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A STUDY OF THE DESIGN CONSIDERATIONS FOR LOW OBSERVABLE AIRCRAFT

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

LCDR James R. Seaman, Jr., USN

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Abstract

Stealth, or low observable, technology is now a requirement for virtually every weapons platform in development. The generations of stealth technology began with the U-2 and SR-71. The B-1B and F-117 followed as second generation stealth aircraft. The A-12 and B-2 were designed with third generation stealth technology. The Advanced Tactical Fighter (ATF) and Naval ATF were considered fourth generation. Currently, the F-22 and AX are fifth generation technology. The growth in low observable technology has been explosive and its implementation requires a different design frame of reference. Design trade-offs must be made in terms of low observability over the entire electromagnetic spectrum.

An aircraft which incorporates stealth characteristics enhances survivability. Operationally, this equates to the aircrew being able to deliver ordnance on a target and return home safely. This study will give insight to design criteria for low observable platforms and discuss some of the negative aspects of the technology.

All research was done at the unclassified level. Additionally, information was gathered from subject matter experts at the Naval Air Weapons Center, China Lake, Ca.

Incorporation of stealth technology was found to be imperative for survivability. The design trade-offs in airframe size, engine performance, and weapons carriage capabilities are well worth the effort.

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Nomenclature

BPR	Bypass Ratio
CIA	Central Intelligence Agency
EO	Electro-optical
ECM	Electronic Counter Measures
IR	Infrared
Laser	Light Amplification by Stimulated Emission of Radiation
Radar	Radio Detection and Ranging
RAM	Radar Absorbing Material
RCS	Radar Cross Section
RF	Radio Frequency
SDI	Strategic Defense Initiative
TSFC	Thrust Specific Fuel Consumption
UV	Ultraviolet

Chapter I

INTRODUCTION

Background

The word stealth or low observable when applied to combat platforms refers to the level of detectability of that platform. Stealth applies to all the "observables" of an aircraft, i.e., shape of the aircraft, electro-optical radiation, visual cross-section, RF Radar Cross Section (RCS) and noise signature. The purpose of stealth is to enhance the weapon systems ability to carry out its mission by delaying detection or reducing the threat's capability to track the system after detection. The goal of a true stealth weapons platform is to reduce the probability of detection to zero.[1] The trade-off in stealth aircraft design is quickly driven by the requirements of advancing current technology and the limited size of the development budget. Reducing the probability of detection at a range where a stand off weapon has already been released and the aircraft is turning outbound (with active Electronic Counter Measures) from the threat may be as acceptable as "invisible", if the aircraft were to have to fly over the target. Generally, the less stealth possessed by an aircraft, the cheaper the production.

The first use of the concept of Stealth was possibly in 1917 when Germany attempted to cover a Dornier E.1 fighter and a Gotha bomber with cellophane in order to make them less visible. The cellophane covering did not have sufficient strength for the imposed air loads, so the

[1]Sweetman, Bill (1986), Stealth Aircraft, pg. 6, Osceola: Motorbooks International

question of whether these aircraft were less visible was never answered. The concept of low observables was not taken seriously until the mid-fifties. The US reconnaissance and intelligence communities drafted a specification for this aircraft which stated, "consideration will be given ... to minimize the detectability by enemy Radar".[2] Lockheed's Advanced Development Project Organization (nicknamed "Skunk Works") joined forces with the CIA to develop a high altitude reconnaissance aircraft (Project Aquatint) in November 1954. The first flight of the aircraft was August 1, 1955. The aircraft was designated the U-2 shortly afterward. The next generation aircraft was again developed by Skunk Works under the code name of Project Oxcart beginning in August 1959. This aircraft was later designated the A-12 and was the precursor to the SR-71. This aircraft was significant because of the emphasis in design on keeping the RCS small. This included the long and slender fuselage, smooth contours, and vertical fins canted inward. Subsequent to Project Oxcart, there were several drone programs which greatly expanded US stealth technology. Very little unclassified information is available on the history of stealth technology since approximately 1974.

Purpose

The purpose of this study was to investigate the different methods of reducing the observables of aircraft. Topics covered are RCS reduction, electro-optical signature minimization, and aircraft paint schemes in reducing visual detection ranges. All research was obtained

[2]Sweetman, Bill (1986), ibid., pg. 14

from unclassified sources. References which could be attributed to any system under development were carefully avoided.

The question of what stealth technology encompasses, and its capabilities governed by the laws of Physics are somewhat of a mystery to most military aircrew and procurement activities. This thesis applies to the individual or group with a need to know how low observable technology can be integrated in aircraft design and how to make existing airframes less observable by combining a variety of techniques.

Chapter II

RADAR CROSS SECTION REDUCTION

Discussion of Radar Theory

Radar, an acronym adopted in 1940, stands for "radio detection and ranging". A Radar is a device which generates an electromagnetic field which makes certain variables of a target observable. Variables of interest are presence, shape, position, velocity, size, motion and reflectivity of an object. The most important of the variables from the Radar operator's perspective with respect to aircraft are altitude, range and relative motion (which includes velocity). The crew of the aircraft is most concerned with the reflectivity of the aircraft based on the Radar's parameters. Parameters of a electromagenetic wave generated by a Radar system include its frequency, wavelength, polarization, amplitude and direction of propagation.

A Radar system radiates electromagnetic waves into space and determines the nature of echoes reflected by objects in the resulting field. The wave which is returned to the receiving antenna will be delayed in time by the two-way propagation time, shifted in frequency by the Doppler shift based on the relative motion of the target, and altered in amplitude and direction of propagation by the reflectivity of the target and the characteristics of the intervening medium[3].

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[3]Masters, George W. (1981), Radar System Test and Evaluation, pg. 2.1, Patuxent River: USNTPS

By modulating the outgoing wave the system can determine the distance to the target by recognizing a portion of the returning waveform and measuring the elapsed time. Azimuth and elevation can be determined by using directional antennas and measuring the direction from which the returning signal is greatest. This method is used in older type systems and results in numerous ambiguities. A more precise method is measuring the difference in phase between the signals observed at two antennas to determine target bearing. This is also referred to as interferometry. By measuring the difference in frequency between the transmitted and returned signal the target's velocity can be determined. This is referred to as the Doppler shift. Other characteristics, such as size, shape, and aspect angle, can be determined by processing the basic measurements of phase shift, Doppler shift and amplitude differences of the transmitted and returned signals.

The following partial derivatives will give an insight as to how a system extracts information from Radar returns. Information about the target is based on rates of change of return signal amplitude (A) and phase (Φ) with respect to time (t), position of observance (x), and transmission frequency (f):

(1) $(\delta\Phi/\delta f)_{t,x}$ = Range

(2) $(\delta\Phi/\delta x)_{t,f}$ = Angle

(3) $(\delta\Phi/\delta x)_{x,f}$ = Velocity

(4) $(\delta A/\delta f)_{t,f}$ = Size

(5) $(\delta A/\delta x)_{t,f}$ = Shape

(6) $(\delta A/\delta t)_{x,f}$ = Rotation

(1) As the frequency of the return signal is changed, the phase will change by an amount proportional to target range. (2) As the position of observance is changed, the direction of maximum rate of change of phase will be in the direction of the target. (3) The time rate of

change of phase is proportional to the velocity of the target (Doppler frequency shift). (4) When frequency is changed, the amplitude of the return (Radar Cross Section of the target) will change as a function of the ratio of the dimension of the target to the wavelength which allows determination of the size of the target. (5) When the target is viewed simultaneously from several positions of observation, the variation in return amplitude with position gives information about the shape of a target (an algorithm of this gives airborne Synthetic Aperture Radar (SAR)). (6) When the return amplitude is observed as a function of time, information is obtained about target rotation.[4] These equations give a relatively simple explanation as to what the Radar attempts to do when processing signals. Understanding the principles will give a better understanding on how not to be detected by Radar.

Radar Systems

RCS reduction is the most important issue in stealth design as Radar is the system which will detect a non-radiating aircraft first. From the partial derivative $(\delta A/\delta f)_{t,f}$ = size, reducing the amplitude of the return to zero will result in no detection of the target. This amplitude corresponds to the RCS of the target. In order to design for low RCS, the type of threat Radar which will be encountered must be defined. The two major types of threat Radar set-ups are monostatic and bistatic systems. A monostatic system is where the Radar transmitter and receiver are co-located. A bistatic system is where the transmitter and receiver are widely separated. Bistatic systems give some advantage

[4]Masters, George W. (1981), ibid. pg. 2.2 - 2.3

to the threat by reducing vulnerability to anti-radiation missiles and electronic counter measures (ECM). Designing an aircraft to have a low RCS for both monostatic and bistatic systems is relatively difficult. Aircraft designed to have a low monostatic RCS could have a large RCS at certain bistatic angles dependent on the target aspect.

RCS

The amount of energy a Radar will receive from an illuminated target is determined by four factors[5]:

1. The average power - rate of flow of energy - of the radio waves radiated in the targets direction.

2. The fraction of the wave's power which is intercepted by the target and scattered back in the Radar's direction.

3. The fraction of power which is captured by the Radar antenna.

4. The length of time the antenna beam is trained on the target.

More specifically, the maximum range of detection is dependent on transmitter power, free space attenuation, atmospheric absorption and scattering, system internal and external noise, RCS, and the signal-to-noise ratio at the receiver required to perform a specific function.

From the aircraft designer's frame of reference, the factor which can be controlled is the fraction of the propagated wave's power which is scattered back in the Radar receiver's direction (directivity). Directivity is dependent on target aspect, configuration, and relative phase of backscatter. The directivity may range anywhere from a small

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[5]Stimson, George W. (1983), Introduction to Airborne Radar, pg. 170, El Segundo: Hughes Aircraft Company

fraction to a large number. This factor is directly related to RCS. RCS is the effective reflecting area of the target, and involves the product of geometric cross section (cross-sectional area of the target as seen from the Radar), Reflectivity (fraction of the power scattered by the target), and Directivity (ratio of the power scattered back in the Radar's direction to the power which would have been backscattered had the scattering been isotropic).[6] In equation format:

RCS = Geometric Cross Section * Reflectivity * Directivity

Some typical values of RCS (σ) are presented in Table II-1.

Table II-1

RCS Values for Common Vehicles

Vehicle	σ (m^2)	σ (db)
Insects	0.001	-30
Birds	0.01	-20
Creeping/travelling wave[1]	~0	1
Fighter	100	20
Bomber/Transport	1000	30
Ship	10,000	40

1. Travelling waves are caused by changes in the dielectric constant of two mediums. To adjust to the new dielectric constant, some of the incident energy is reflected. An example of this is the wing/aileron interface where the components are of different materials. A creeping wave is caused by bending of incident waves around objects whose size is comparable to the wavelength of the Radar.

[6]Stimson, George W. (1983), ibid., pg. 172

Radar Range Equation

In order to understand the importance of RCS (σ) in the probability of detection, a derivation of the Radar range equation follows:[7]

P - transmitted power

p_T - density of wave incident on target

R - range from target to transmitter/receiver (assume monostatic system)

$$p_T=P/\{4\pi R^2\} \qquad \{watts/m^2\}$$

The above equation describes free space attenuation based on spherical spreading of the waves independent of atmospheric absorption and scattering, and antenna directivity. Inserting antenna directive gain (G) into the equation results in:

$$p_T=PG/\{4\pi R^2\} \qquad \{Watts/m^2\} \qquad (1)$$

The power density of the wave incident on the target is dependent on the targets RCS. Therefore,

$$P_T=p_T\sigma=PG\sigma/\{4\pi R^2\} \qquad \{Watts\} \qquad (2)$$

Where P_T is the power intercepted by the target. The power density at the receiver (p_R) is a result of free space attenuation on the reflected wave. So, from equation (2):

$$p_R=PG\sigma/\{4\pi R^2\}^2 \qquad \{Watts/m^2\} \qquad (3)$$

The power actually captured by the Radar (P_R) is dependent on the effective capture area (A) of the antenna and is presented in equation form by:

$$P_R=p_RA=PGA\sigma/\{4\pi R^2\}^2 \qquad \{Watts\} \qquad (4)$$

---

[7]Masters, George W. (1981), ibid., pg. 2.14 - 2.16.

