /dB.m^2	I_n/W/sr	I_h/W/sr	T/K
m_0	7.6142	533.1166	204.9310	592.4057
M^*	−5.4598	158.3156	75.3664	522.5354

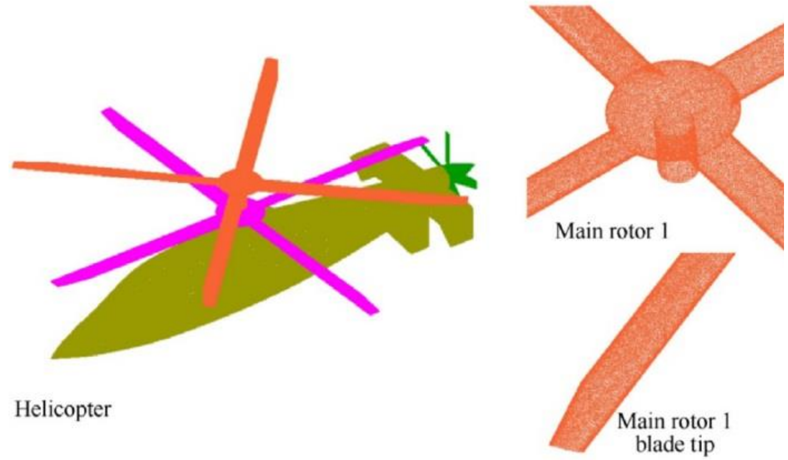
Hovering (RAH-66)

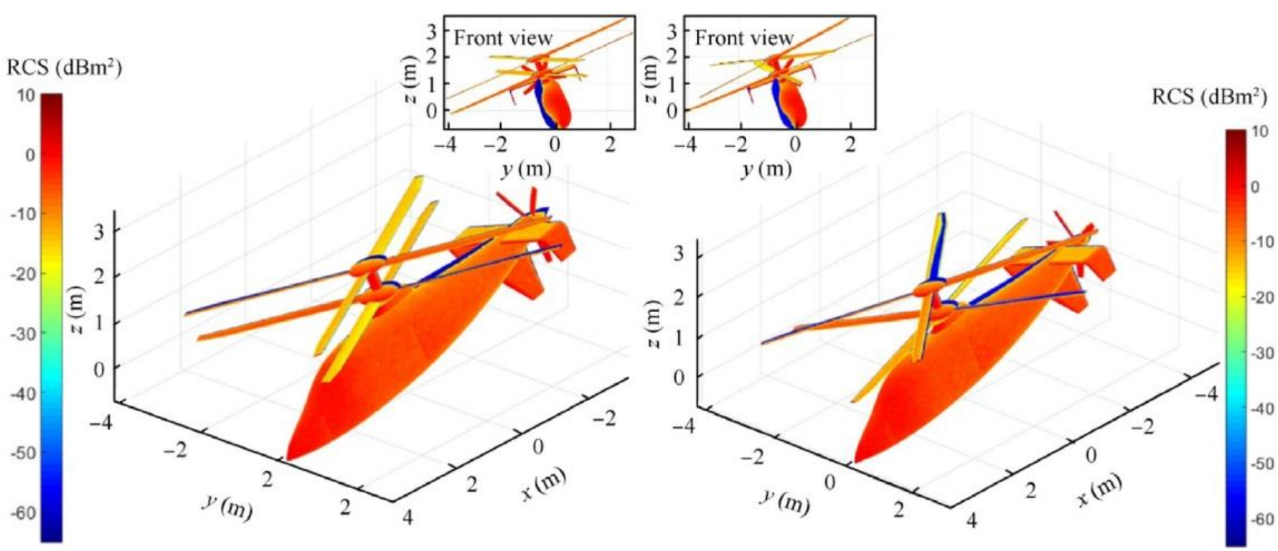
10 GHz & HH (PO+PTD)

피탐성 저감 이슈 5: Multi-rotor 해외 연구 사례

중국 Beihang 대학 (Z. Zhou et al., CJA, 2021)





