NAWCWD TP 8773

Aircraft Infrared Principles, Signatures, Threats, and Countermeasures

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SEPTEMBER 2012

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FOREWORD

This document is a supplementary text to the electronic warfare (EW) short courses, EW-101 and EW-102, which are taught annually at the Naval Air Warfare Center Weapons Division (NAWCWD), Point Mugu, California. Like the EW courses, this material is intended for a general audience without an infrared (IR) background who is looking for a practical overview of the field directed toward the problems of aircraft defense.

Details of military IR technology, missiles, and countermeasure systems are necessarily classified, and the EW courses at NAWCWD Point Mugu are taught at that level. This report is unclassified for distribution to a larger audience than is able to attend the courses. This report being unclassified limits the material included to general principles and the figures provided to drawings and photographs that have been released to the public domain. The IR images used are of F-4 and F-14 aircraft that are no longer operational in the United States.

This report was reviewed for technical accuracy by Balaji Iyer.

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26 September 2012

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Released for publication by
S. O'NEIL
Director for Research and Engineering

NAWCWD Technical Publication 8773

Published by..Technical Communication Office
Collation..Cover, 64 leaves
First printing.. 12 paper, 13 electronic media

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)*** 26-09-2012	**2. REPORT TYPE** Technical publication	**3. DATES COVERED (From - To)** 1 January 2012 – 31 March 2012

4. TITLE AND SUBTITLE
Aircraft Infrared Principles, Signatures, Threats, and Countermeasures (U)

5a. CONTRACT NUMBER N/A
5b. GRANT NUMBER N/A
5c. PROGRAM ELEMENT NUMBER N/A

6. AUTHOR(S)
Jack R. White

5d. PROJECT NUMBER N/A
5e. TASK NUMBER N/A
5f. WORK UNIT NUMBER N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Air Warfare Center Weapons Division
575 I Avenue, Suite 1 (Code 456000E)
Point Mugu, California 93042

8. PERFORMING ORGANIZATION REPORT NUMBER
NAWCWD TP 8773

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSOR/MONITOR'S ACRONYM(S)
N/A

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
N/A

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
None.

14. ABSTRACT

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(U) The object is to convey the key concepts primarily through drawings and images. A few equations are provided when words and figures are inadequate but are not essential to grasping the concepts. A deeper understanding of IR requires much more theory than contained here; but, ideally, the material here will provide a basis to build upon for those interested in continuing in this most interesting of fields.

15. SUBJECT TERMS
Absolute Signature, Aircraft, Antiaircraft, CCM, Contrast Signature, Counter-countermeasures, Countermeasures, Decoy, Discrimination, Emissions, Emissivity, Exhaust Plume, Flare, Infrared, IR, Irradiance, Jammer, Missile Warning Receiver, Missile, Projected Area, Pyrotechnic Flare, Radar, Radiance, Radiant Intensity, Radiation, Reflectivity, Signature, Solid Angle, Spatial, Spectral, Spin-Scan Tracker, Target Acquisition, Temporal, Tracker.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Ed Becerra
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	126	**19b. TELEPHONE NUMBER** *(include area code)* (805) 989-0662

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

CONTENTS

ACKNOWLEDGMENTS

Special thanks are given to Thomas Yang, whose dedication to passing the knowledge of electronic warfare on to a new generation of engineers has made the Naval Air Warfare Center Weapons Division (NAWCWD), Point Mugu, California, courses a reality, and without whose assistance and encouragement this report would never have been written.

This report is dedicated to coworkers in the infrared (IR) group at NAWCWD Point Mugu who, over the last 40 years under the most austere conditions, designed and built four generations of airborne test and measurement systems and who shared so many hours on the flight line in baking heat and freezing cold desperately preparing systems for flight. Especially, this document is dedicated to the young engineers in the group, who are already designing more advanced systems and dreaming bigger dreams than the author ever imagined.

OVERVIEW

The most fundamental property of infrared (IR) is the one most important to the military: warm materials emit IR radiation (see Figure 1). IR is electromagnetic radiation with wavelengths longer than those of visible light and shorter than those of microwaves. IR cannot be seen with the human eye but can be felt by the skin as warmth. The following holds true: the higher the temperature of a material, the stronger the radiation and the shorter the wavelength of the maximum power emitted. This property of direct emission has life-threatening consequences for aircraft.

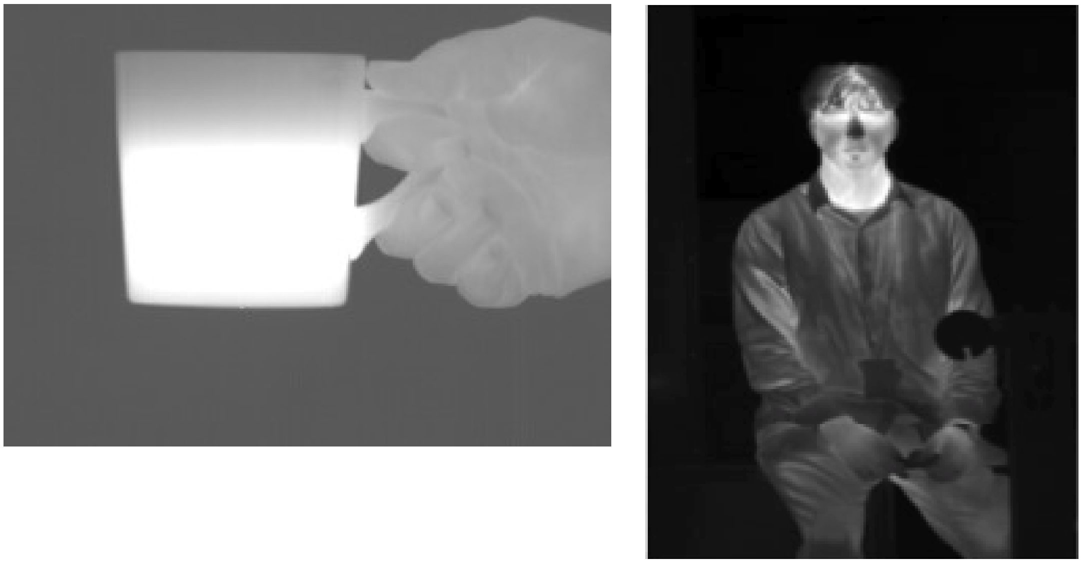

FIGURE 1. IR Images of Cup of Coffee (Half-Full) and of Human Body. (These images illustrate the military value of the IR spectrum. Warm objects emit in the IR, and these emissions enable passive detection day or night.

Aircraft engines and exhaust gases have high temperatures and consequent strong emissions. The skin of an aircraft is warm in contrast against the sky background and reflects radiation from the sun and from the earth. These direct emissions and reflections enable passive detection and tracking and make aircraft vulnerable to a wide proliferation of IR-guided missiles and search/track systems.

CONSEQUENCES OF AIRCRAFT IR EMISSIONS

Detection of a target with radar requires illumination by a transmitter to get a reflection back to the receiver. This illumination can warn the target that it is being tracked, and the frequency and modulation can be used to identify the type of radar.

With IR, the target aircraft itself radiates, so no illumination is required. This direct emission enables passive detection. Passive detection and tracking of a target's radiation by an airborne or ground sensor give no warning to the target. The first indication of danger that a target may have is the flash of a missile launch. At that point, survival depends upon deploying an effective countermeasure within the next few seconds. Direct emission and passive detection make defense against IR sensors and weapons a formidable challenge.

The first, and still the primary, military use of IR is against aircraft. Aircraft are highly susceptible to detection and extremely vulnerable to destruction. Unlike ground vehicles viewed against terrain backgrounds, aircraft are easily detected at long range against their natural sky background (see Figure 2). Therefore, a large aircraft can be brought down with a very small missile warhead.

FIGURE 2. Image of Aircraft Nose-on at 23-Nautical-Mile Range Taken With Commercial IR Camera.

SIDEWINDER

The first antiaircraft IR-guided missile was named Sidewinder after a desert rattlesnake of the pit viper family that uses IR to detect and strike its prey. Sidewinder was developed by the U.S. Navy at the Naval Ordnance Test Station (NOTS) (now the Naval Air Warfare Center Weapons Division [NAWCWD]) at China Lake, California, in the late 1940s specifically for air-to-air combat between jet aircraft.

Its first combat engagement was in 1958 by the Nationalist Chinese on Taiwan (then the island of Formosa) against mainland Communist Chinese flying MiG-17s. This brief and small military action forever revolutionized air warfare. Almost immediately, Sidewinder became one of the most successful and copied weapons in history.

The proliferation of antiaircraft IR-guided missiles drove infrared countermeasure (IRCM) development. Figure 3 shows a Sidewinder being fired by an F/A-18A.

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FIGURE 3. Sidewinder AIM-9M Missile Fired From F/A-18A by
Marine Fighter Attack Squadron (VMFA) 314 Personnel
Over Naval Air Station Fallon Firing Range.

ANTIAIRCRAFT IR MISSILE PROLIFERATION

IR-guided missiles have proliferated to almost every country on the globe through domestic manufacture or through foreign military sales. Aircraft defense is challenged not only by the sheer numbers of missiles but also by the variety of designs.

Early missiles copied much of the Sidewinder design, but new missile designs have evolved and diversified greatly, and missiles fielded within the past 10 years employ a variety of counter-countermeasure (CCM) techniques to defeat conventional IRCM.

Advances in missile design force a corresponding development of countermeasure systems and techniques. This situation, in turn, demands more missile advances to defeat those countermeasures. Countermeasure versus CCM is a never-ending endeavor. It is a deadly game in which survival depends upon knowledge, accurate intelligence, tight security, and the ability to test and field new systems more rapidly than one's adversary.

Given time and information, every missile design can be defeated, but details of many of the newer designs are unknown to the intelligence and countermeasure community. Figure 4 shows an advanced surface-to-air missile in service with the Japanese Self-Defense Forces.