Inserting a dimensionless loss factor (L) which represents non-specific losses in the system, and solving equation (4) for the maximum range attainable (R_{max}) for a given required minimum power at the receiver (P_{min}) results in:

$$R_{max}=[PGA\sigma/(\{4\pi\}^2LP_{min})]^{1/4} \qquad \{m\} \qquad (5)$$

R_{max} is more dependent on the signal to noise ratio (S/N) than upon signal power alone. P_{min} can be expressed as

$$P_{min}=(S/N)_{min}N \qquad \{watts\} \qquad (6)$$

where N is the noise in the system referred to the input. The minimum attainable noise is thermal noise which is a function of the absolute temperature (T) in Kelvin or Rankin of the system, the noise bandwidth (B_n) in Hz of the system, and Boltzmann's Constant (k). So,

$$P_{min}=kTB_nF_n(S/N)_{min} \qquad \{watts\} \qquad (7)$$

where F_n=Noise output actual/Noise output of ideal receiver.

Substituting equation (7) into equation (5) results in:

$$R_{max}=[PGA\sigma/(\{4\pi\}^2LkTB_nF_n(S/N)_{min})]^{1/4} \qquad (9)$$

Even though the Radar Range Equation derived above is limited to a single sweep, non-integrated pulse it has empirical application. For instance, a reduction in an aircraft's RCS by 1/2 results in a decrease in the maximum detection range of 13 nm (80 nm to 67 nm were the values used in the calculation). If the aircraft had to close within 10 nm of a target prior to weapons release, the RCS would have to be reduced by a factor of 0.00024 (-36db) to avoid detection. Designing an aircraft which would reduce RCS by this factor in all quadrants would be extremely expensive and not possible based on present technology. Figure II-1 depicts the RCS diagram for a B-26 bomber.

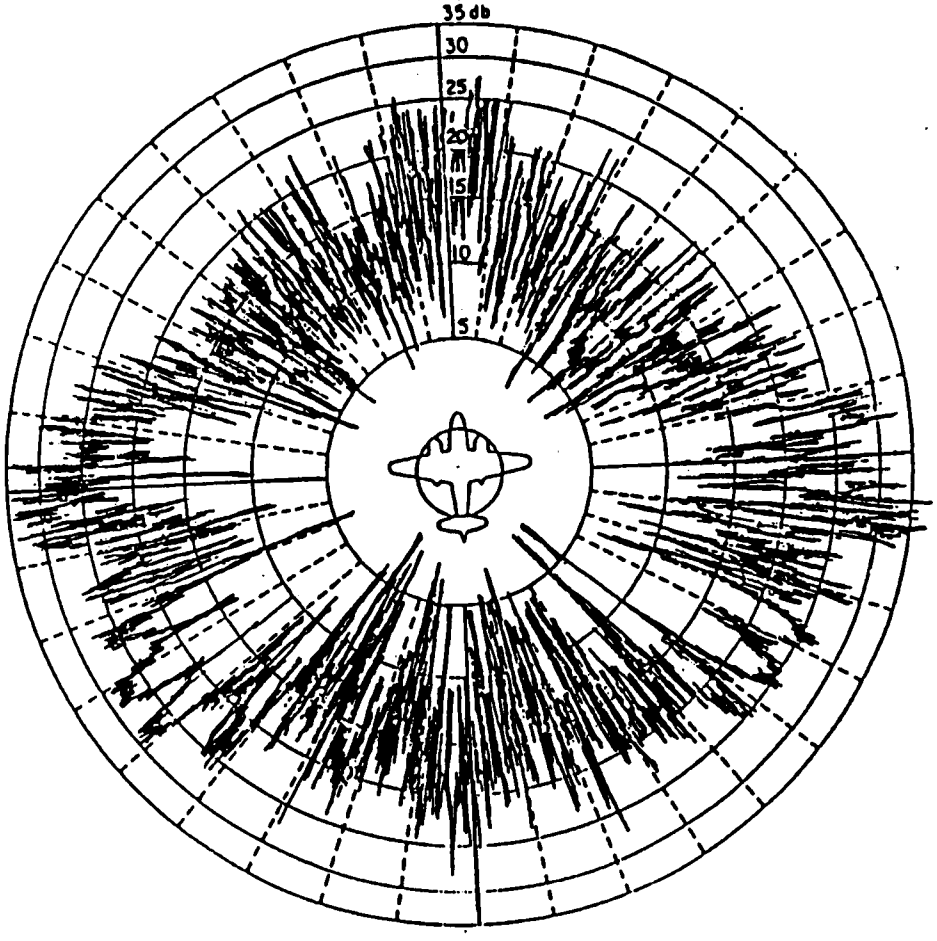


Figure II-1

Radar Cross Section of a B-26

Source: Masters, George W. (1981), Electro-optical Systems Test and Evaluation, pg. 2.17c, Patuxent River: USNTPS

The detection ranges for a given RCS reduction based on the Radar range equation alone do not accurately reflect what the true detection range would be. A surface search Radar has a figure of merit of how much

area/time can be searched whereas an air search Radar searches volume/time. Decreased detection probability can be estimated by the following equations:

$R_2/R_1 = (\sigma_1/\sigma_2)^{1/4}$ Range

$(R_2/R_1)^2 = (\sigma_1/\sigma_2)^{1/2}$ Search Area

$(R_2/R_1)^3 = (\sigma_1/\sigma_2)^{3/4}$ Search Volume

Based on these equations, a decrease of σ by 0.1 db will decrease the figure of merit for a surface search Radar to 32 percent and an air search Radar to 18%. If the RCS is reduced, the volume or area search rates decay rapidly which makes detection more unlikely.[8]

Noise

Obviously, the easiest way to reduce detection range is to reduce RCS. More importantly, the aircraft must have a RCS which results in a returned signal at the Radar receiver which is below the minimum signal strength required for detection (S_{min}). The Radar will have a set threshold level. A signal from a target plus the noise level of the system which is above the threshold level will result in a target indication on the display (blip). Figure II-2 presents this graphically.

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[8]Fuhs, Allen E. (1984), Radar Cross Section Lectures, pg. 117, New York: American Institute of Aeronautics and Astronautics

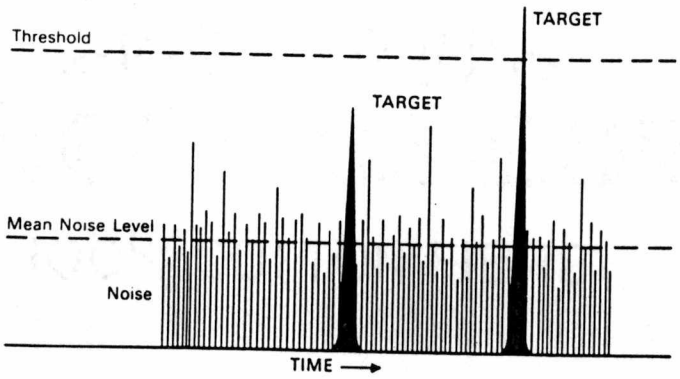


Figure II-2

Signal vs. Threshold Levels

Source: Stimson, George W. (1983), Introduction to Airborne Radar, pg. 175, El Segundo: Hughes Aircraft Company

The best possible case would be for the isotropic scatter and any spikes of Radar return caused by aircraft shape to be below the mean noise level and threshold of the system. The trade-off to designing an aircraft to this costly specification would be to leave some spikes in its Radar return, and control the aircraft's RCS by managing the direction the spikes point in. By planning routes which optimize an aircraft's RCS, some savings in design are possible. Figure II-1 shows large spikes at the 90,110,250 and the 270 degree positions relative to

the B-26's nose. Even though the B-26 was a far cry from an aircraft designed for low RCS, the pilot could minimize detection by keeping the nose of the aircraft pointed at the Radar site.

The following are major contributors to RCS:[9]

ORDNANCE/EXTERNALTANKS - Missile may have its own Radar which can have a large RCS.

RUDDER-ELEVATOR DIHEDRAL - Possibly large due to action of retroreflector.

EXHAUST - Waves can propagate within the engine cavity and reflect from internal parts.

RUDDERS - RCS is small except glint at broadside

WING - RCS small except when viewed as to see a flat area.

ANTENNAS/IRREGULAR SHAPES - Large at certain aspects.

COCKPIT - Large contributor to RCS.

RADOME - Large contributor to RCS. Antenna acts as a reflector.

ENGINE INLET - Large contributor to RCS.

ENGINE FACE - Large contributor to RCS.

The B-26 had many 90 degree corners, several cavities for gun ports, large metal propellors, and an unshielded (for Radar) cockpit. This would not be a good aircraft to bring into a Radar intensive threat environment even at its best aspect angle for lowest RCS. Presenting a planform of the aircraft to the threat would only increase the already large probability of detection.

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[9]Fuhs, Allen E. (1984), ibid., pg. 94-95

RCS Reduction

The three methods for reducing RCS are:

1. Geometric shaping
2. Radar Absorbing Materials (RAM)
3. Impedance loading

Shaping is the preferred method in designing for low RCS given the technology available in producing RAM and the drawbacks associated with RAM application (these will be covered later). RAM is generally effective only in specific frequency bands. This implies an aircraft invisible to a k-band Radar may very well be seen by a UHF band Radar if RAM were the only technique used in making the aircraft low observable. The designer must decide how the aircraft will employ its weapons, or what aspect of the aircraft will be facing the threat most of the time. He would not have to design for minimum RCS in all aspects. The designer is not as constrained with aircraft shape in regard to stability and control with the advent of computerized flight control systems. Possibilities exist for flight control surfaces to move to minimize RCS as well as maximize aerodynamic efficiency. Swing wings and pop-up vertical stabilizer are just a few of the possibilities.

Engine inlets and exhaust are generally the largest contributor to RSC. The engine face itself resembles a flat plate which gives a RCS several orders of magnitude greater than its geometric cross-section. For example, an engine with a first stage rotor diameter of one meter will have an RCS of 20,106 m^2 (43 db) if illuminated at the right geometric aspect with a 12 GHz Radar (based on the formula $\sigma_{flat\ plate} = 4\pi A^2/\lambda^2$).

Shielded inlets are an absolute must if RCS is to be reduced from a nose on aspect. Shielding the inlets within the fuselage with long, curved, baffled ducts significantly reduces RCS. This technique also reduces the possibility of identifying an aircraft through turbine blade counting processors on sophisticated fighter Radars. All turbine engines produce a characteristic "beat" which is engine dependent by which the host aircraft may be identified.[10] Flush mounting of the inlets in the fuselage reduces the inlet aperture visible to the Radar. If engine performance permits, a small wire mesh covering could be used to reduce RCS. The mesh spacing would have to be small fractions of λ which would scatter or absorb incident waves. Supersonic aircraft present a difficult problem to the aircraft designer. The airflow in the inlet must be subsonic prior to entering the first stage of the engine. This is traditionally done with movable or stationary ramps which are good retroreflectors. This is not acceptable for stealth design. A technique which is acceptable is the use of movable or stationary shock cones blended into the body of the aircraft and coated with RAM.

Exhaust nozzles can be masked by using venetian blind type vanes. The vanes should be blended into the body of the aircraft and reduce the number of angles which the exhaust contributes to RCS. Additionally, shielding the exhaust in this matter opens the ability to vector thrust giving a possible edge in performance.