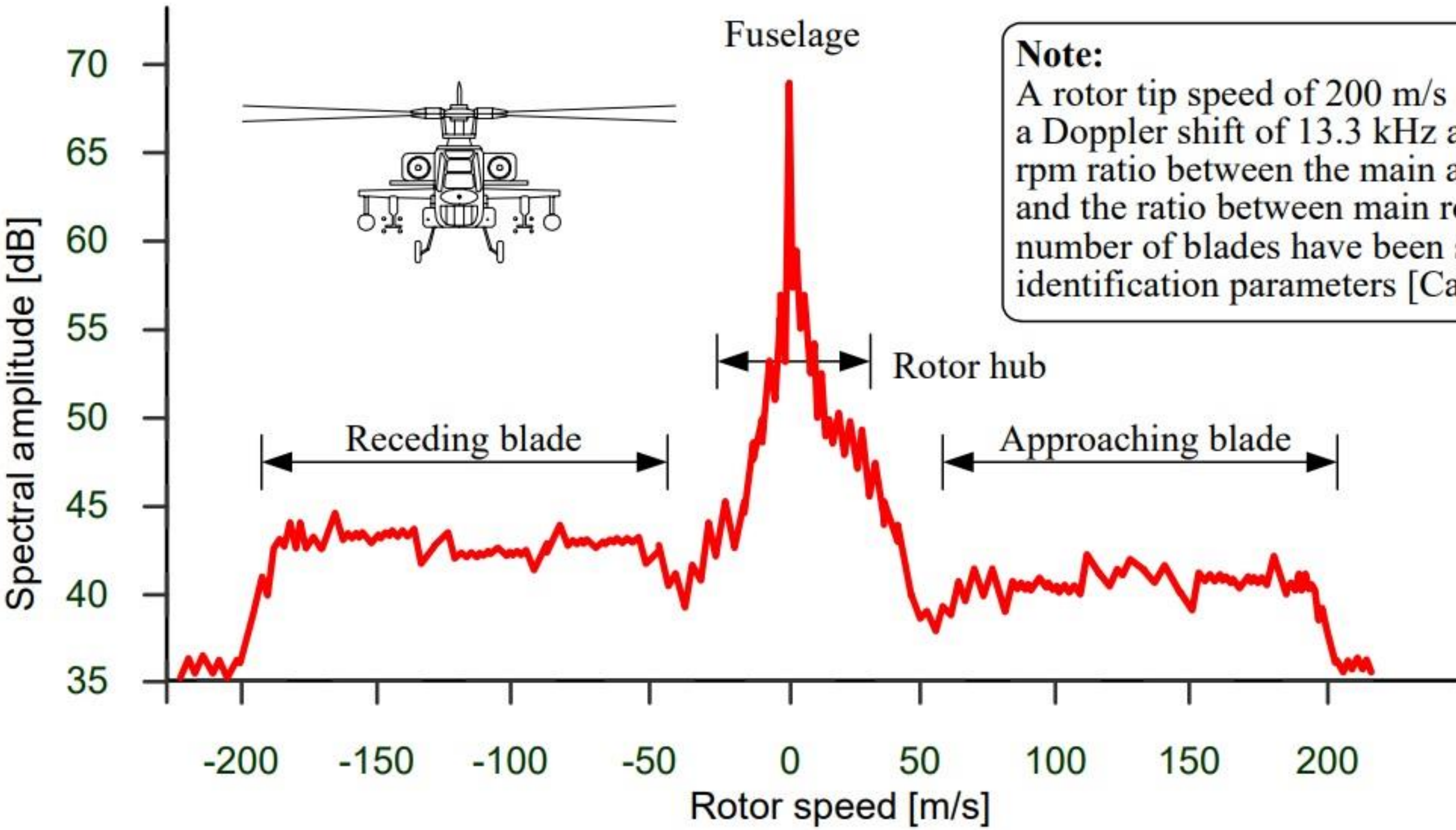


Multi-rotor
dynamic scattering
(RCS) calculation
based on PO+PTD

6 GHz & HH

피탐성 저감 이슈 6: 회전 Rotor Blade

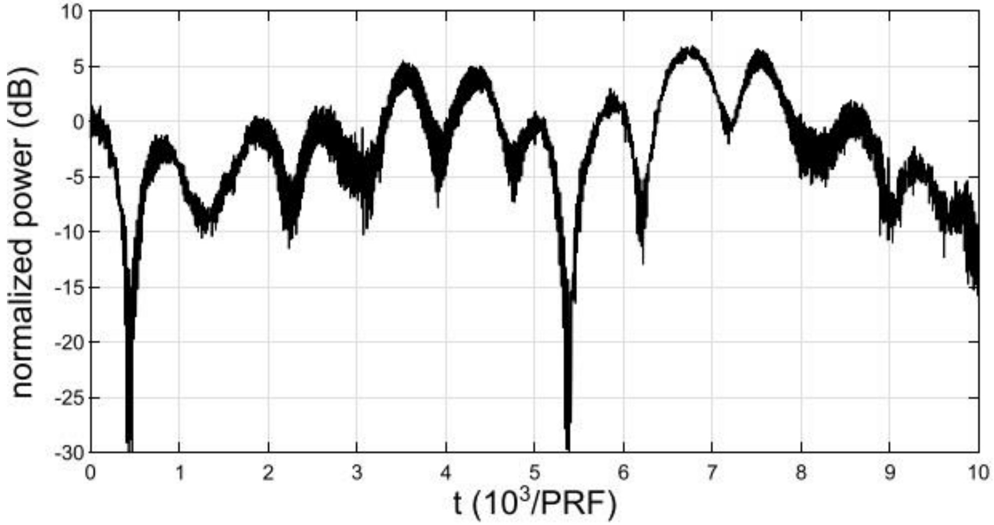
Radar helicopter detection and classification