FIGURE 4. Japanese Type 91 SAM-2 Shoulder-Launched Missile Used During Japanese Self-Defense Forces Training With United States Forces During Red Flag-Alaska 07-3.

Elements of Defense

Aircraft IR defense has three main elements:

1. The suppression of aircraft emissions to reduce the range at which the aircraft can be acquired and tracked.
2. A warning receiver to detect missile launch and cue a countermeasure response.
3. Countermeasure devices and systems, of which there are two types: off-board (decoys) and onboard (jammers). Figure 5 shows a salvo of decoy flares from a C-17 aircraft.

These elements are connected in the following manner: the intensity of an aircraft's IR emissions determines the distance at which a missile can acquire and track the aircraft and the intensity of the countermeasure that is required to protect it. The countermeasure, whether a decoy or a jammer of the directed energy (laser) type, requires reliable missile warning to be employed. Reliable missile warning requires knowledge of the emission characteristics of rocket motors and, especially, of features that can be used to distinguish the missile from natural backgrounds.


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FIGURE 5. Flare Salvo From C-17. (A C-17 Globemaster III aircraft releases flares over the Atlantic Ocean during a local exercise over Charleston, South Carolina, 6 May 2006.)

Suppression of Aircraft Emissions

The IR signature of an aircraft is the total of its detectable emissions and reflections (see Figure 6). Its signature is what makes an aircraft susceptible to detection and tracking by threat sensors and missiles. Signature is the quantity that countermeasure devices and systems must defend.

The most effective countermeasure is to achieve aircraft signature values that are too low for a missile to acquire. Complete denial of acquisition can never be achieved for all conditions due to limitations in size, weight, and the laws of physics.

However, significant reductions in the range at which missiles can acquire an aircraft can be achieved through signature suppression. Because aircraft engines are the primary source of IR emissions (radiation), the greatest initial gain in signature reduction is usually achieved through engine suppression. Therefore, any effort to reduce the IR emissions of an aircraft starts with the engines.

Signature suppression has two objectives:

1. Reduce the range at which an IR missile or sensor can detect and track the aircraft.
2. Increase the effectiveness of countermeasure systems and devices.

FIGURE 6. IR Image of Navy F-14A.

Missile Warning

Both decoy countermeasures and the newer directed energy laser jammers are heavily dependent upon missile warning for their effectiveness. Effective missile warning is the most critical element of and is essential to aircraft defense, as well as the most difficult to achieve. Figure 7 shows the typical receiver placement on a large fixed-wing aircraft.

IR missiles may be launched from long distances. The missile's tracking is passive, and emissions from their rocket motors are embedded in background radiation clutter.

Achieving an acceptable compromise between high probability of detection and a low false alarm rate in a system that is integrated into other aircraft systems presents technical and operational challenges that will never be completely solved.

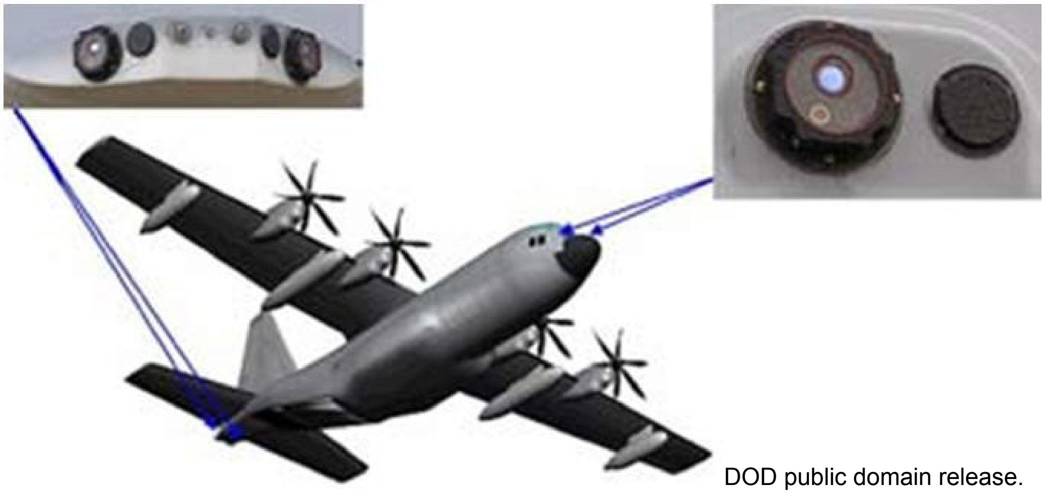

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FIGURE 7. Missile Warning Receiver (MWR) Installation on KC-130 Aircraft.

Countermeasures

When the limit of what can be achieved through suppression is reached, a countermeasure must be used. The two basic types of countermeasure are decoys and jammers.

Decoys. A decoy is an off-board countermeasure that is ejected from and separates away from the aircraft. As the name implies, a decoy attempts to lure the track of a missile away from the target aircraft.

To be effective, the decoy must provide a more attractive source for the missile than the real aircraft target. Most IR missiles are not able to search and reacquire a target after launch; so, once the track has been pulled far enough that the aircraft is no longer in the missile field of view (FOV), the missile has been defeated.

The term *decoy* is a general name applied to a variety of off-board devices. The decoy most commonly associated with IR is the pyrotechnic flare, such as the ones shown in Figure 8. All flares are decoys, but not all decoys are flares.


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FIGURE 8. Flares Dispensed From F/A-18E. (An F/A-18E from Strike Fighter Squadron (VFA) 81 deploys flares during an air power demonstration over the Nimitz-class aircraft carrier USS *Carl Vinson* [CVN 70]).

Jammers. A jammer is an onboard countermeasure that stays attached to the aircraft. Through the modulation of an intense IR source, a jammer introduces a false signal into the missile track loop that creates a kind of electronic illusion of a target in another location. Through this method, a jammer pushes the missile's track away from itself and the aircraft. One example is the Large Infrared Countermeasure (LAIRCM) system (see Figure 9), which is a laser jammer that injects false target information into a missile's track loop.


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FIGURE 9. LAIRCM on CH-53E. (Marines in theater conduct maintenance on a CH-53E equipped with LAIRCM.)

Countermeasure Effectiveness Testing

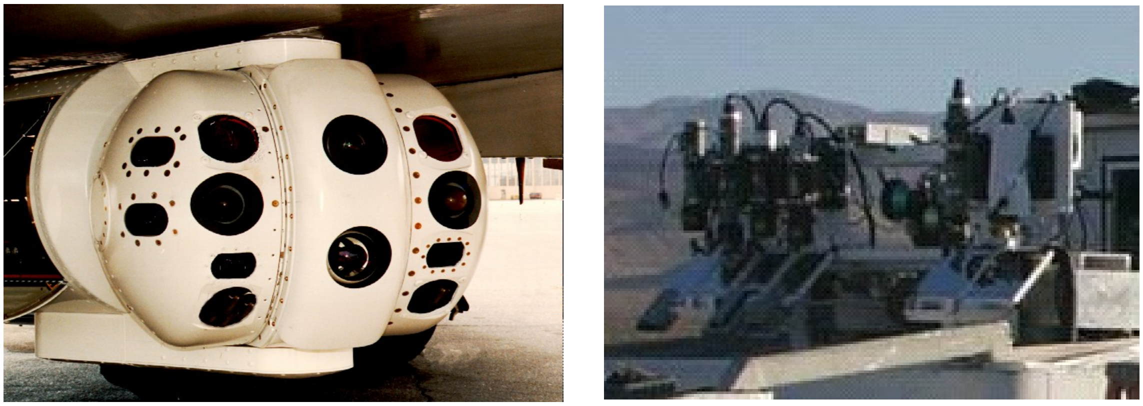
As countermeasure systems become more complex and more integrated into a suite of sensors, processors, and queued countermeasure systems, the ability to quantify effectiveness is becoming increasingly difficult; expensive; time-consuming; and, sometimes, questionable.

Of all the areas of IRCM system development and deployment, effectiveness testing presents—and will continue to present—the greatest challenges in the years ahead.

Present methods involve a piecemeal mixture of field and flight test data and models and simulations. Each has its strengths and limitations. All are required.

- Field and flight tests use captive missile seekers viewing a real aircraft against a real background and dispensing or engaging a real countermeasure system but do not include the all-important missile closure on the target.
- Simulations perform a simulated fly-out with a modeled aircraft, countermeasure, and missile. Simulations are of two basic types: (1) hardware in the loop (HIL), which uses an actual missile guidance system wired into a computer simulation and (2) all digital, which models the missile circuitry in the computer.

Both simulation types require extensive stage-by-stage validation with test and measurement data. Figure 10 shows air-to-air and ground-to-air systems used to test countermeasure effectiveness.



(a) Airborne Turret Infrared Measurement System (ATIMS) II turret with captive missiles.

(b) NAWCWD China Lake seeker test van.

FIGURE 10. Examples of Air-to-Air and Ground-to-Air Systems Used To Collect Countermeasure Effectiveness Data.

PRINCIPLES OF IR FOR AIRCRAFT

HISTORY

Most encyclopedias and physics books credit the great British astronomer Sir William Herschel with the discovery of IR in 1800. This accreditation is not exactly correct and trivializes the real significance of Herschel's findings. IR was "discovered" by the first human that warmed himself or herself before the coals of a fire. At a very young age, we all discover that warmth can be felt at a distance from any hot object, and we know these rays are invisible because warmth can be felt in total darkness.

What Herschel discovered was subtler than the existence of invisible radiation. Through a series of simple experiments with a prism and with mercury thermometers as sensors, Herschel proved that light and what he referred to as "radiant heat" have the same optical properties. This finding was the first solid evidence that light and IR are the same quantity, which we know today to be electromagnetic radiation. The term *infrared* entered scientific vocabulary sometime in the 1880s, but historians have been unable to trace its exact origin.