Designing the Vertical Stabilizers to cant inward will reduce the possibility of presenting the surface at a 90 degree angle to the Radar

[10]Sweetman, Bill (1986), ibid., pg. 42

site. And prevents a 90^{o} corner reflector between a vertical and horizontal stabilizer. The largest return occurs when the incident and reflected waves are parallel. Another way to reduce the contribution of RCS from the Vertical Stabilizer is to have them lay flat in subsonic flight controlling yaw with wing tip speed brakes (similar to the B-2), and then pop-up for supersonic flight where stronger yaw control is normally required.

The idea of designing the aircraft components for stealth is to not have any surface normal vectors pointed at the Radar. Avoiding long, straight surfaces reduces the amount of surface area visible to the Radar at any given angle, but increases the number of angles the aircraft can be detected at. Although RCS is spread over a large angle, RCS is small. Surfaces which are long and slightly curved may have a very high RCS. For this reason, the curves should use compound curvature, changing the radius of curvature constantly ($\sigma = \rho_1 \rho_2$ where ρ_1 and ρ_2 are radii of curvature). A rounded wing tip has a small ρ_1 and ρ_2.[11]

Parallel surface areas minimize the number of surface normal vectors available which reduces the probability of detection at all but a few small angles. This also reduces the detection of creeping waves by not having the trailing edges of control surfaces normal to the Radar site. Creeping waves are propagated by bending the incident wave around the structure and returning it back to the Radar site.

Additionally, where possible, control surfaces should be one piece, e.g., stabilator or vertical stabilizer instead of using rudders and

[11]Fuhs, Allen E. (1984), ibid.

elevators. Blending the wing and fuselage structures together, minimizing breaks and reducing the amount of dissimilar material junctions also reduce RCS by reducing the propagation of travelling waves. These aberrations on the aircraft change the electric field around the aircraft caused by wave energy. This in turn changes the magnetic field of the wave or polarization. Polarization can be used as an aid in target identification.

The ordnance load most likely has the largest number of retroreflectors on the aircraft. Making a standard bomb loaded on a Multiple Bomb Rack low observable would be exceptionally difficult as well as cost prohibitive. For these reason, the ordnance load should be carried internally. The increased size of the aircraft required to carry ordnance internally is a major design consideration and drawback; however, reducing the drag associated with externally carried ordnance to zero is a major plus.

The interior of an unshielded cockpit has several retroreflectors. Pilots require good visibility which requires high profile cockpits. The best design for stealth is a low profile cockpit with some type of shielding material coated on the canopy (such as a thin layer of gold which screens out microwaves).

The aircraft's Radar antenna may be one of the largest contributors to RCS. One advanced technique to reduce RCS would be to use conformal antenna arrays imbedded in the airframe. The application of conformal arrays will not be ready for operational use for several years as the technology is still in the experimental stage. A more practical method of reducing the RCS contribution of the aircraft's Radar antenna is by

using an "opaque radome". A radome which is transparent at the wavelength of the aircraft's Radar would enable use of the Radar while not allowing the threat Radar to "see" through to the antenna. Small amounts of RAM effective at the aircraft's Radar wavelength would cover the portion of the spectrum which the opaque radome would let through. Since the energy received from the reflected wave is proportional to $1/R^4$, the RAM would degrade the aircraft's Radar very little and would result in a significant reduction of energy received by the threat Radar's receiver.

Achieving very small RCS on aircraft with RAM material alone is not practical. Covering the B-26 from Figure II-1 with RAM may result in a low RCS, however, the aircraft probably would not be able to fly because of the amount and high density of the RAM. RAM is designed to absorb microwave energy and turn it into heat (similar to I^2R loss). Goals for RAM are:

1. Application of RAM should be similar to spraying paint
2. Broad band absorption
3. Insensitive to polarization
4. Insensitive to aspect angle

Perfect RAM material has the impedance of free space (377 ohms). In this case, incident waves are not reflected. Paint-like RAM tends to be effective only in narrow band widths because as incident waves impinge the surface they are gradually absorbed by the material. The degree of absorption tends to be proportional to the thickness of the material. RAM is made up of a number of different materials whose exact composition is highly classified. In general, RAM is composed of

compounds which are absorbent dielectrics with finite conductivity, such as Carbon and ferrites.[12]

Some RAM materials do not absorb but redirect the incident wave. As the wave impinges the surface, some of the energy is absorbed by the RAM and the rest of the main lobe energy is redirected to elsewhere. Using a design typical of the SR-71 leading edge, shown in Figure II-3, results in the Radar energy being redirected by the sawtooth design several times which results in a very low energy reflected wave.

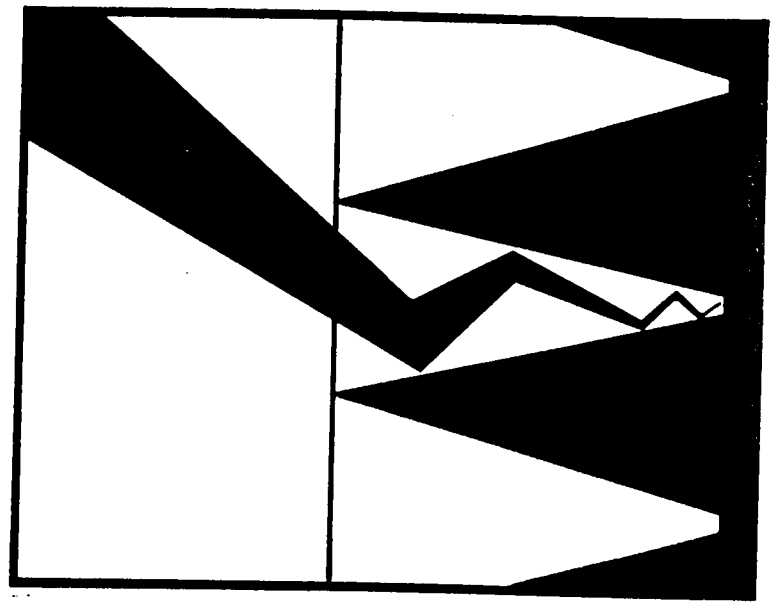


Figure II-3

SR-71 Absorbent Structure

Source: Sweetman, Bill (1986), Stealth Aircraft, pg. 48, Osceola: Motorbooks International

[12]Fuhs, Allen E. (1984), ibid., pg. 113

The high density of RAM result in very heavy material which adversely affects aircraft performance. Additionally, the thickness of material required for absorbing or redirecting waves robs volume from volume limited vehicles. Generally, RAM has low structural strength. Developing RAM with the strength to hold up to the rigors associated with leading edges of control surfaces on high speed aircraft or on helicopter blades is difficult. RAM is extremely expensive to design, install and maintain. The environmental aspects of RAM on carrier based aircraft have yet to be operationally tested. The above listed reasons are justification for only using RAM where shaping fails to result in a small RCS. RAM should be used at retroreflector problem areas, such as, intersections of wing to fuselage, internal cockpit boxes, ejection seats, etc... Contribution of retroreflectors to RCS, such as a black box on a shelf in the cockpit, can be estimated by the following equation for trihedral corner reflectors:

$$\sigma = 12\pi x^4/\lambda^2$$

Where x = length of the retroreflector and λ is the wavelength. A box 0.2 m long detected by a Radar with wavelength of 0.5 m, results in a RCS of 742 m^2 or 29 db.

Supersonic Flight

Electrostatic disturbances in the atmosphere are generated by supersonic flight. These disturbances can be detected by Radar. Electrostatic field generating techniques used in the leading edge of the B-2 may help reduce RCS by masking thermal signature created by

aerodynamic perturbations of the air.[13] Negatively ionizing the atmosphere ahead of the aircraft along with charging leading edges to the same polarity tended to alter the flow path molecules.

Summary

The best technique for reducing RCS is shaping the airframe to reflect very little wave energy toward the threat. RAM should only be used where shaping alone cannot keep RCS at an acceptable level. While reducing RCS to a very small level contributes greatly to reducing detectability, the aircraft is still open to exploitation in the rest of the electromagnetic spectrum. Specifically, an aircraft designed to have a low RF RCS without its electro-optical emissions taken into account, will have a significantly reduced chance of survivability.

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[13]Scott, William B. (1992), "'Black World' Engineers, Scientists Encourage Using Highly Classified Technology for Civil Applications", Aviation Week and Space Tecnology, March 9, 1992, pg. 67, New York: McGraw-Hill

Chapter III

ELECTRO-OPTICAL SIGNATURE REDUCTION

Overview

This chapter will cover a brief discussion of electromagnetic theory as it applies to the electro-optical (EO) spectrum and Infrared (IR) detection. Detecting an aircraft by exploiting the electro-optical energy released, primarily by the engines, is the second best way to find an aircraft. A technological breakthrough in the sensitivity of electro-optical detectors has been made in recent years making this method of detection a serious threat. F-14 airplanes have been detected up to 60 km with a tail-on aspect by F-117 airplanes with the infrared acquisition and designation system (IRAD).[14] One distinct advantage of electro-optical systems is that they are passive systems. A conventional Radar will set off indications in the cockpit which identify the type of Radar and its approximate location. This enables the pilot to take action and neutralize the Radar. With an electro-optical system, the pilot does not know he has been detected until a missile is launched and he sees it (or a plume detector on the aircraft sees the missile trail). Plume detectors were one of several methods used during Desert Storm in finding Iraqi Scud missiles as they launched.

Laser Radar technology is expanding rapidly as a spin-off of Strategic Defense Initiative (SDI) research. Laser Radar may prove

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[14] Jane's Defence Weekly, 22 February 1992, "F-117 Has Air Combat Ability", pg. 276, Vol. 17, No. 8, United Kingdom: Sentinel House

airplanes designed for stealth in the conventional Radar frequency band obsolete. This technology shows extreme promise in the terminal guidance of missiles as well very precise detection of target aircraft. The disadvantage of a Laser Radar is it must actively emit radiation, as a conventional Radar does, which means the pilot will know when his aircraft is being illuminated and approximately where the Laser is.

In general, the advantages of EO systems as compared to RF systems are:

1. Passive detection (visual and IR).

2. Difficult to conceal targets (virtually all military targets dissipate heat).

3. Very accurate position determination resulting from the narrow beamwidths possible with EO sensors.

4. Greater information bandwidth from the extremely high EO carrier frequencies.

5. Narrow beamwidth and bandwidth make intercepting or jamming emissions from EO systems difficult.

The principle disadvantages in comparison with RF systems are:

1. Much greater atmospheric absorption which greatly reduces range (IR and Laser systems cannot see through clouds).

2. Prevalence of natural clutter and noise in the IR region.

Discussion of Electromagnetic Theory

The optical frequencies of the electromagnetic spectrum are infrared, visible and ultraviolet radiation. This band is bordered by extremely high RF on the lower end and x-rays on the upper end.

Appendix A depicts the spectrum. Conventional (RF) stealth technology applies to L-band Radar through K_a-band. As can be seen from Appendix A, there are many frequency ranges for which aircraft detection is possible. Of particular interest are the IR, visible and ultraviolet (UV) spectrum.

Lambertian Sources

All bodies above absolute zero degrees emit electromagnetic radiation which produces a thermal image or plume. The problem in developing electro-optical detectors is defining the energy flow of essentially incoherent radiation fields. Incoherent radiation refers to radiation of different amplitudes and phase. Assuming electro-optical sources from aircraft to be incoherent, and the propagation of radiation through empty space and optical systems can be treated using the laws of geometry, the Radiometric Quantities and Units in Table III-1 apply in defining electro-optical sources.