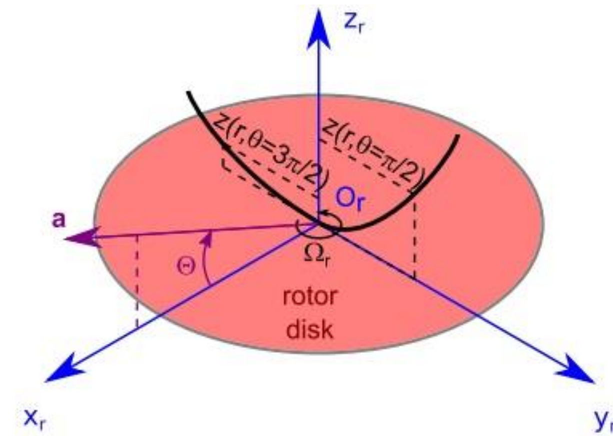


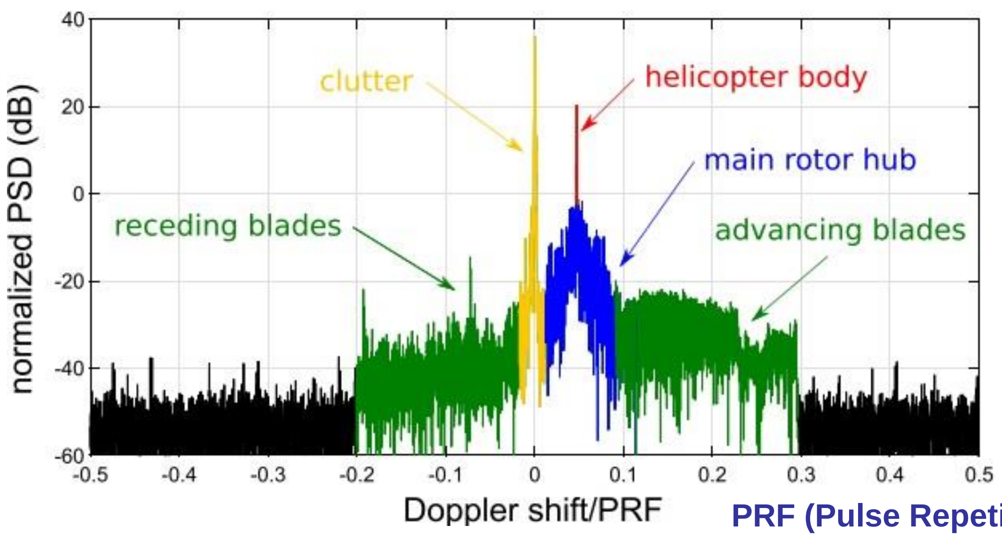
Note:
A rotor tip speed of 200 m/s corresponds to a Doppler shift of 13.3 kHz at 10 GHz. The rpm ratio between the main and tail rotors, and the ratio between main rotor length and number of blades have been suggested as identification parameters [Car92, Rot97].

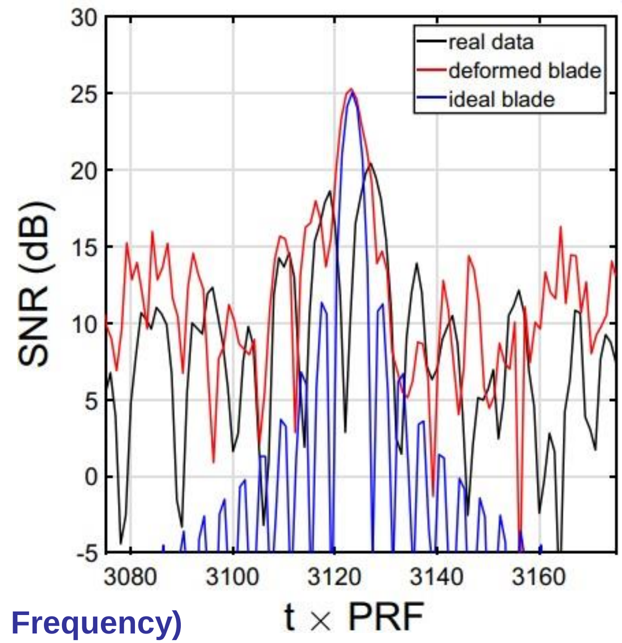
피탐성 저감 이슈 6: 회전 Rotor Blade
(Point et al., IET Radar, Sonar & Navigation, 2021)

Need to take basic helicopter flight dynamics and resulting deformation effects of the rotor blades into account









PRF (Pulse Repetition Frequency)

피탐성 저감 이슈 7: 편대 비행

Tactics, 효율성, 유무인 복합 비행 등

편대 비행의 생존성 영향성?

피탐성 저감 이슈 7: 편대 비행