Little about IR terms and units is universally agreed upon, even among those working in the field. Different reference books give different names and locations for the sub-bands within IR and sometimes use different terms and units for the expressions of radiant power. And often, some of the most important terms and concepts are not mentioned at all. IR is a contentious part of the spectrum.

Figure 11 is an example of the complexity of IR emissions from an aircraft.

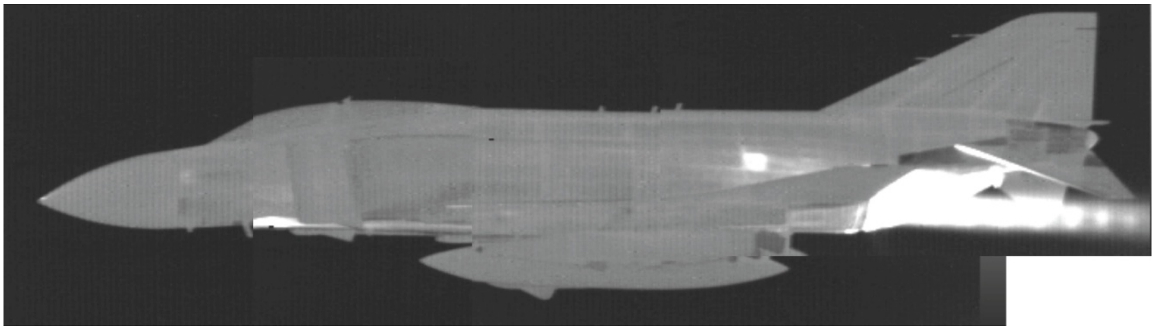


FIGURE 11. Mid-Wavelength Infrared (MWIR) Image of Navy F-4N.

PROPERTIES OF IR

IR is electromagnetic radiation, with all that implies about its composition, propagation, and interactions with matter. Like all electromagnetic radiation, IR travels at the speed of light in a vacuum (about 300,000 km/s) and at slower speeds in transparent media, such as air or glass. The speed in glass, for example, is approximately two-thirds the speed in vacuum. The speed of propagation of an electromagnetic wave through a medium is a function of the material properties of permeability and permittivity.

Frequency and wavelength are related by speed. The length of a wave is equal to the propagation speed in that medium divided by the frequency. Frequency does not change as a wave enters or exits a medium, so the length of a wave in a slower medium will be shorter than in a vacuum. Locations in the IR part of the spectrum are usually specified by wavelength rather than frequency. The common unit of wavelength is micrometers (μm).

Another term often used is wave number. Wave number is the number of waves in a specified distance. A common unit for wave number is inverse centimeters, which is the number of wavelengths in a 1-cm distance.

IR Interactions With Matter

Like all electromagnetic radiation, IR interacts with matter in a variety of ways:

- Reflects—A wave is reflected from a surface. The angle of reflection equals the angle of incidence.
- Refracts—The direction of a wave bends when passing between two transparent media with different propagation speeds (Snell's law).
- Scatters—Scattering occurs upon interaction with particles whose size approaches the length of the wave (why the sky is blue).
- Diffracts—This interaction occurs around the edges of an obstruction.
- Interferes–This interaction occurs in both a constructive and destructive manner.
- Absorbs—When absorbed by matter, radiation is converted into another form of energy. The most common conversion is to heat.
- Emits—Radiation is emitted from matter by conversion from another form of energy.
- Transmits—IR propagates through a transparent medium (or vacuum).
- Polarizes—An electric field is partially polarized by reflection from dielectric.

IR on Electromagnetic Spectrum

Light and IR are the only parts of the electromagnetic spectrum that humans are able to directly sense. Our eyes see light, which occupies a narrow band of wavelengths centered approximately where the sun's radiant power is at its maximum. Our skin feels warmth across the spectrum, but mainly from IR, which spans the range of wavelengths between light and microwaves.

Sensing light and IR is one of our most familiar sensations, but nothing in everyday experience would lead us to believe that light and IR are the same quantity. There was no concept of electromagnetic radiation in 1800, but it was Herschel's great insight to connect two parts that we sense through their optical properties.

The short wavelength side edge of IR begins where our eyes' response ends, which is approximately 0.7 μm (700 nm). The long wavelength limit is less sharply defined but is usually specified as about 1,000 μm. The practical long wave limit with today's sensor technology goes only to about 14 μm. Figure 12 shows the location of IR on the electromagnetic spectrum.

Properties vary greatly across the IR, with several sub-bands of particular interest to aircraft.

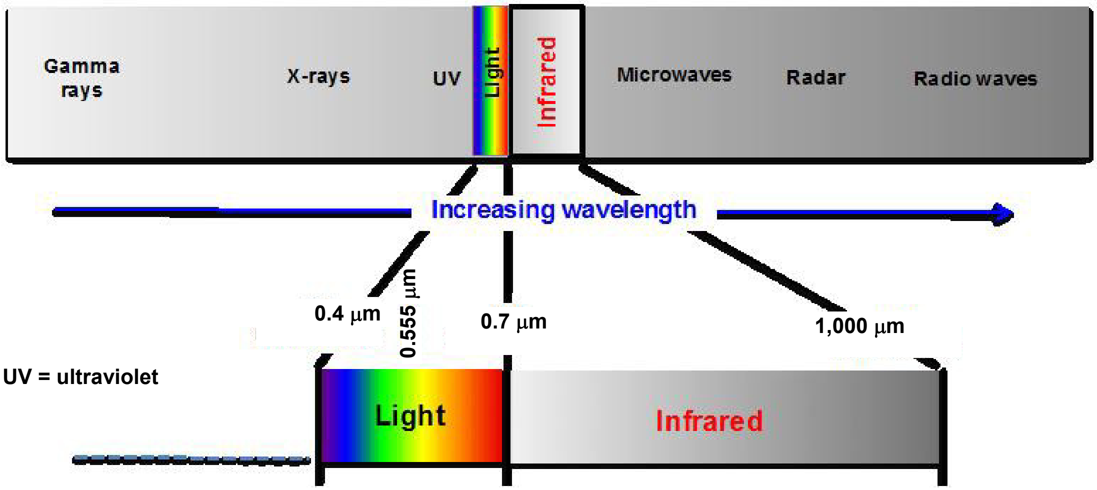


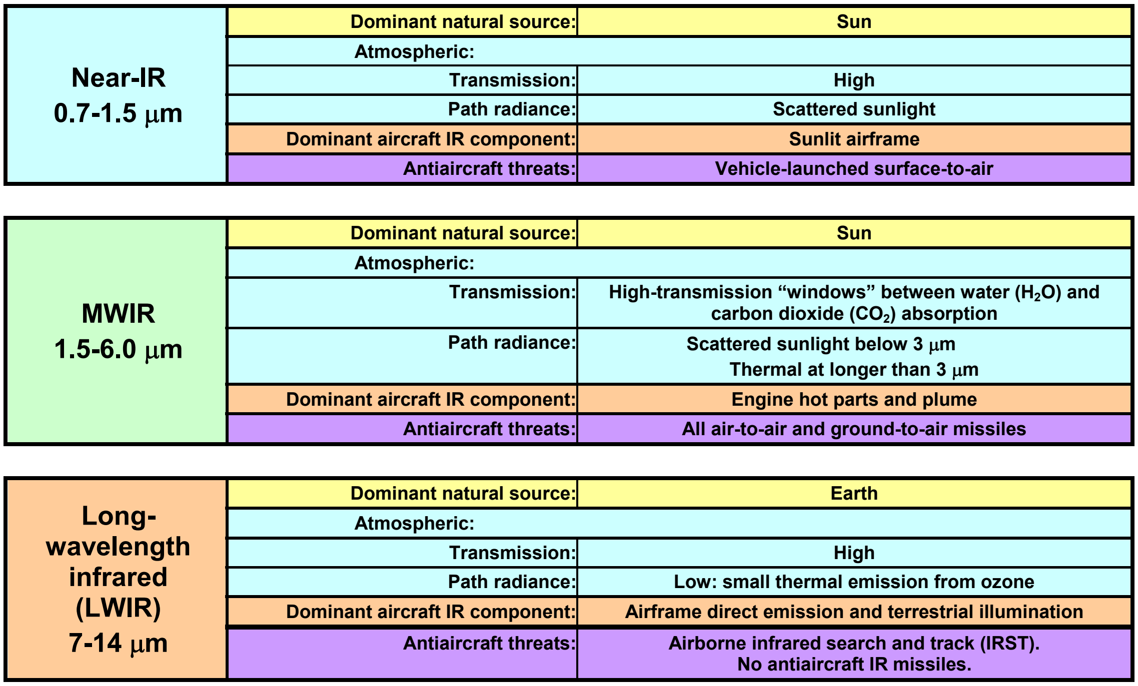
FIGURE 12. Electromagnetic Spectrum.

IR Sub-Bands, Properties, and Threats

Three sub-bands (see Figure 13) are of particular military interest. Of these, the MWIR from approximately 1.5 to 6.0 µm is of greatest concern to aircraft because that is where most of the antiaircraft missiles operate.

Properties vary greatly even within a sub-band. Toward the short wavelength side of the MWIR, reflected sunlight from airframe surfaces dominates the aircraft appearance. Sky background is dominated by scattered sunlight, and terrain background is dominated by direct emissions.

The long wavelength side of the MWIR is dominated by direct emissions from both the aircraft and sky and terrain background.



Near-IR 0.7-1.5 μm	**Dominant natural source:**	**Sun**
	Atmospheric:	
	Transmission:	**High**
	Path radiance:	**Scattered sunlight**
	Dominant aircraft IR component:	**Sunlit airframe**
	Antiaircraft threats:	**Vehicle-launched surface-to-air**
MWIR 1.5-6.0 μm	**Dominant natural source:**	**Sun**
	Atmospheric:	
	Transmission:	**High-transmission “windows” between water (H_2O) and carbon dioxide (CO_2) absorption**
	Path radiance:	**Scattered sunlight below 3 μm Thermal at longer than 3 μm**
	Dominant aircraft IR component:	**Engine hot parts and plume**
	Antiaircraft threats:	**All air-to-air and ground-to-air missiles**
Long-wavelength infrared (LWIR) 7-14 μm	**Dominant natural source:**	**Earth**
	Atmospheric:	
	Transmission:	**High**
	Path radiance:	**Low: small thermal emission from ozone**
	Dominant aircraft IR component:	**Airframe direct emission and terrestrial illumination**
	Antiaircraft threats:	**Airborne infrared search and track (IRST). No antiaircraft IR missiles.**

FIGURE 13. IR Sub-Bands of Military Interest.