Table III-1

Radiometric Quantities and Units

Quantity	Symbol	Definition	Unit
Radiant energy	dQ	Φdt	J
Radiant energy density	u	dQ/dV	J/m^3
Radiant flux (power)	Φ	dQ/dt	W
Radiant exitance	M	$d\Phi/dA$	W/m^2
Irradiance	E	dF/dA	W/m^2
Radiance	L	$d^2\Phi/dA_{proj}d\Omega$	W/m^2 sr
Radiant intensity	I	$d\Phi/d\Omega$	W/sr

The radiant exitance (M) is the flux per unit area leaving the surface of a source of radiation and is the primary concern of the designer minimizing electro-optical emissions of an aircraft. Radiant exitance is dependent on the energy of the source (which is directly related to temperature), and the radiant flux. Empirical deduction shows most incoherent radiation sources produce radiation which is approximately independent of the angle of observation.[15] A Lambertian source is one whose radiance is independent of viewing angle. Obviously, avoiding Lambertian sources should be avoided when designing for stealth. A good approximation of a Lambertian scatterer is white paper except at grazing incidences of observation. No matter which angle the paper is viewed from, the brightness of the paper does not change at a set distance. However, if the same piece of illuminated paper is masked with vertical black slats, as shown in Figure III-1, the radiance of the paper when viewed at oblique angles approaches zero. When the paper is viewed at a normal angle of incidence, the paper has a large radiance.

[15]Boyd, Robert W. (1983), Radiometry and the Detection of Optical Radiation, pg. 20, New York: John Wiley and Sons

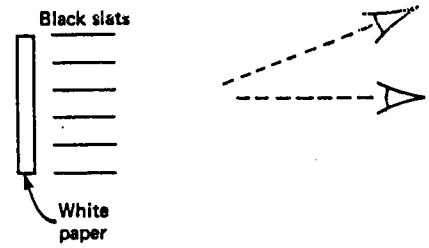


Figure III-1

Non-Lambertian Source

Source: Boyd, Robert W. (1983), Radiometry and the Detection of Optical Radiation, pg. 22, New York: John Wiley and Sons

For a point Lambertian source, i.e. distance the source is viewed from being much greater than the radius of the source, the radiant flux (Φ) on an area detector at a certain distance (r) from the source is given by the following equation:

$$d^2\Phi = L_o(dA_o)(dA_1)/r^2 \qquad \text{(Watts)}$$

L_o is the radiance of the source, A_o is the area of the opening of the source and A_1 is the area of the detector. Radiant flux is proportional to the inverse square of the distance from the source.

A jet engine can be considered to be a non-coherent Lambertian source. For this reason, masking the intake and exhaust ducts of engines with vertical slats reduces the IR signature at other than normal aspect angles. If designed with thrust vectoring in mind, the

baffled ducts have three purposes. Reduction of IR signature, reduction of RCS, and possible enhancements to performance with thrust vectoring.

Black Body Radiation

Electromagnetic radiation exhibits both particle and wave characteristics. The behavior of the radiation is dependent on the frame of reference. On the scale of a system of molecular or atomic size, quantities being measured are in the quantum domain. Systems of the size of an aircraft are considered non-quantum. The previous paragraphs have dealt with the non-quantum domain, or rather the wave theory portion. Whenever electromagnetic radiation interacts with matter the result can be described in particle-like terms. However, as described in the previous paragraphs on Lambertian sources, electromagnetic radiation can be diffracted which is a wave-like phenomena. Therefore, the propagation of electromagnetic radiation is wave-like and its interaction with matter is particle-like.[16]

A jet engine approximates a blackbody. One of the primary goals of blackbody radiation theory is to predict the spectral distribution of a blackbody radiation field. This cannot be done using non-quantum physics only. The correct theoretical expression for the spectral distribution of blackbody radiation was discovered by Planck in 1900.[17]

Planck based his theory on the atomic processes taking place in the cavity of a black body. His assumption was the atoms which make up the

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[16]Eisberg, Robert M. and Lerner, Lawrence S. (1981), Physics: Foundation and Applications, pg. 1433, New York: McGraw Hill

[17]Boyd, Robert W. (1983), ibid., pg. 39

walls behave as tiny electromagnetic oscillators, each with a characteristic frequency of oscillation. The oscillators both emit and absorb energy from the cavity walls. He further assumed the oscillators can have only energies given by the following equation:

$$E = nh\nu$$

Where n is the quantum number of the energy level of the emitted quanta (or jumps), h is now called Planck's constant (6.626196×10^{-34} joule-sec), and ν is the frequency of the oscillator. This equation asserts the oscillator energy is quantized. Additionally, he assumed the oscillators do not radiate energy continuously; only in quanta. The quanta are only emitted when an oscillator changes from one of its quantized energy states.[18] Quantum theory is valid on the microscopic scale and not necessarily representative of the macroscopic scale. For large scale oscillators (mass-spring type), quantum numbers are huge and quantized nature of the oscillations are not apparent.

The spectral radiance (in frequency units) is given by the following where h is Plank's constant, k is Boltzman's constant, c is the speed of light, and T is the temperature:

$$L = \{2h\nu^3/c^2\}\{1/(e^{h\nu/kT} - 1)\}$$

This is known as Planck's radiation law and is graphically presented in Figure III-2.

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[18]Halliday, David and Resnick, Robert (1974), Fundamentals of Physics, pg. 760-762, New York: John Wiley and Sons

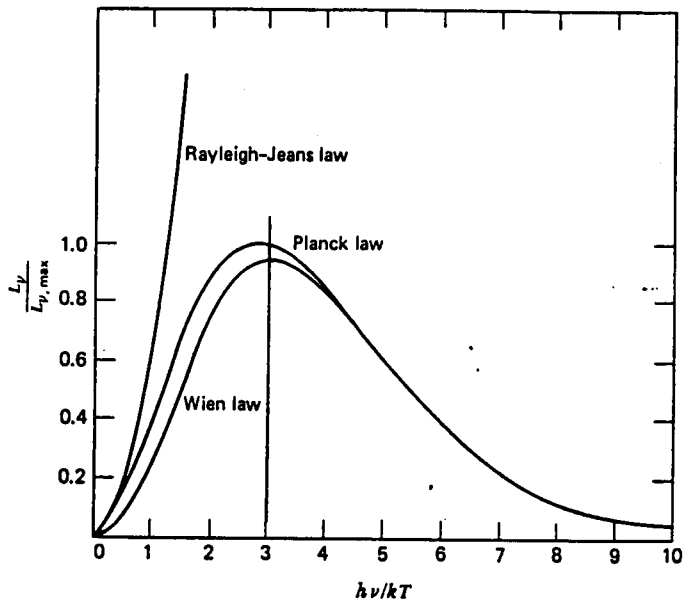


Figure III-2

Normalized Planck Radiation Law (units of frequency)

Source: Boyd, Robert W. (1983), Radiometry and the Detection of Optical Radiation, pg. 52, New York: John Wiley and Sons

The above equation can be written in terms of wavelength and solved for when L_λ is a maximum (Wien's Law):

$$\lambda_{L(max)}T = 2.898 \times 10^{-3} \text{ (m K)}$$

A complete derivation is contained in Boyd, pg.51-55. As an example, an engine with an exhaust gas temperature of 500 °C (773 K) has its peak spectral radiance at a wavelength of 3.8 μm. From Appendix A, this wavelength is just about the middle of the spectrum at which the majority of IR seekers are effective.

Radiation temperature is the variable which determines spectral radiance. Figure III-3 demonstrates the Planck radiation law for a

blackbody at several temperatures. It is important to note that the curves on the figure never cross. This shows the value of the Planck function at a single wavelength uniquely defines the temperature of the source. Even a source which is not a blackbody can be described at any wavelength by its radiation temperature.

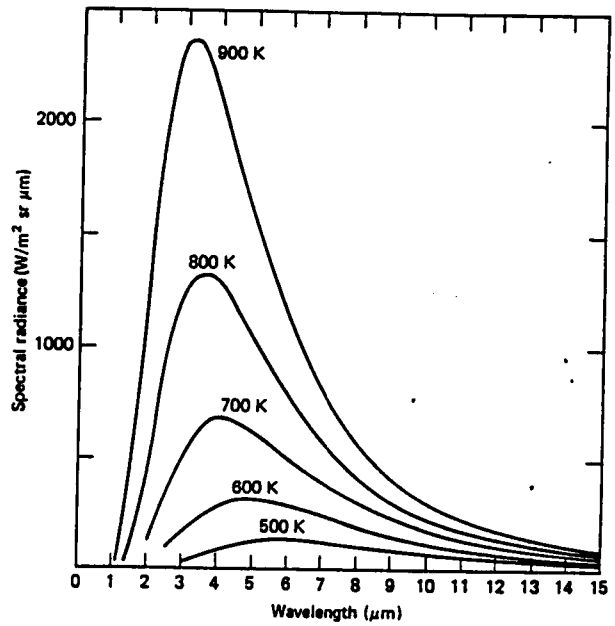


Figure III-3

Planck Radiation Law for Several Blackbody Temperatures

Source: Boyd, Robert W. (1983), Radiometry and the Detection of Optical Radiation, pg. 61, New York: John Wiley and Sons

The important point in terms of detection is, the hotter the exhaust gas the further away detection is probable because of the higher spectral radiance discounting atmospheric absorption. The largest band of atmospheric absorption of IR energy (CO_2 and H_2O) occurs between wavelengths of 5.5 - 8 μm. This corresponds to a temperature range of 254 - 89 °C. 254 °C is an average idle exhaust gas temperature for most jet engines. A jet engine with a 500 °C exhaust gas temperature is

close to where maximum transmission for H_2O occurs in the atmosphere. Since the primary mediums for IR propagation in an exhaust plume are CO_2 and H_2O , this is good if one intends to minimize the detectability of an aircraft as approximately 10% of the plume is made up of these gases. Appendix B contains the approximate concentrations of engine combustion products which make up the exhaust plume.[19]

For supersonic aircraft, the temperature of the leading edge reaches approximately 65 °C at about 1.25 MACH (sea level) due to kinetic heating. All aspect IR missiles will detect radiance associated with a temperature this low, but the spectral radiance is very low requiring the seeker to be very close to the aircraft for a lock. More of a threat are thermal imaging systems which operates in the 7.5 - 14 μm transmission window. Infrared tracking systems are becoming more of a threat as the technology advances.

Reducing IR Signature

There are actually two problems with regard to reducing the IR signature of the engine exhaust. The first is reducing the aspect angle from which the hot section of the engine/tailpipe can be "seen", and the second is reducing the temperature of the exhaust gas itself. The temperature of the plume could be outside the window of detection for an IR seeker but if the seeker is looking directly at the source, it will still track the target. Appendix C shows the components of a typical jet engine configurations.

[19]Oates, Gordon C. (1989), Aircraft Propulsion Systems Technology and Design, pg.138, Washington D.C.: American Institute of Aeronautics and Astronautics

Vertical black slats will reduce the aspect angle from which the hot section of the engine can be seen but will do little in reducing the temperature of the exhaust gas. Methods of reducing exhaust gas temperature are all dependent on cooling the engine liner with ambient air and then cooling the exhaust gases before leaving the tailpipe. Some of the methods for cooling the liner are listed below (Figure III-4 depicts the different techniques):

1. Louver cooling. This technique was primarily used on early jet engines and consisted of a liner fabricated from a number of cylindrical panels. This provided a series of annular air passages. These allowed a film of air to be injected along the hot side of each panel providing a thermal barrier. This technique did not work particularly well because of the nonuniformity along the walls and severe metal temperature gradients.

2. Film cooling. This technique uses machined injection holes instead of louvers. Airflow metering is more accurate and cooling more uniform. Current engines use this technique. However, this technique is not sufficient to cool exhaust gas to an undetectable level.

3. Convection/film cooling. This technique permits much reduced airflow but much greater cooling efficiency and uniform metal temperatures. This technique is suited for the high temperature rise combustion of more advanced engines. Similar in appearance to the louvered technique, this design provides a much more efficient system but is heavier and more complex.

4. Impingement/film cooling. This is well suited to high temperature rise combustion. Like convection/film cooling, this is a very efficient method but it is heavier and more complex.