IR TERMS AND UNITS

IR has three essential terms: (1) *irradiance*, (2) *radiant intensity*, and (3) *radiance*. The first applies to radiation at the receiver: irradiance describes the area density of the power that is received by a missile or sensor. The other two terms apply to the source: radiant intensity, usually shortened to intensity, describes angular density of the power emitted from a source. Radiance describes the angular power density per unit area of the source. (Radiance can be thought of as intensity per unit area.)

Irradiance

All IR detectors respond to irradiance, that is, to the density of the radiant power that is incident on their surface. The SI unit for radiant power is the watt. The SI unit for area is the square meter. Irradiance is sometimes expressed in watts per square meter; but, in aircraft applications, area is more commonly expressed in units of square centimeters; thus irradiance usually has units of watts per square centimeter. The conventional symbol used for irradiance is the capital letter E. (Older books often use the letter H.) Like other IR quantities, irradiance varies as a function of wavelength. The Greek letter *lambda* (λ) is usually used for wavelength.

Radiant Intensity

Intensity is the most widely used measure of the IR signature, or the susceptibility of an aircraft to detection by threat IR sensors. In that sense, intensity is analogous to (but very different in nature from) radar cross section (RCS) in the radar world.

Care must be taken using analogies between IR and radio frequency (RF) because the target aircraft in the IR is an active emitter rather than the passive reflector of a distant RF illuminator. For this reason, intensity is actually more closely related to RF effective radiated power (ERP), which combines transmitter power with antenna beam width.

Irradiance was defined as the area power density at the receiver. Intensity is defined as the angular power density from the source. The units of intensity are watts per steradian. The conventional symbol for intensity is the capital letter *I*. (Older books often use the letter *J*.) Because radiation propagates in three dimensions, the angle must be a solid unit. Solid angle appears throughout IR terms and units.

Irradiance and intensity are related by the square of the distance.

$$E = \frac{I}{R^2}$$

and

$$I = ER^2$$

where:

E = irradiance ($W \cdot cm^{-2}$)
I = radiant intensity ($W \cdot sr^{-1}$)
R = range, cm

The three basic IR terms are related (1) by the inverse square of distance, (2) by area, or (3) by the ratio of area to the square of the distance. The ratio of the area to the square of the distance is a particularly important concept. In solid geometry, the ratio of the area on the surface of a sphere to the square of the radius is the unit of solid angle, or steradian in the SI system of units. Steradian is usually abbreviated as *sr*, and the symbol most often used for solid angle is the Greek letter *omega* (*Ω)*.

Solid Angle

The solid angle (see Figure 14) is the three-dimensional version of the more familiar plane angular measure in radians. Angle in radians is defined as the ratio of distance along the circumference of a circle divided by the radius of the circle. For small angles, the solid angle in steradians is approximately equal to the product of two plane angles in radians.

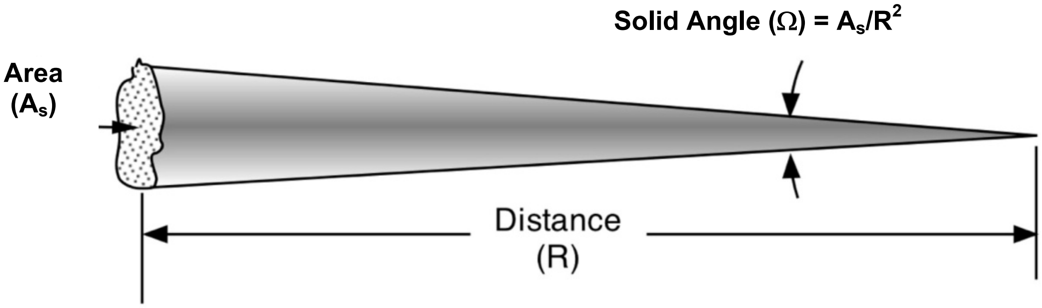


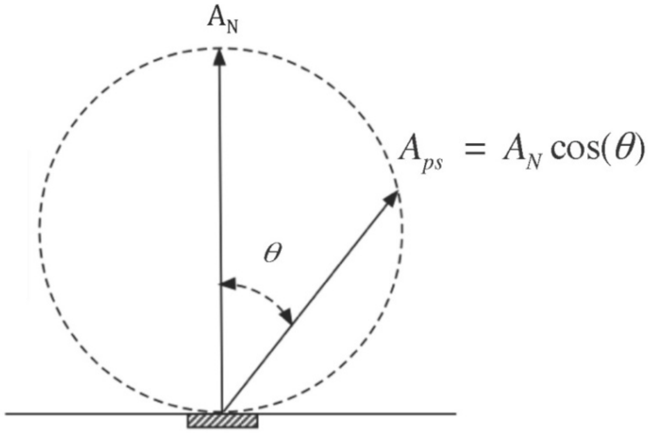
FIGURE 14. Drawing Showing Solid Angle Is Ratio of Area to Square of Distance.

Projected Area

Projected area is the cross-sectional area of the source surface that is visible to a distant sensor. Projected area can be thought of as directional area. Intensity in a particular direction is directly proportional to the projected area in that direction.

IR sources come in all sizes and shapes, but the shape of greatest interest is a plane or flat surface. Complex shapes can always be approximated by a number of flat facets at different orientations. The projected area of a plane facet varies as the cosine of the angle from normal to the surface.

The convention is to use the angle formed with the normal to the surface. As Figure 15 shows (also see Figure 16), the projected area of a facet, indicated by the length of the vector (A_{ps}), is equal to the area normal to the surface (A_N) times the cosine from normal.



The area term that appears in IR units is usually projected area. Projected area varies as the cosine of the angle from normal to the surface.

FIGURE 15. Graph of Projected Area as Function of Angle From Normal.

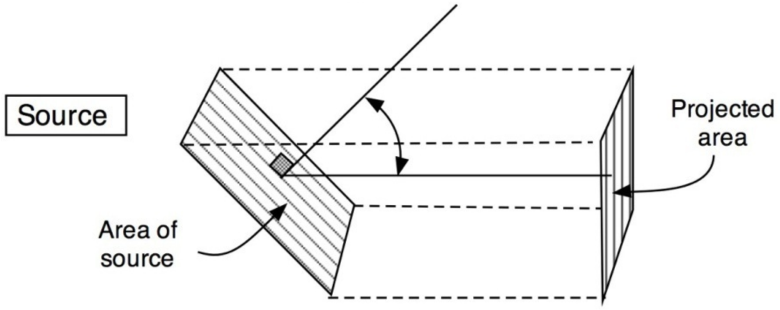


FIGURE 16. Drawing Showing Projected Area and Area of Source. (Projected area of plane source seen by distant sensor varies as cosine to normal. Intensity of a source is directly proportional to projected area.)

Radiance

While intensity specifies radiation from the total visible area of a source, radiance specifies that from only a small area. Radiance can be thought of as intensity per unit area. In other words, radiance is the power per unit solid angle per unit area ($W \cdot sr^{-1} \cdot cm^{-2}$). (Radiance is sometimes expressed per square meter to remain consistent with SI units.) Radiance is analogous to the quantity, *brightness* in visible or photometric terms.

The conventional symbol for radiance is the capital letter *L*. (Older books often use the capital letter *N*.) Like irradiance and radiant intensity, radiance usually begins life as a spectral quantity, that is, radiance as a function of wavelength. As with irradiance and radiant intensity, the total radiance in a wavelength band is obtained by integrating over a wavelength range.

Radiance is the quantity seen of a target that is optically resolved. In the resolved condition, a sensor's view is restricted or directed by optics to view only a part of the source (see Figure 17). Three features of the resolved condition are as follows:

1. An image is formed.
2. Each spot on the image receives radiation from only a small area of the total source surface area.
3. As the distance between the sensor and the source changes, the ratio of the source area seen by the sensor to the square of the distance to the source stays constant. As a result (neglecting atmospheric effects), the irradiance received remains constant with distance.

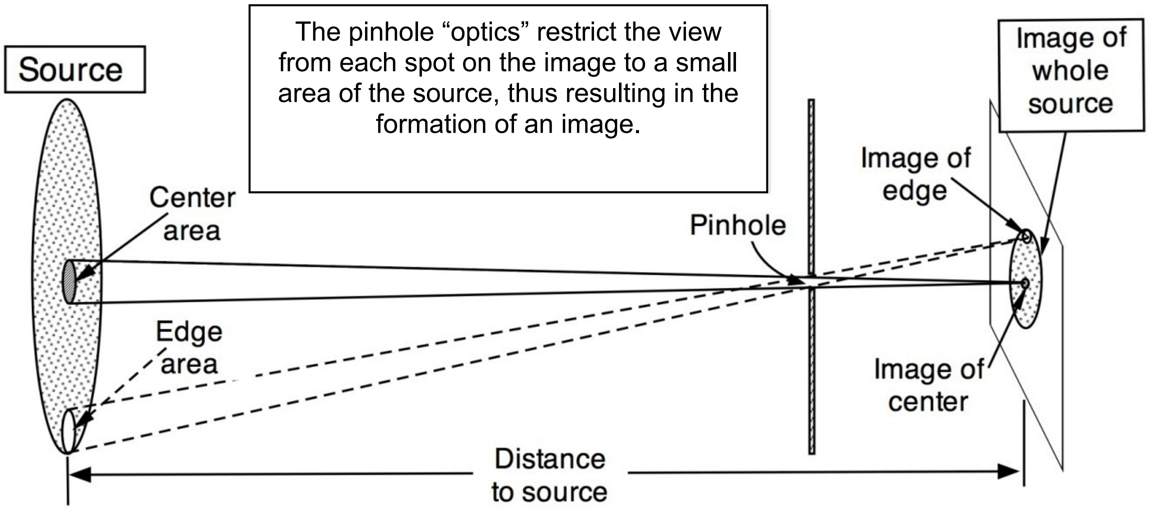
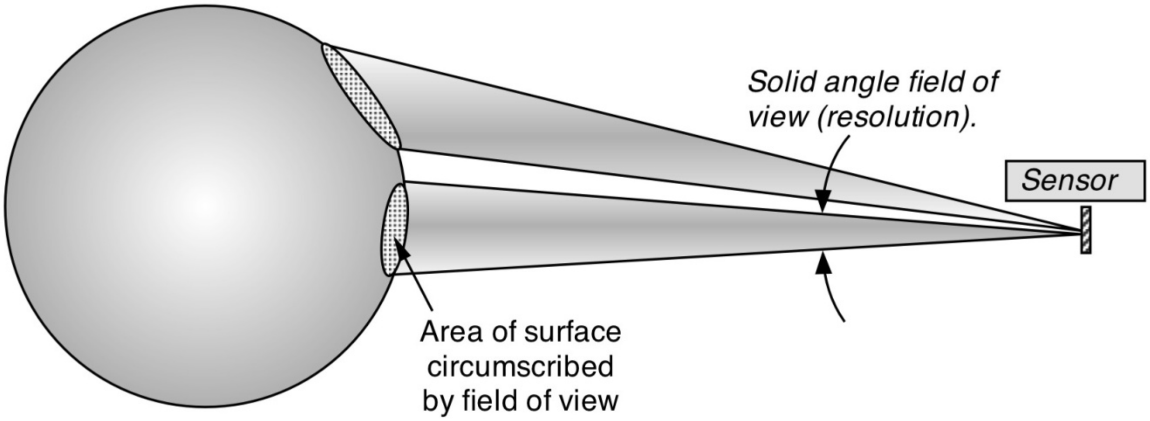


FIGURE 17. Resolved Condition Illustrated by Pinhole Camera.

Sensors respond to irradiance regardless of whether the source is optically resolved or not. The difference is that the irradiance received from a source that is optically resolved by the sensor is directly proportional to radiance. Consequently, when a source is resolved, the radiance perceived by a sensor is

1. Constant with distance (neglecting atmospheric absorption).
2. Constant with angle to the surface (up to a limit near grazing).

Constant radiance can be illustrated by the surface of a sphere that is resolved by a sensor (see Figure 18). With uniform illumination, a sphere will appear to have fairly constant radiance over its surface. This aspect is because the solid angle FOV is constant; thus, the irradiance on the detector is almost the same from an area near the side as from an area near the center.



Except at grazing angles, the radiance of a surface is constant with viewing angle. A sphere, for example, appears uniform over most of its surface and, if optically resolved by a constant solid angle FOV, produces constant irradiance on the sensor.

FIGURE 18. Illustration of Uniform Radiance on Surface of Sphere.

Summary Relationships

There is a progression to the relationship between IR terms. Irradiance varies with the inverse square of distance and intensity. Intensity is directly proportional to projected area and radiance. The resultant mathematical expression shows the final relationship in which radiance and irradiance are related by the solid angle subtended by the source.

Irradiance, intensity, and radiance are related by the square of distance, by area, and by solid angle.

$$E_R = \frac{I_S}{{R_r}^2} = \frac{L_S A_S}{{R_r}^2} = L_S \Omega_S$$

where:

E_R = irradiance at receiver ($\mathrm{W \cdot cm^{-2}}$)
I_S = radiant intensity of source ($\mathrm{W \cdot sr^{-1}}$)
R_r = distance from the receiver to the source (cm)
L_S = radiance of the source ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$)
A_S = projected area of the source ($\mathrm{cm^2}$)
Ω_S = solid angle subtended by the source (sr)

CONVERSION FROM HEAT: PLANCK'S LAW

Energy can neither be created nor destroyed but only transformed through interactions with matter. The most common transformation, and the one most important to aircraft IR emissions, is the conversion from heat to electromagnetic radiation.

The distribution of radiant power as a function of temperature was derived mathematically by Max Planck in 1900. Radiant power has a spectral distribution that resembles a wave of water, with a steep rise in power on the short wavelength side of the peak and a tailing off on the long wavelength side.

Figure 19 shows curves and images of direct emissions from objects at different temperatures. As temperature is increased, two changes occur: (1) power at every wavelength increases and (2) the curve translates toward shorter wavelengths.

We see objects at room temperature by reflected light. The person and the cup of coffee emit in the IR but not sufficiently in the visible to see. At around 700°C, the short wavelength edge of the distribution reaches the long wavelength edge of the visible, and we see a red glow.

The curve defined by Planck's law (see Figure 20) is fundamental to almost every aspect of aircraft detection and defense. The key to understanding much of aircraft IR lies with understanding specific applications of Planck's law.

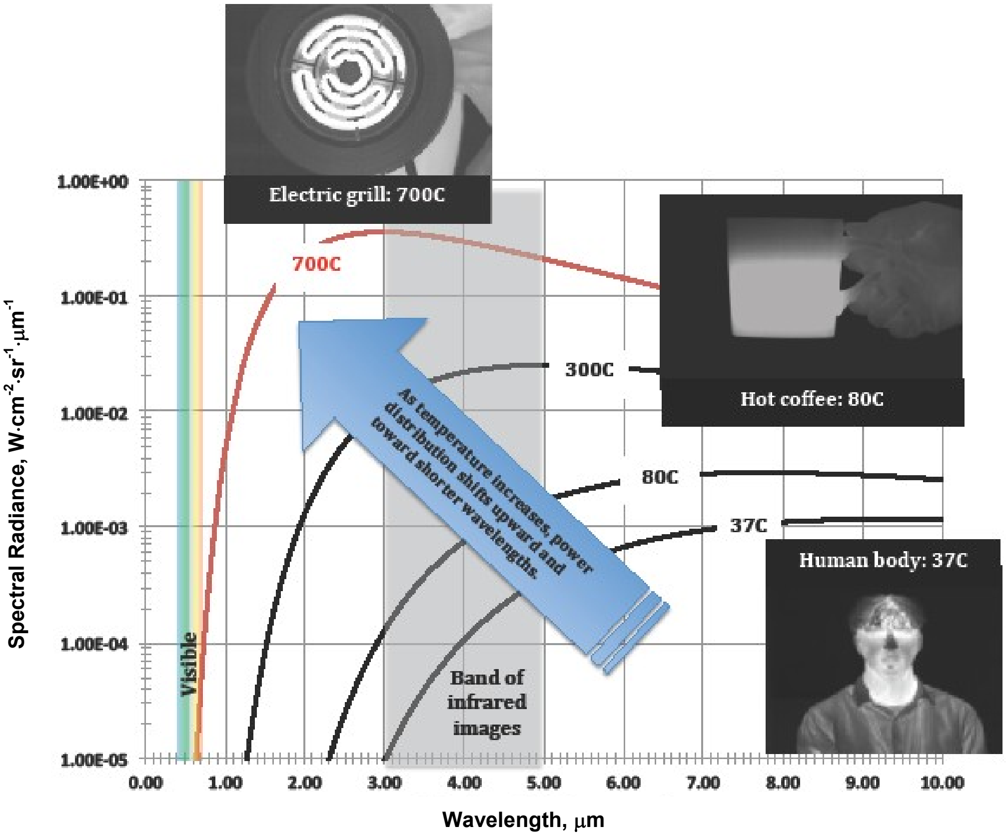
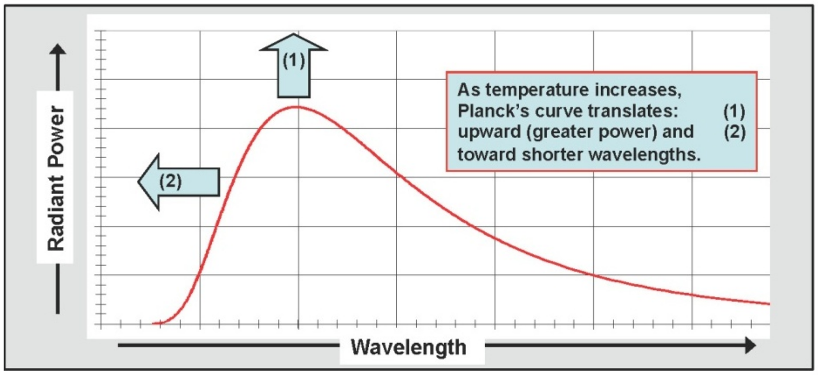


FIGURE 19. Translation of Spectral Radiant Power With Temperature.



As temperature increases, Planck's curve translates: (1) upward (greater power) and (2) toward shorter wavelengths.

Planck's law describes the spectral distribution of radiant power as a function of temperature. Below is Planck's 1909 formula for what he referred to as *spectral intensity*, which is different from the way that intensity is defined today.

$$E_\lambda = \frac{hc^2}{\lambda^5}\,\frac{1}{\left(e^{\frac{ch}{\lambda kT}} - 1\right)}$$

For aircraft applications, Planck's formula is commonly modified to include a term for emissivity, several of the constants are combined, and units of length are converted to convenient forms for wavelength and area, thus yielding the following:

$$L_\lambda = \in \frac{\alpha}{\lambda^5}\,\frac{1}{\left(e^{\frac{b}{\lambda T}} - 1\right)}$$

where:
L_λ = spectral radiance ($\text{W}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}\cdot\mu\text{m}^{-1}$)
ε = emissivity (0 to 1.0, often assumed to be 1 in Planck's formula)
h = Planck's constant ($6.62606957 \times 10^{-34}$ $\text{W}\cdot\text{s}^2$)
c = speed of light ($2.99792458 \times 10^{10}$ $\text{cm}\cdot\text{s}^{-1}$)
k = Boltzmann's constant ($1.3806488 \times 10^{-23}$ $\text{J}\cdot\text{K}^{-1}$)
λ = wavelength (μm)
T = absolute temperature (K)
a = $(10^{16})2hc^2$ (1.19042868×10^4 $\text{W}\cdot\text{cm}^{-2}\cdot\mu\text{m}^4$)
b = $(10^4)\frac{ch}{k}$ (1.43877696×10^4 $\mu\text{m}\cdot\text{K}$)

FIGURE 20. Planck's Law for Distribution of Power.