5. Transpiration cooling. This is the most advanced cooling scheme available. Cooling air flows through a porous liner simultaneously providing a thermal barrier. Several materials are being experimented with. The fabricated porous transpiring materials like Lamilloy (developed by Detroit Diesel Allison, General Motors Corp.) alleviate plugging and contamination problems associated with conventional transpiring material.

Cooling the liner may seem trivial in comparison to cooling the exhaust plume. However, the advent of IR imaging and tracking systems has enabled tracking the hot section of the engine at virtually all aspect angles (except where the exhaust plume blanks out the hot section). Keeping the emission wavelength in the 5-8 μm region is important. Figure III-5 shows liner cooling characteristics for the methods listed above. Transpiration cooling appears to be the best solution for liner cooling.

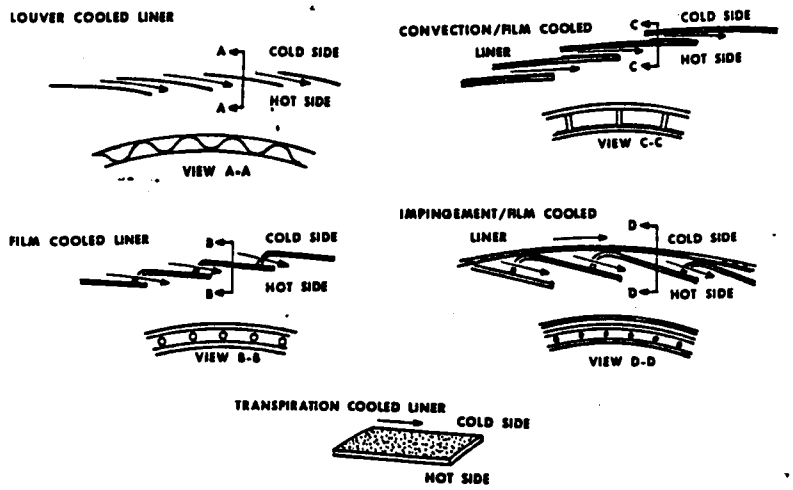


Figure III-4

Cooling Techniques

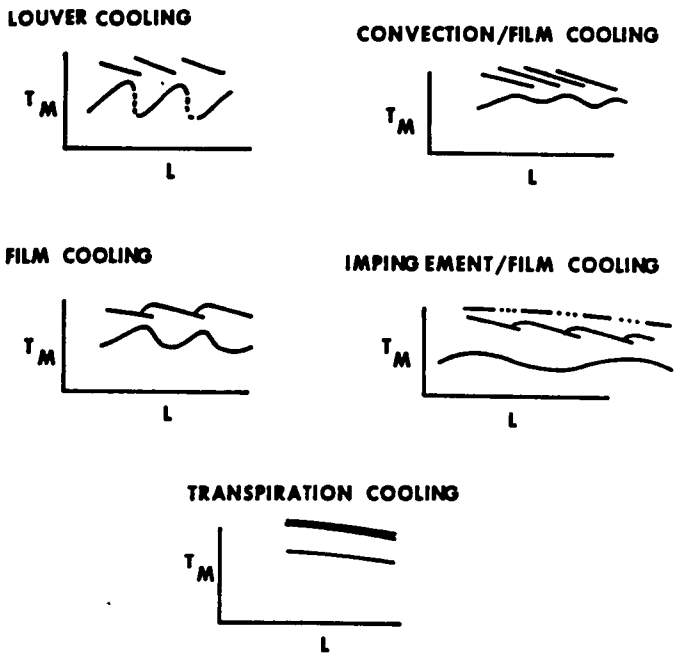


Figure III-5

Liner Cooling Characteristics

Source: Oates, Gordon C. (1989), Aircraft Propulsion Systems Technology and Design, pg. 125-127, Washington D.C.: American Institute of Aeronautics and Astronautics

Low Infrared and Low Reflectance Coatings

Solar spectral irradiance occurs primarily in the 0.45 - 2.7 μm (near and mid IR) region. The atmosphere transmits contrast in this bandwidth very well because aircraft paints have different UV and IR reflectances than their backgrounds. Figure III-6 shows the spectral distribution of the sun's energy.

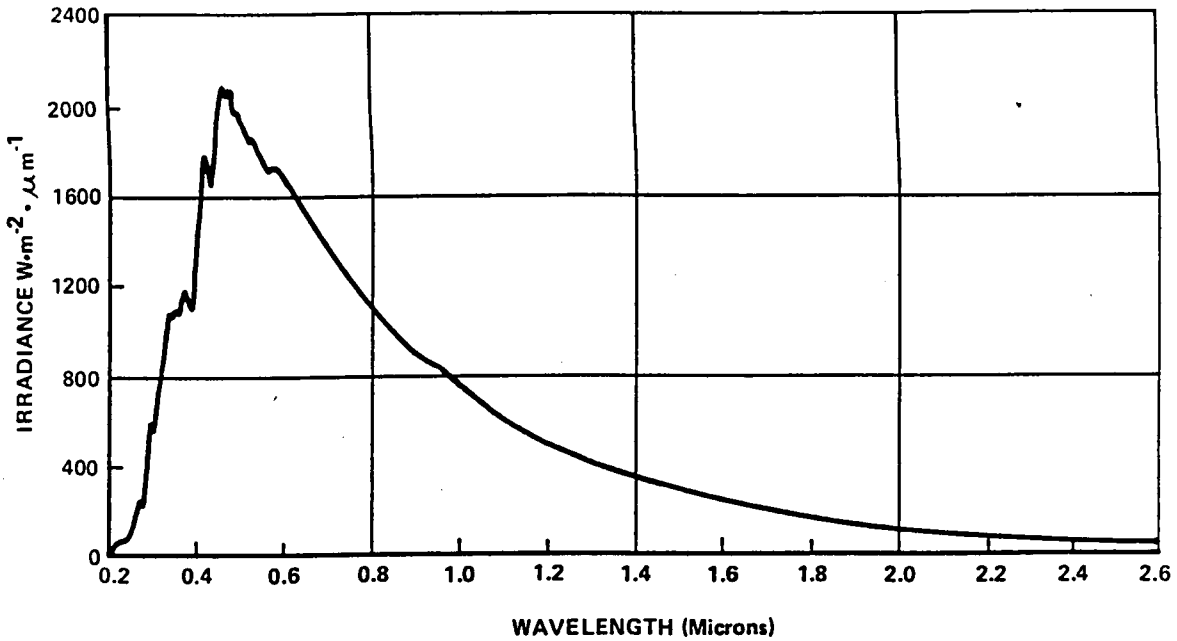


Figure III-6

Solar Spectral Irradiance

Source: Calspan Corporation (1985), Camouflage Handbook, Final Report AFWAL-TR-86-1028, pg. 1.4-3 Wright-Patterson Air Force Base: Air Force System Command

High glossy exterior aircraft coatings are very susceptible to IR tracking devices. A mirror like reflection from glossy surfaces near 1μm produces a signature in the passband of several missiles. Paint schemes were developed which minimize the capability of tracking devices to lock onto painted surfaces which reflect in the near to mid IR

regions. Coatings were developed with IR countermeasure capabilities, protective coating properties, and acceptable surface finish, the following criteria were considered:[20]

1. Coating should exhibit low sheen and contain specific additives to obtain low reflectance in the desired wavelengths.
2. Selected near IR topcoats should exhibit chemical and physical properties comparable to standard high gloss topcoats.
3. Low IR topcoats should provide a smooth aerodynamic finish.

The coatings were developed to be "transparent" in the near IR (0.45 - 2.7 μm) region with a total reflectance of less than 10%. The best product was a low IR corrosion inhibitive primer formulated with additives to lower total reflectance to 8% when scanned in the near IR field. The primer was then covered with a topcoat of gray camouflage (Navy aircraft) or various green camouflage schemes. The highly diffuse schemes significantly reduced the aircraft's near IR detectability as well as reduced visual acquisition distances.

Turbofan Engine

Cooling the exhaust gas presents a much more difficult engineering problem. The best designs to date involve mixing ambient ram air and ducted air from the fan section of the engine (assuming a turbofan engine) with the exhaust gases in a mixing chamber large enough to cool the plume to a level where the spectral radiance is lower than the IR

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[20]Charves, E. (1977), Development of Low Infrared and Low Reflecting Coatings, Final Report NADC-77103-30, pg. 9, Warminster: Naval Air Development Center

detector's noise threshold. Or, where the radiant emissions wavelengths are primarily in the maximum atmospheric absorption band of 5-8 μm.

The best type engine for a stealth application is the turbofan engine. The dual compressor turbofan with afterburner shown in Appendix C is perfectly suited for cooling the exhaust gas. An added advantage of the turbofan engine is its low noise level as compared to a turbojet. The turbofan has at least one additional turbine to drive the fan which significantly reduces the velocity of the engine exhaust and subsequently, noise.

The variables involved with matching an engine to a specific airframe, or application, are well beyond the scope of this study. A few variables for consideration follow:

1. The bypass ratio (BPR) of a turbofan is ducted airflow/primary airflow. As BPR increases, the propulsive efficiency increase as does the weight of the engine. The effect of increased propulsive efficiency is a decrease in Thrust Specific Fuel Consumption (TSFC). The limiting factor of the BPR is weight. As BPR increases, so does the weight of the drive turbine and associated fan. AS BPR gets very large (5.0 or more), reduction gear boxes are required to slow fan speed in order to prevent high sonic losses. For typical fighter aircraft, the BPR is approximately 1.15.[21]

2. In most cases the higher the BPR, the larger the diameter of the fan rotor. This increases the inertia of the engine which negatively impacts power response. Power response is critical in terms of carrier suitability. Instant power addition or reduction is desired

[21]Course Notes on Propulsion (1984), USNTPS: Patuxent River

when a throttle movement is initiated. An example of good power response is the J79 engine as installed in the F-4. An example of poor power response is the TF-41 as installed in the A-7. However, fans are generally superior to pure jets in this respect. Evidence of this is the GE F-404 engine as installed in the F/A-18. Technology has enabled advanced digital fuel control techniques and burner flow patterns to overcome many drawbacks of turbofan engines while keeping the attributes.

3. Baffles around the engine inlet help in reducing engine exhaust temperature. However, they increase the frontal area of the aircraft resulting in a larger geometric cross-section. This could lead to a larger RCS negating the effect of reducing engine exhaust temperature.

Reducing the spectral radiance of the exhaust plume is necessary, however, it should not be done at the expense of severely degrading power response or increasing RCS. Exact numbers are classified, but the ability to reduce the temperature of the exhaust plume several hundred degrees in non-afterburning engines has been demonstrated. An advanced technique used on the B-2 is based on an electrostatic heat transfer phenomenon which charges the exhaust stream to disperse the heat. Reduction of the thermal signature by a factor of 800 has been observed.[22]

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[22]Scott, William B. (1992), ibid., pg. 67

Afterburner Capabilities

First, if the airplane is equipped with an afterburner, it should not be used when the IR threat is predicted to be high. The temperature of an afterburner plume is approximately 2500 °C which has a very large spectral radiance making the aircraft very detectable. Cooling the afterburner plume is not really an option because it would be very difficult to design a mixing chamber aft of the burner section large enough to cool the plume appreciably. The debate on whether an afterburner is worth the expense on a stealth aircraft continues. The pilot should have the option of generating energy quickly if all the designed stealth technology fails and he is faced with defeating an immediate threat. The advantages of a capability which enables the pilot to rapidly increase his energy state far outweighs the disadvantages of an afterburner.

Afterburning engines generally imply supersonic capabilities. As previously stated, leading edge temperatures can easily reach 65 °C. A method of cooling leading edge surfaces is needed to reduce the possibility of thermal imaging. Fuel, routed through the leading edges has been successfully used on the SR-71 for keeping the surface temperature down. The added weight of the cooling apparatus and associated engine feed fuel coolers is well worth the effort in terms of reducing electro-optical cross section.