CONTRAST AND TARGET DETECTION

The IR part of the spectrum is of military importance because objects at low temperatures have their peak emissions there, a factor that enables passive detection day or night. But more important than the location of the maximum is the location of the difference between objects and their natural backgrounds.

Figure 21 shows the spectral distribution for a human body (37°C) and earth background (about 20°C). If the human is the target viewed against a terrain background, the difference between their two curves is the contrast, which forms a curve that peaks at a slightly shorter wavelength.

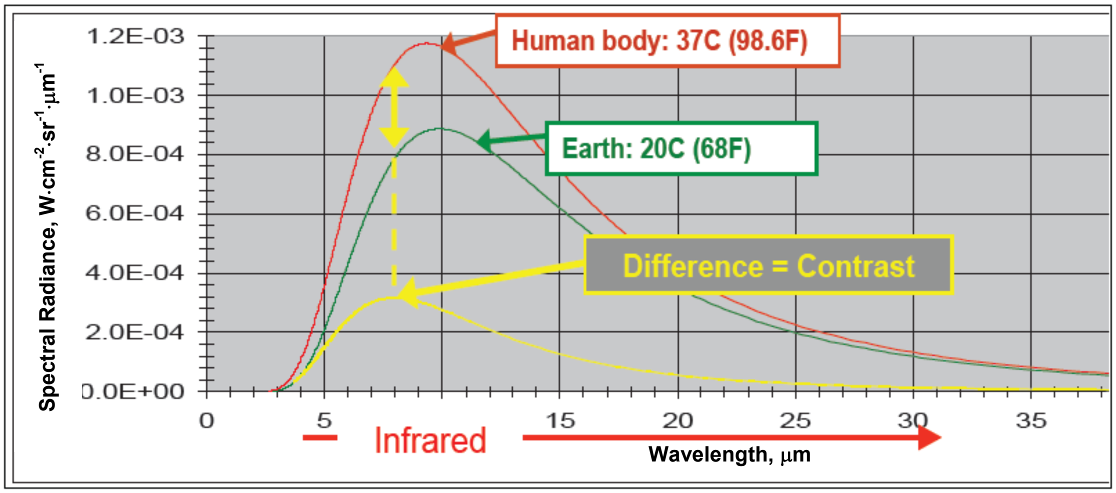


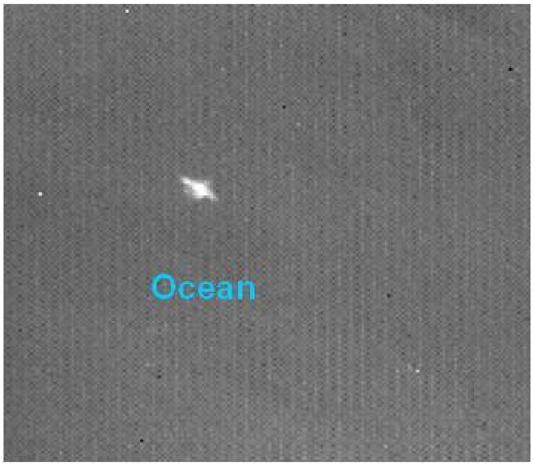
FIGURE 21. Illustration of Spectral Contrast.

It is contrast that makes target detection possible. If there were no difference, that is, no contrast, then the target would be undetectable. Low contrast is the IR equivalent of camouflage or protective coloration used by animals. An example for the visible is a polar bear seen against snow or an ice background.

Contrast can be positive, zero, or negative. The IR images in Figure 22, taken approximately 20 seconds apart, show the same aircraft viewed against three different backgrounds.

Over ocean, the aircraft is seen in a bright, positive contrast against the cool water. As the aircraft crosses an area of mixed vegetation and bare terrain, the contrast is nearly zero as the aircraft is lost in the clutter.

In the final image (Figure 22c), the cooler aircraft airframe is seen as a dark image in strong negative contrast against the warm, uniform terrain.



(a) Positive contrast.

(b) Nearly zero contrast.

(c) Negative contrast.

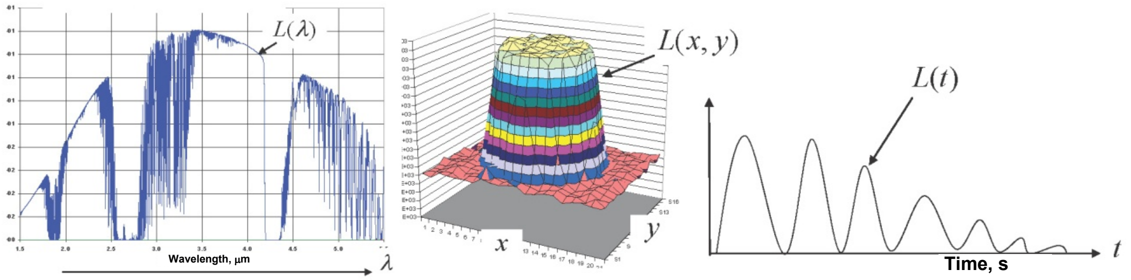
FIGURE 22. IR Imagery of Unidentified Aircraft Over Three Different Backgrounds.

DOMAINS OF DISTRIBUTION

Planck's curve shows the distribution of radiant power in the spectral domain, i.e., as a function of wavelength (see Figure 23). Radiant power is also distributed across other domains (dimensions) (see Figure 23). For aircraft and most other thermal sources, the most important domains are

1. Spectral—distribution of radiant power with wavelength.
2. Spatial—distribution with direction, size, shape. (Example: missile tracking, e.g., determining target direction, is a spatial parameter.)
3. Temporal—distribution with time or frequency.
4. Polarizing—distribution with polarization. This domain is not a strong factor with thermal sources, but is with lasers. Natural, partial polarization occurs with reflections from dielectric materials (paint, water, etc.) and from scattering from particles.

Knowing the distribution of power across different domains is fundamental to almost every IR signature, propagation, and detection scenario.



(a) Spectral. (b) Spatial. (c) Temporal.

FIGURE 23. Three Domains (Dimensions) Across Which IR Is Distributed.

EMISSION FROM SOLIDS

Properties of a surface have a direct effect on the amount of radiant power that is emitted or reflected. Aircraft can be detected by radiation that is directly emitted from hot components, by radiation from the sun or the terrain that is reflected from airframe surfaces, or by both.

Emissivity

The most important surface property affecting the magnitude of radiation from a source is its emissivity (ϵ). Emissivity quantifies the efficiency of a surface as either an absorber or emitter. In 1859, Gustav Kirchhoff expressed what we now call Kirchhoff's law, which says that, for opaque objects in thermal equilibrium, emissivity is equal to absorbance. In other words, good emitters are also good absorbers. Emissivity is a dimensionless quantity between 0 and 1. A surface with an emissivity of 1.0 emits or absorbs the maximum radiation possible.

Emissivity is directly related to reflectivity through the conservation of energy. Incident radiant power striking a surface is absorbed, transmitted, or reflected, so the sum of the quantities describing each equals 1.

$$\epsilon + \tau + \rho = 1$$

where:

ϵ = emissivity or absorbance (0 to 1.0, dimensionless)
τ = transmission (0 to 1.0, dimensionless)
ρ = reflectivity (0 to 1.0, dimensionless)

If the material is opaque, transmission = 0, and emissivity and reflectivity become complements. This relationship has significant implications for aircraft detectability.

$$\epsilon + \rho = 1$$

Reflectivity

Every encounter of electromagnetic radiation with the surface of any material results in some fraction of the incident power being reflected. The law of reflection says that the angle from normal of the reflected radiation will be equal but opposite to the angle of incidence.

We usually classify reflections as either (1) specular (mirror-like) or (2) diffuse (scattered from a rough surface). Most surfaces exhibit both types of reflection to some degree, so it is more a matter of which dominates.

Specular Reflection

Reflections from smooth surfaces are specular. Mirrors are the most familiar specular reflectors. We look into a mirror and see an image of the scene just as we would see it looking directly but with the apparent right–left reversal as a consequence of the law of reflection.

The radiance of any source image one sees from a specular reflection is the radiance of the original source diminished by some loss because no mirror is a perfect reflector. The ratio of the reflected power to incident power is the surface reflectance.

Reflectance is a dimensionless quantity from 0 to 1 (or sometimes expressed as a percentage). A source with a reflectance of 1 would be a perfect reflector. A surface with a reflectance of 0 would reflect no power. The symbol often used for reflectance is the Greek letter *rho* (ρ), although this is not universal.

Diffuse Reflection

Diffuse reflectance occurs when radiation strikes a rough surface and is scattered randomly over a broad angular range. A diffuse reflection does not provide an image as specular does. Most of the objects we see around us are the result of diffuse reflections of some light source. Instead of a reflected image of the source, we see the broadly illuminated surface of the material.

If a surface produces a perfectly diffuse reflection, then an incident ray may be reflected at any random angle. Such a surface is known as Lambertian, and the intensity of reflection from any facet of area will vary as the cosine of angle from the normal.