Summary

The primary objective of reducing the electro-optical signature of an aircraft is to cool the exhaust plume as much as is practical. This

is best done with turbofan engines with as high a bypass ratio as possible with consideration given to aircraft carrier suitability and possible increases in RCS.

Another option is to design the aircraft with a definite cold side and hot side. The F-117 is an example of this technique. A mid to high altitude bomber could have a cold underside routing exhaust gases through the top of the aircraft. This would reduce the probability of IR detection from ground based Radar sites.

Afterburning engines obviously increase the IR signature of an engine when it is used. However, when all other stealth characteristics have failed, the afterburner provides a method to the pilot for instant energy generation.

Chapter IV

LASER RADAR

Overview

Laser Radar is developing into one of the most accurate methods for terminal guidance of missiles. The shortness of the wavelength (approximately 10 μm for infrared systems) of these Radars resulted in very precise angular resolution for small antenna sizes. The very narrow beamwidth associated with high angular resolution allowed extremely precise pointing and tracking to be achieved. The short wavelength implies high frequency which results in extremely accurate velocity measurements due to the large Doppler shift with modest target velocities. The high frequencies of Laser Radar implies a potential for high system bandwidths. Bandwidths larger than 1 GHz have been achieved at 10 μm wavelength and bandwidth-limited pulse of duration shorter than 100 nsec are easily achieved.[23] Range resolutions of 0.1m are achievable. Clear weather attenuation of Laser Radars is approximately 0.5 db/km. This limits ground based or low altitude airborne Radars to approximately 10-20 km (infrared type systems). Nominal bad weather reduces useful range to approximately 3-5 km. High altitude range performance is much better.

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[23]Harney, Robert C. (1981), Proceedings of SPIE - The International Society for Optical Engineering, "Physics and Technology of Coherent Infrared Radar", Vol. 300, pg. 3, Bellingham: SPIE - The International Society for Optical Engineering

Operational Employment

Expected employment of this system is in conjucntion with other sensors (RF Radar, passive IR, visual). Current development is in systems which provide precision tracking of incoming aircraft or missiles and subsequent command guidance for interceptor missiles.[24] Developments in data processing have enabled employment of some of these systems with operational units.[25]

Laser RCS Reduction

Because of the narrow beamwidth and high frequency associated with these systems, shaping of the aircraft does not significantly reduce reflectivity. A very small imperfection in the aircraft's skin will cause a large Laser RCS. As an example, one possible application under development is as a power line detector for low flying aircraft. The primary method in defense of these types of systems will be some type of Laser RAM. For an IR type Laser this essentially requires a flat black paint scheme which has very low IR reflectance.[26] Unfortunately, little research has been done in this area as the systems are not prevalent yet.

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[24]Harney, Robert C. (1981), ibid., pg. 6

[25]Becherer, Richard J. (1990), Proceedings of SPIE - The International Society for Optical Engineering, "Laser Radar V", Vol. 1222, Bellingham: SPIE - The International Society for Optical Engineering

[26]Kennedy, William S. (1974), Infrared Countermeasures Prototype Program Summary an Test Results, ASD/YPS 74M-04, pg. 46, Wright-Patterson AFB: Aeronautical Systems Division

Chapter V

VISUAL ACQUISITION

Overview

Reducing the visual cross section of aircraft has evolved into a semi-art and science ever since military aircraft have been flying. Even today, in the age of very outstanding Radars of all types, the best way to defeat an aircraft is to acquire it visually and employ weapons to shoot the aircraft down. Obviously, this should be done before the pilot of the aircraft has visual acquisition on his target.

Camouflage, which blends the aircraft in with its background, and paint schemes which confuse an aircraft's orientation are the primary methods of defeating visual acquisition. An example of a good camouflage technique is the SR-71. The black paint scheme blends the aircraft with its normal operating environment (fringes of space). A bad example of this technique would be painting an aircraft black which is primarily designed as a day, low altitude penetrator. Figure V-1 is an example of this. These aircraft are acquired from above at distances up to 15 nm. An example of a deceptive paint scheme is the CF-18 Hornet. These aircraft have a cockpit painted on the belly. The effect can temporarily confuse an opposing pilot during air combat maneuvering (dog-fighting). Determining the direction of the opposing aircraft's lift vector is very important when determining the best course of action in response to maneuvers by the opposing aircraft. A moments hesitation could prove fatal.

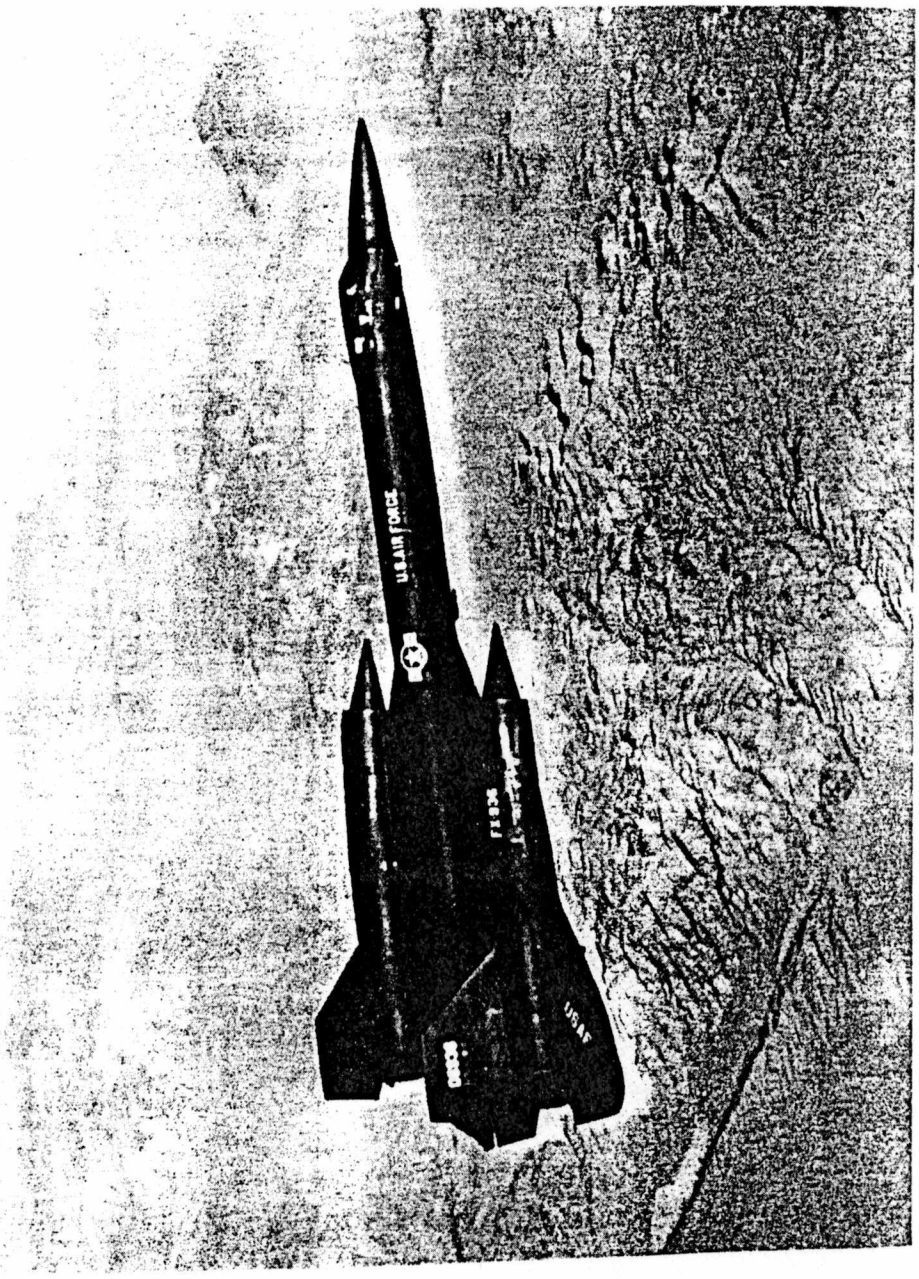


Figure V-1

SR-71 With Desert Background

Source: Calspan Corporation (1985), Camouflage Handbook, Final Report AFWAL-TR-86-1028, pg. 2.4-12, Wright-Patterson Air Force Base: Air Force System Command

The predominant factor in determining an aircraft's visual detectability is the reflectance of the paint scheme. Different colored paints have a different Luminance for the same illumination because they have different reflectances.

A number of USAF tactical aircraft and most all Navy aircraft are painted a very dull gray with virtually zero contrast between insignia, side numbers, etc... However, a single gray paint scheme cannot match both the aircraft's top and bottom luminance. Therefore, modern paint schemes incorporate different reflectance paints between top and bottom as well as some paint pattern optimized for the predicted operational environment. The countershading technique applied to F-16 and F-15 aircraft is very effective in reducing the visual detectability of the aircraft. Figure V-2 is an example of a countershading gray paint scheme.

The objective of countershading is to reduce the aircraft's detectability by making it indistinguishable from background clutter. For example, an F-15 with an all gray paint scheme when viewed from planform in some type of engagement will have some reflectance depending on sun angle. By shading the center portion of the wing and fuselage, the reflectance is reduced hopefully delaying visual detection. The object is to employ several different shades so part of the aircraft is of negligible luminance. This technique reduces effective area contrast.

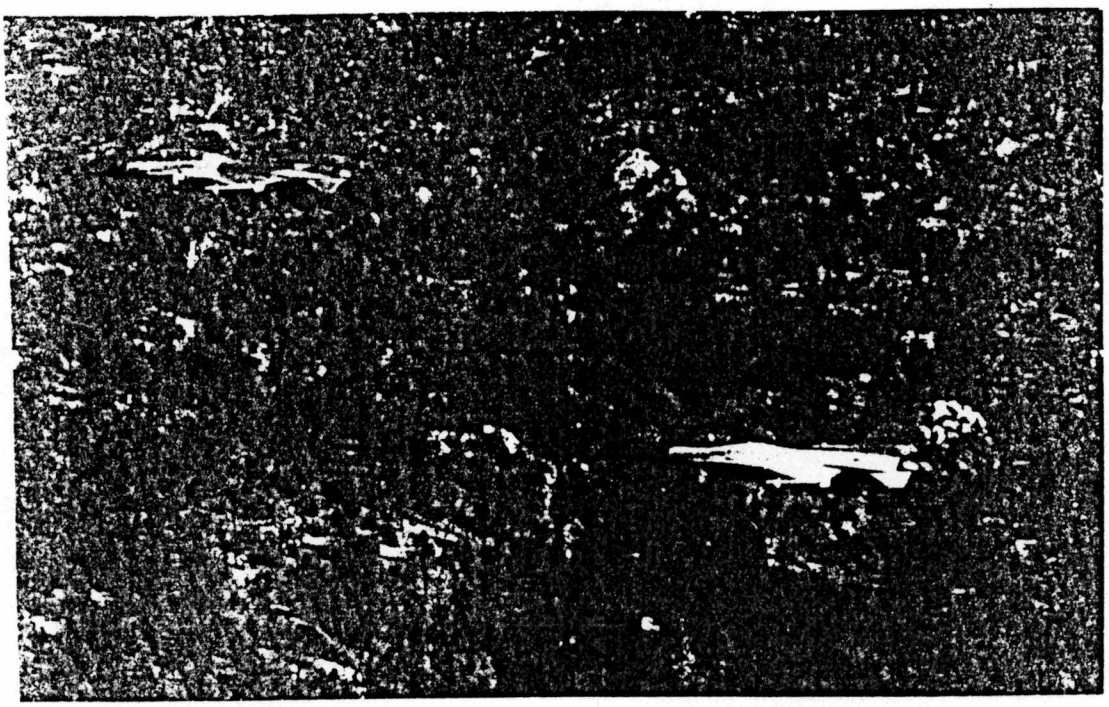


Figure V-2

Gray and Gray Only Countershaded F-16's (Vegetation Background)

Source: Calspan Corporation (1985), Camouflage Handbook, Final Report AFWAL-TR-86-1028, pg. 1.1-4, Wright-Patterson Air Force Base: Air Force System Command

In general, a paint scheme should be selected which delays detection or generates confusion for the part of the aircraft's operational profile most significant to survivability. Reflectance values of the paint are the most important factor of camouflage, with pattern and color as secondary factors. The trend of modern paint schemes is toward grays and away from traditional camouflage blending. Appendix F summarizes paint schemes currently in use

Other Factors

Contrails produced by condensation of exhaust gases enables visual location of an aircraft. Visual detection is only limited by the earth's horizon and prevailing visibility. The location of an aircraft can be accurately determined at ranges of 60 nm or more simply by following the trail to its head. Contrails are normally produced at altitudes above 30,000 ft but can be produced lower altitudes depending on specific humidity and temperature. Fuel additives aid in suppressing contrails; however, the best method is to fly below an altitude where there is a high probability of contrail formation. The probability of contrail formation is routinely calculated by military weather forecasters.

Second to contrails, Exhaust smoke is the best method of detecting an aircraft at altitude (sky background) visually. Smokeless engines are an absolute necessity. Table V-1 contains visual detection ranges made by F/A-18 pilots with experience levels ranging from 1000-3000 total flight hours. A sample data card is shown in Appendix D.

Table V-1 depicts detection distances under operational conditions. Pilots were actively looking for targets as well as operating Electronic

Warning systems and keeping track of their wingmen. In other words, there were many changing variables. Therefore, conclusions on a certain type paint scheme as being better than the other cannot be ascertained from V-1. However, it does show producing shadows on the ground and engines which smoke excessively against a sky background will result in relatively quick detection. Appendix E shows minimum altitudes for avoidance of shadows. External stores also increase visual detection ranges. This mainly is attributed to high contrast in colors between the aircraft and the stores.

Table V-1

Detection Ranges

TYPE A/C	RADAR/HUD[1]	BACKGROUND[2]	VISUAL CUE	RANGE(nm)
A-6	YES	TERRAIN	SHADOW	5.5
A-6	YES	SKY	WING FLASH	9.0
A-6	NO	MOUNTAINS	PLANFORM	~3
B-2	NO	SKY	PLANFORM	~15+
F-4	YES	SKY	SMOKE	16.3
F-4	NO	SKY	SMOKE	~12
F/A-18	YES	TERRAIN	SHADOW	4.5
F/A-18	YES	SKY	PLANFORM	14.0
F/A-18	YES	SKY	NOSE	3.2
F/A-18	YES	TERRAIN	SHADOW	4.8
F/A-18	YES	MOUNTAINS	WING FLASH	2.7

1. Aircraft was detected by Radar which displayed an approximate location of the aircraft on the pilot's Head-up Display (HUD).
2. Data were obtained during day, clear air (visibility of 50+ miles) conditions and in a desert environment.

Night Considerations

Flying at night does not necessarily mean visual detection has been reduced to zero even if the pilot has done the obvious and turned the external lights off and dimmed cockpit lighting to the lowest possible level. Nighttime detectability of aircraft during World War II led to the development of two black paint schemes, termed "Coffin" and "Black Widow".[27] The Coffin paint formulation resulted in a 2.2 percent luminous reflectance. However, when the aircraft was illuminated with searchlights it appeared white in high contrast to the night sky. This led to the use of Black Widow with a luminous reflectance of 0.1

[27]Bush, V. (1946), Visibility Studies and Some Applications in the Field of Camouflage, DDC No. AD 221102

percent. This paint scheme was a black gloss which was detectable at much more restrictive viewing geometries than the Coffin scheme. B-52's were flown in Southeast Asia during the Vietnam War with high gloss black paint applied to the bottom of the aircraft.

Summary

The B-2, F-117, SR-71 and A-12 were all painted in black paint schemes which gives an idea of there predicted operating environments. Day, low-altitude missions would greatly increase the probability of detection of these aircraft with black (low IR) paint schemes. Visual camouflage is just an important part of stealth design as low RCS.

Chapter VI

CONCLUSIONS

Specific

Threat systems have been developed which consist of an integrated Radar, IR, Laser Radar and Optical tracking devices. Future aircraft will have to be designed for minimum detectability for virtually the entire electromagnetic spectrum in order to be survivable. The following are specific conclusions for reducing the total detectability of an aircraft:

RCS

- Reducing RCS is more than coating the aircraft in RAM and expecting zero detectability. Shaping is the primary determinate in the magnitude of the RCS. RAM should be used to cover imperfections in the aircraft's skin, at known corner reflectors and on any surface which could be normal to a threat Radar site (leading edges). Wing sweep, as well as control surface cant in the vertical, should also be used to reduce the possibility of having a surface normal to a threat.

- One of the largest contributors to RCS is the large frontal area of the engines. Reducing the engines' contributions to total RCS is one of the biggest engineering obstacles. Effectively hiding the frontal area of the engine by aircraft design is one technique but there are many tradeoffs in terms of fuel and possible payload. The best techniques appear to be curved intakes with RAM placed at strategic points to absorb energy. The idea of the design is to cause the

incident energy to bounce as many times a possible and eventually be absorbed by RAM.

- Coating an aircraft in RAM significantly increases the weight which severely degrades performance. So this material should be used only at critical reflectance points. The type of RAM used today consist of ferromagnetic particles suspended in a dielectric plastic. The dielectric reduces the energy of the incident wave and the ferromagnetic particles absorb it. The total pathway of energy within the RAM should equal half the wavelength of the Radar. The theory is some portion of the incident wave will travel through to the aircraft's structure and then reflect out through the RAM where the rest of the wave energy will be absorbed. RAM can be much thinner than the nominal wavelength of the Radar and still achieve cancellation, because the wavelength within the material is much shorter than in free space.

- RCS contribution from the cockpit can be reduced by proper design combine with canopies and windscreens coated with Indium-tin Oxide. This type coating reflects Radar energy while passing 85 percent of the visible spectrum.

- Reduction of the thermal signature of aircraft by electrostatic charging of the atmosphere around the aircraft has led to a reduction in RCS on aircraft such as the B-2.

Infrared Signature Reduction

- IR coating or paints reduce total IR emissions from the aircraft by a factor of ten without adding significant weight or detracting from the effectiveness of RAM coatings.

- The hottest part of the aircraft is the engine tailpipe and exhaust. Masking the tailpipe can be accomplished by embedding the engine in the fuselage and exhausting the over an aerodynamically shaped lip which bends the flow back in the proper direction (F-117 technique). This gives the aircraft a very distinct hot and cold side.

- High BPR fan engines exhaust gas temperatures are significantly cooler than turbojet engines which reduces IR signature.

- Electrostatic charging of the exhaust gas reduces temperature by a factor of 800 by the electrostatic heat transfer phenomena. This is employed on the B-2.

Camouflage

- Blending the aircraft into its operating environment is absolute necessity. Visual acquisition of a target is the best way to guide a weapon to the target.

- The reflectance of the paint is more important than color in terms of blending an aircraft with its environment. Choosing the correct reflectance is dependent on the aspect from which the aircraft is viewed.

- Deceptive techniques, such as the cockpit painted on the underside of the fuselage on the CF-18, are outstanding for temporarily confusing an opponent.

Summary

Stealth does not mean invisible. Any Radar or Electro-optical detector will detect a stealth aircraft if the range is close enough.

Stealth must work in concert with other factors in order to be of value. Specifically, the aircraft must be in its designed operating environment and it must have an accurate threat missile warning system.

Chapter VII

RECOMMENDATIONS

General

A very important item in designing a stealth aircraft is to defining the operating environment. Will the aircraft be employed at night minimizing exposure to threat Radars through accurate mission planning, or will it primarily be a day bomber constantly in the threat envelope? The design should be developed as a total package starting from how the pilot of the aircraft will plan his mission and how threats along the ingress route will be defeated to how weapons will be employed.

Specific

- Definition of the operating environment is exceptionally important.

- Development of a mission planning system compatible with the design of the aircraft are needed to complete a total weapon system package concept. The capability exist to accurately plan routes which minimize aircraft exposure to known threats. However, the majority of these systems are not compatible with aircraft in inventory today. Significant dollar savings can be realized by reducing the amount of stealth technology required if this planning system was accurate and compatible. This will enable the aircraft to thread the gaps in coverage by threat systems or make an accurate assessment of the best

way to manage the signature of the aircraft if it were to fly directly through a high threat zone.

- Decisions on the type of missile warning/missile defense systems required for the best aircraft survivability must be taken into account. Active systems, such as the ALQ-126B and ASPJ, have strong points but consideration should be given to using these type systems on stealth aircraft. These system could provide a beacon for a missile to home on. An accurate (zero false alarm rate) system is desired to let the pilot know if he is being targeted and if a missile has been launched and from where. This is particularly important in the case of Laser Radar and IR seeking missiles. Advanced warning enables the pilot to maneuver or a last ditch automatic system to engage the inbound missile. One the most powerful countermeasures in any aircraft is the pilot's situational awareness.

- One of the most promising as pects of stealth technology would be the continued development of reactive coatings. Theoretically, these coatings receive the incoming wave, compute the magnitude and direction, then send an exact replica of the wave half a wavelength out of phase.

Bibliography

Bachman, C.G., Laser Radar Systems and Techniques, Dedham: Artech House, Inc., 1979

Becherer, Richard J., Proceedings of SPIE - The International Society for Optical Engineering, "Laser Radar V", Vol. 1222, Bellingham: SPIE - The International Society for Optical Engineering, 1990

Boyd, Robert W., Radiometry and the Detection of Optical Radiation, New York: John Wiley and Sons, 1983

Bush, V., Visibility Studies and Some Applications in the Field of Camouflage, DDC No. AD 221102, 1946

Calspan Corporation, Camouflage Handbook, Final Report AFWAL-TR-86-1028, Wright-Patterson Air Force Base: Air Force System Command, 1985

Central Tactics and Trials Organization, QWI Handbook, High Wycombe: Royal Air Force, 1981

Charves, E., Development of Low Infrared and Low Reflecting Coatings, Final Report NADC-77103-30, Warminster: Naval Air Development Center, 1977

Conrad, Pelt and Nydahi, John E., Measurement of Missile Position and Attitude, Redstone Arsenal: U.S. Army Missile Command, 1975

Conrad, Robert G. and Brown, David B. (1975), Techniques for Remote Sensing of Missile Position and Attitude, Redstone Arsenal: U.S. Army Missile Command, 1975

Eisberg, Robert M. and Lerner, Lawrence S., Physics: Foundation and Applications, New York: McGraw Hill, 1981

Fuhs, Allen E., Radar Cross Section Lectures, New York: American Institute of Aeronautics and Astronautics, 1984

Grossman, Jeffrey D., Feasibility Study of a FLIR/Imaging Seeker System, China Lake: Naval Weapons Center, 1977

Halliday, David and Resnick, Robert, Fundamentals of Physics, New York: John Wiley and Sons, 1974

Harney, Robert C., Proceedings of SPIE - The International Society for Optical Engineering, "Physics and Technology of Coherent Infrared Radar", Vol. 300, Bellingham: SPIE - The International Society for Optical Engineering, 1981

Jane's Defence Weekly, "F-117 Has Air Combat Ability", pg. 276, Vol. 17, No. 8, United Kingdom: Sentinel House, 22 February 1992

Kennedy, William S., Infrared Countermeasures Prototype Program Summary an Test Results, ASD/YPS 74M-04, Wright-Patterson AFB: Aeronautical Systems Division, 1974

King, Ronold W.P. and Prasad, Shiela, Fundamental Electromagnetic Theory and Applications, Englewood Cliffs: Prentice Hall, Inc., 1986

Masters, George W., Electro-optical Systems Test and Evaluation, Patuxent River: USNTPS, 1981