For a perfectly diffuse reflection, the radiance of an illuminated surface is related to the incident irradiance as

$$L_\lambda = \frac{E_\lambda}{\pi} \rho_\lambda$$

where:

L_λ = spectral radiance ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}}$)
E_λ = spectral irradiance ($\mathrm{W \cdot cm^{-2}}$)
ρ_λ = spectral reflectivity (dimensionless)

EMISSION FROM GASES

Planck's curve describes spectral distribution of radiation emitted by a solid. In a solid, tightly bound molecules emit a continuum, i.e., a continuous spectrum.

In a gas, molecules are free to oscillate. Emission and absorption of radiation occur at discrete spectral "lines." Location of these lines depends upon the gas molecules, as shown in Figure 24.

Two gases with emission/absorption lines in the MWIR are carbon dioxide (CO_2) and water vapor. CO_2 and water vapor are the main combustion products of every hydrocarbon fuel.

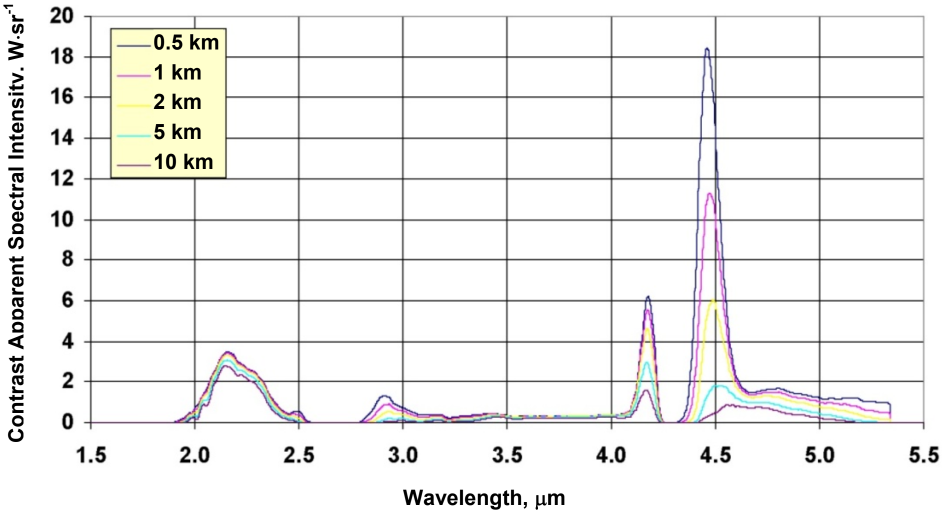


FIGURE 24. Spectral Plot of Line Emission From Jet Engine Exhaust Gases.

PRINCIPLES: KEY POINTS

The IR portion of the spectrum is important to military aircraft for two main reasons:

1. Direct emission enables passive detection and tracking.
2. Target contrast against background is at its maximum in the IR.

The essential IR terms and their units are:

1. Irradiance: Received power density ($W \cdot cm^{-2}$).
2. Radiant Intensity: Emitted power per solid angle ($W \cdot sr^{-1}$).
3. Radiance: Emitted power per solid angle per unit area ($W \cdot sr^{-1} \cdot cm^{-2}$).

Planck's law describes the spectral distribution of radiant power as a function of temperature. As temperature increases, the curve of radiant power increases in magnitude and translates toward shorter wavelengths.

The power emitted from a surface is proportional to its emissivity, which is a relative measure of surface absorption and emission efficiency. The complement of emissivity is reflectivity.

Radiant power is distributed in multiple domains. The most important for aircraft defense are (1) spectral, (2) spatial, and (3) temporal.

Gases emit and absorb at spectral lines according to molecular resonances. The most important emissions for aircraft exhaust gases are from the products of combustion CO_2 and water vapor.

AIRCRAFT IR SIGNATURES

DEFINITION

The IR signature of an aircraft is the total of its detectable emissions and reflections (see Figure 25). Its signature is what makes an aircraft susceptible to detection and tracking by threat sensors and missiles. Signature is the quantity that countermeasure devices and systems must defend.

The word *signature* is widely used but can be misleading because nothing about an aircraft's IR signature uniquely identifies the aircraft type. Signature usually means an aircraft's total contrast intensity; but, like other IR terms and quantities, signature usually requires several additional terms to describe the quantity with precision.

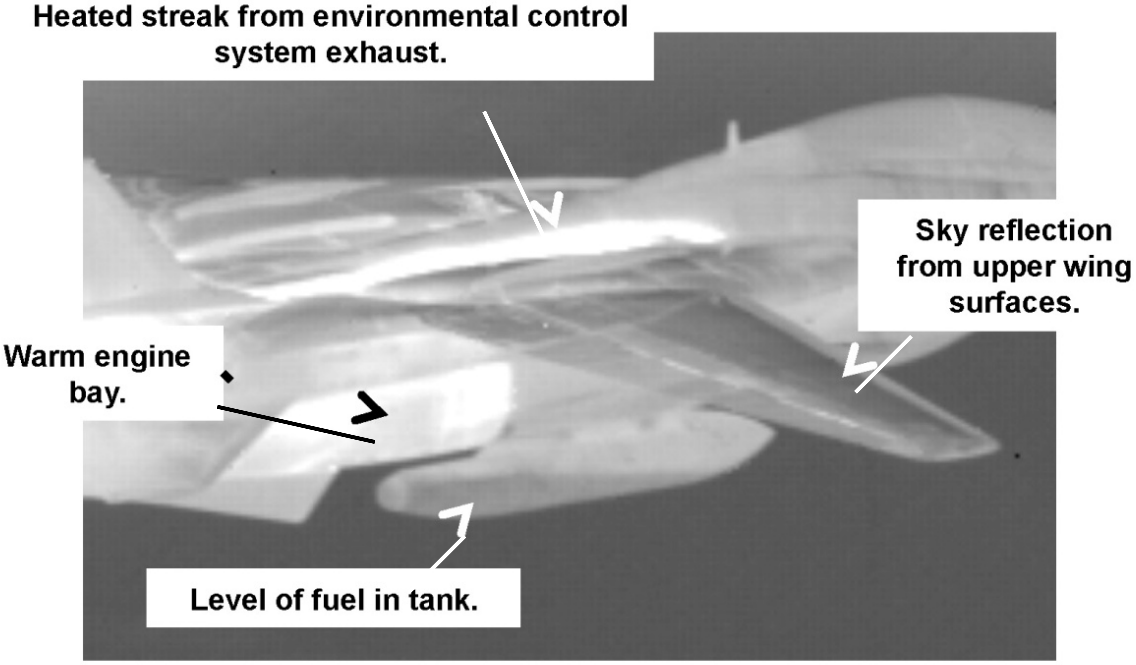


FIGURE 25. IR Image of F-14A. (Some of the complexity of a typical aircraft IR signature can be seen in this image.)

COMPLEXITY

An aircraft’s signature is a complex mixture of emissions and reflections from different materials with different emissivity and different areas. Signature is complex in its spectral distribution, in its contrast against background, and in its dependence on conditions. Aspect angle, altitude, airspeed, ambient air temperature, power setting, and sun angle are only a partial list of conditions affecting signature values.

PRIMARY SIGNATURE COMPONENTS AND COMPONENT DOMINANCE WITH ASPECT

All aircraft IR problems and scenarios are best approached and analyzed by separating the whole into three separate components, each with its own magnitude, spectral distribution, contrast against background, and propagation through the atmosphere to a sensor. These components, shown in Figure 26, are the following.

1. Engine “hot parts,” which usually consist of the aft turbine face, engine center body, and interior nozzle sidewalls.
2. Engine exhaust plumes, which are emissions from the combustion constituents of CO_2 and water vapor. Note the shock diamonds in the IR image (Figure 26).
3. Airframe, which includes all of the external surfaces of the wings, fuselage, canopy, etc. Airframe signature includes solar and terrestrial reflections in addition to direct emissions.

These components are discussed in more detail in the subsections that follow.

Radiation from each component has a different spectral distribution and, consequently, propagates through the atmosphere with different degrees of attenuation.

The total IR signature of an aircraft is the sum of its components, but each component does not make an equal contribution at all aspects. As Figure 27 shows, a component’s contribution to the total IR signature of an aircraft depends upon aspect angle. For a typical aircraft or helicopter, the dominant mid-wave signature component(s) in each region are as follows:

1. Tail: Engine hot parts
2. Rear Quarter: Hot parts and exhaust plume
3. Beam to Forward Quarter: Airframe and exhaust plume
4. Nose: Airframe and intakes

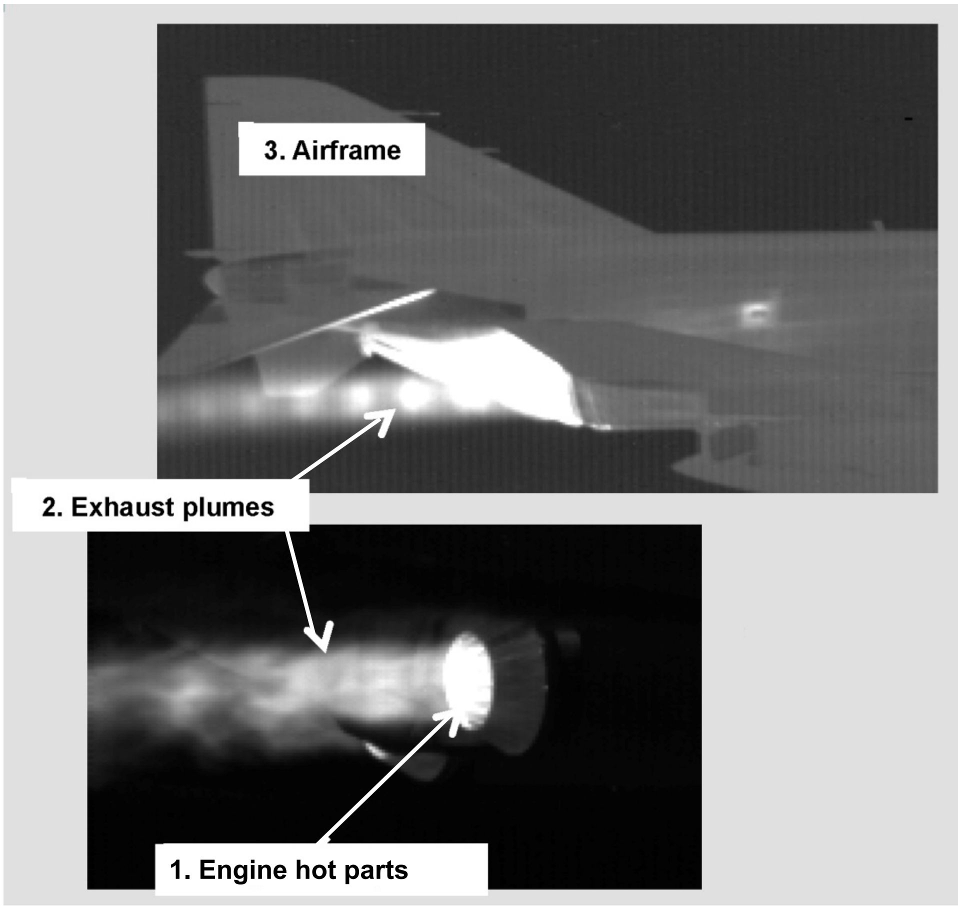


FIGURE 26. IR Images of F-4N. (For measurement and analysis, total aircraft signature is divided into three components with different properties.)