Masters, George W., Radar System Test and Evaluation, Patuxent River: USNTPS, 1981

Oates, Gordon C., Aircraft Propulsion Systems Technology and Design, Washington D.C.: American Institute of Aeronautics and Astronautics, 1989

Pratt and Whitney Operating Instruction 200, The Aircraft Gas Turbine Engine and its Operation, United Technologies Corporation, 1982

Scott, William B., "'Black World' Engineers, Scientists Encourage Using Highly Classified Technology for Civil Applications", Aviation Week and Space Tecnology, March 9, 1992, New York: McGraw-Hill

Stimson, George W., Introduction to Airborne Radar, El Segundo: Hughes Aircraft Company, 1983

Sweetman, Bill, Advanced Fighter Technology, Osceola: Motorbooks International, 1987

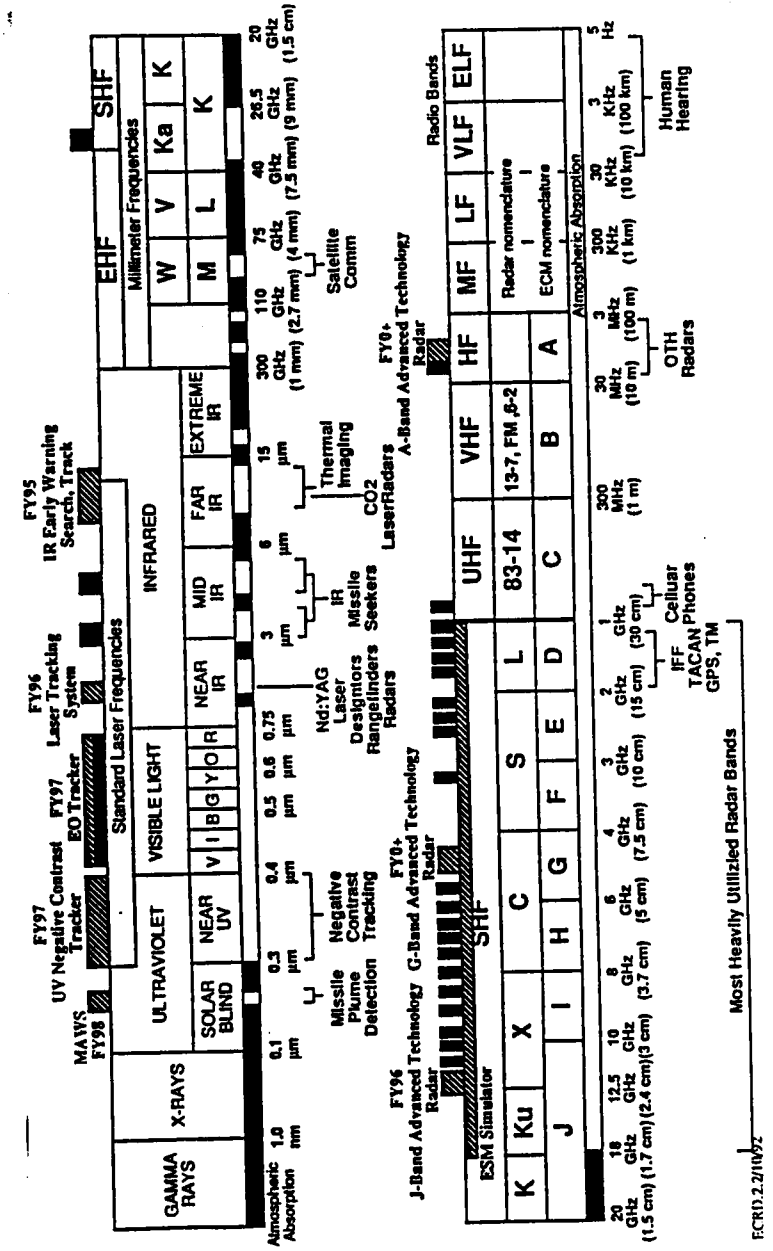
Sweetman, Bill, International Defense Review, "Lifting the Curtain: Stealth Techniques Detailed", February 1992, Vol.25, United Kingdom: Sentinel House, 1992

Sweetman, Bill, Stealth Aircraft, Osceola: Motorbooks International, 1986

Wang, Helen T.G., Electromagnetic Scattering for Low Observable Targets, China Lake: Naval Weapons Center, 1990

Wolfe, William L. and Zissis, George J., The Infrared Handbook, Washington D.C.: Office of Naval Research, Department of the Navy, 1985

APPENDICES



Electromagnetic Spectrum

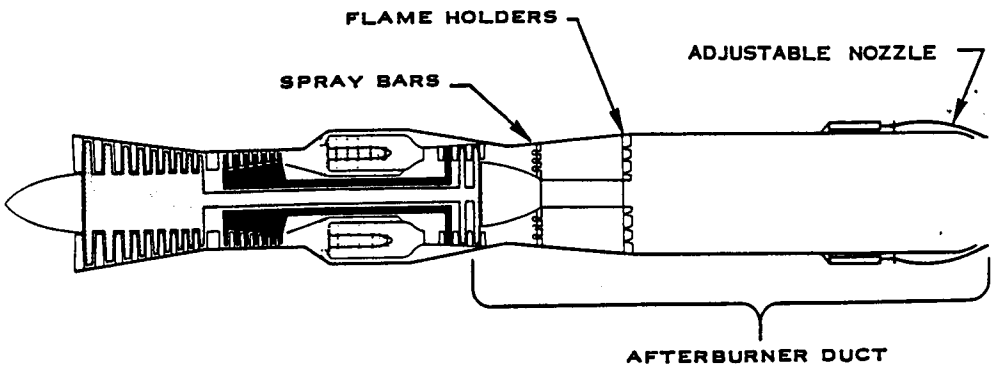
Appendix B

Group	Type	Species	Approximate concentrations		
			Low-power (idle)	High-power (non-AB)	Cruise (with afterburner)
1	Air	N_2	77%	77%	73–76%
		O_2	17.3–19%	13–16.3%	0–13%
		Ar	0.9%	0.9%	0.9%
2	Products of complete combustion	H_2O	1.4–2.4%	3–5%	5–13%
		CO_2	1.4–2.4%	3–5%	5–13%
3	Products of incomplete combustion	CO	50–2000 ppmv	1–50 ppmv	100–2000 ppmv
		Total HC	50–1000 ppmC	1–20 ppmC	100–1000 ppmC
		Partially oxidized HC	25–500 ppmC	1–20 ppmC	?
		H_2	5–50 ppmv	5–100 ppmv	100–1000 ppmv
		Soot	0.5–25 ppmw	0.5–50 ppmw	0.50–50 ppmw
4	Nonhydrocarbon fuel components	SO_2, SO_3	1–5 ppmw	1–10 ppmw	1–30 ppmw
		Metals, metal oxides	5–20 ppbw	5–20 ppbw	5–20 ppbw
5	Oxides of nitrogen	NO, NO_2	5–50 ppmv	50–500 ppmv	100–600 ppmv

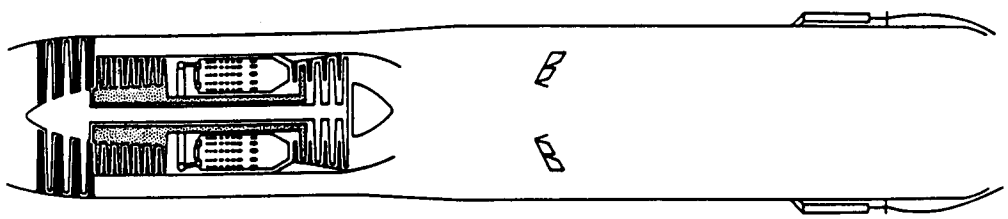
Engine Combustion Products

Source: Oates, Gordon C. (1989), Aircraft Propulsion Systems Technology and Design, pg.138, Washington D.C.: American Institute of Aeronautics and Astronautics

Appendix C



Dual Axial Flow Compressor Turbojet with Afterburner



Dual Axial Flow Compressor Mixed Exhaust Turbofan with Afterburner

Dual Axial Flow Compressor Mixed Exhaust Turbofan with Afterburner

Typical Jet Engine Configurations

Source: Pratt and Whitney Operating Instruction 200 (1982), The Aircraft Gas Turbine Engine and its Operation, pg. 41, United Technologies Corporation

RETURN TO SPURT!!

CONTACT #1	REL ALT: HI LO CO
RADAR ACQ:	VID:
VISUAL ACQ:	BACKGROUD: D V M T
SMOKE GLINT CANOPY WINGFLASH	
CONTACT #2	REL ALT: HI LO CO
RADAR ACQ:	VID:
VISUAL ACQ:	BACKGROUND: D V M T
SMOKE GLINT CANOPY WINGFLASH	
CONTACT #3	REL ALT: HI LO CO
RADAR ACQ:	VID:
VISUAL ACQ:	BACKGROUND: D V M T
SMOKE GLINT CANOPY WINGFLASH	
CONTACT #4	REL ALT: HI LO CO
RADAR ACQ:	VID:
VISUAL ACQ:	BACKGROUND: D V M T
SMOKE GLINT CANOPY WINGFLASH	

DETECTION RANGE DATA CARD

Appendix E

AIRCRAFT TYPE	TYPICAL PLAN AREAS ft^2	ASSUMED AREA ft^2	MINIMUM ALTITUDE (FEET) VS. SOLAR ELEVATION			
			90^o	70^o	40^o	20^o
HELICOPTER	100-200	150	1300	1300	900	500
OBSERVATION	400-500	450	2300	2200	1500	800
FIGHTER	400-1000	700	2900	2700	1900	1000
BOMBER	5000-6000	5000	7700	7200	5000	2600
TRANSPORT	4200-12000	11000	11000	10800	7400	3900

MINIMUM ALTITUDE FOR AVOIDANCE OF SHADOWS

Source: Calspan Corporation (1985), Camouflage Handbook, Final Report AFWAL-TR-86-1028, pg. 1.1-15, Wright-Patterson AFB: Air Force System Command

Appendix F

GENERIC MISSION	OPERATING ALTITUDE REGIME	SCHEME BASED ON AIRCRAFT MANEUVERABILITY	
		LOW	HIGH
VERY LOW PENETRATION OR ATTACK	BELOW 250 FT	A (1ST) B (2ND)	A (1ST) B (2ND)
LOW ALTITUDE ATTACK	1,000-5,000 FT	C	A (1ST) B (2ND)
MID ALTITUDE	5,000-15,000 FT	D	D
AIR COMBAT	15,000-25,000 FT	E	E (1ST) F (2ND)
HIGH ALTITUDE	25,000-40,000 FT	G	G
VERY HIGH ALTITUDE PENETRATION OR ATTACK	OVER 50,000 FT	H	I

DESIGNATED SCHEME	PATTERN TYPE	TOP REFLECTANCE	BOTTOM REFLECTANCE
A	SOLID	TERRAIN MATCH*	TERRAIN MATCH*
B	BLENDING	TERRAIN MATCH*	TERRAIN MATCH*
C	COUNTERSHADED	TERRAIN MATCH*	70%-87% GRAY
D	COUNTERSHADED	15%-30% GRAY	60%-80% GRAY
E	SOLID	35% GRAY	35% GRAY
F	DECEPTION	MULTI-COLOR 35% AVERAGE	MULTI-COLOR 35% AVERAGE
G	COUNTERSHADED	30% GRAY	20% GRAY
H	COUNTERSHADED	30% GRAY	2%-5% BLACK
I	SOLID	2%-5% BLACK	2%-5% BLACK

BASELINE CAMOUFLAGE PAINT SCHEMES

Source: Calspan Corporation (1985), Camouflage Handbook, Final Report AFWAL-TR-86-1028, pg. 1.1-25, Wright-Patterson Air Force Base: Air Force System Command

VITA

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