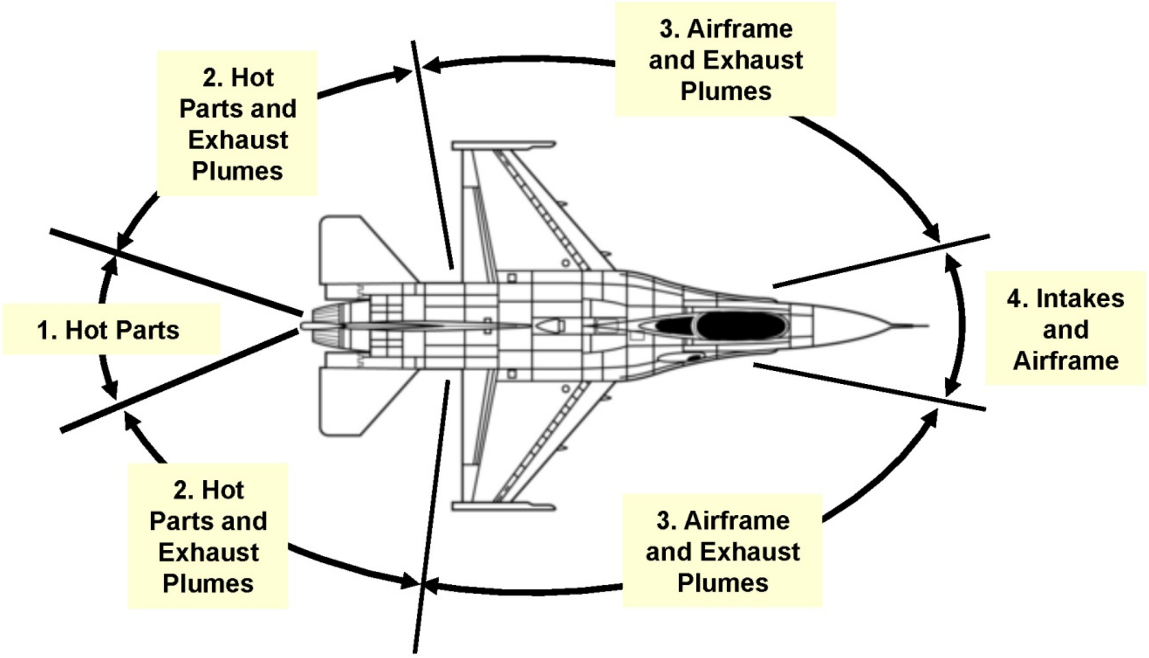


FIGURE 27. Drawing Showing Component Signature Dominance With Aspect Angle.

Engine Hot Parts

Description

The hot parts of an aircraft engine are any visible surfaces within or without that are heated to high temperatures by the exhaust gases. In most jet and turboprop engines, the highest temperature component visible is the face of the last turbine stage, usually called the low-pressure turbine.

The turbine face usually appears as a bright high-radiance ring. In the center of the ring is the hub, or center body cover over the turbine shaft support bearings. The center body usually has a lower radiance than the turbine face. Figure 28, an MWIR image taken up the tailpipes of a jet in flight, shows the bright high-radiance ring formed by the low-pressure turbine face surrounding the lower radiance center body.

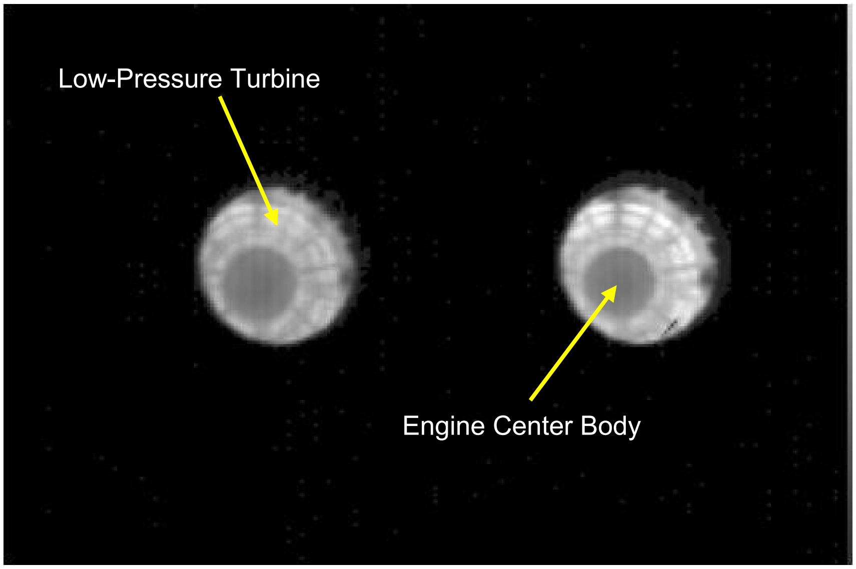


FIGURE 28. MWIR Images of Hot Parts Seen Up Tailpipes of Jet Aircraft. (Older aircraft engines allow a direct view of the aft turbine face, which is the highest temperature component visible.)

These parts are viewed within a cavity whose surrounding walls are typically lower in temperature but often reflect emissions from the hot turbine. Close-up, resolved imagery allows measurement of radiance values of different parts within the cavity.

Spectral Distribution

Hot parts are solid materials and, consequently, have a spectral distribution in accordance with Planck's law (see Figure 29). The temperatures of engine hot parts vary greatly, but typical ranges are from approximately 450 to 650°C. As such, the maximum emissions are in the middle of the MWIR. It is no accident that the spectral response of almost all antiaircraft missiles is located in the mid-wave.

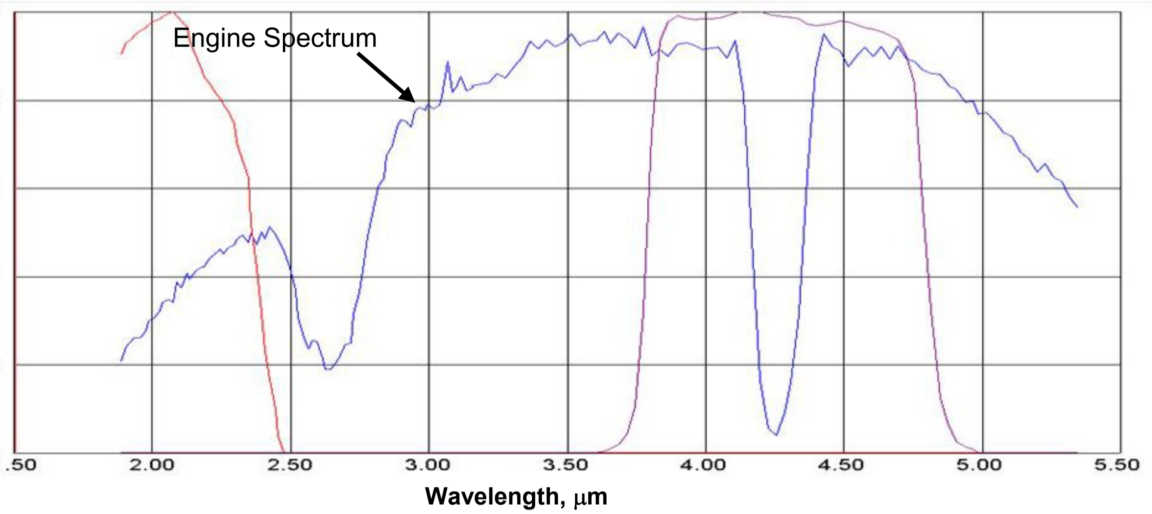


FIGURE 29. Spectrum of Jet Engine at Tail. (Spectral distribution of emissions from hot parts is in accordance with Planck's law. Unsuppressed engines have their maximum emissions in the MWIR, where most antiaircraft missiles operate.)

Engine Exhaust Plumes

In a gas, molecules are not bound together as in liquids or solids and so are free to oscillate. The resonant frequencies of these oscillations cause emission and absorption of radiation in gases to occur at discrete spectral lines. The location of these lines in the spectrum depends upon the type of gas.

Two gases with emission/absorption lines in the MWIR are CO_2 and water vapor (see Figure 30). CO_2 and water vapor are the main combustion products of every hydrocarbon fuel. The atmosphere also contains water vapor and CO_2 with emission/absorption lines at the same wavelengths.

As a result, plume emissions are absorbed by passage through the atmosphere to a greater degree than emissions from hot parts and the airframe. Plume emissions usually have less impact on threat-acquisition ranges than the other signature components. Absorption of plume emissions is significantly greater at lower altitudes where air density is greater.

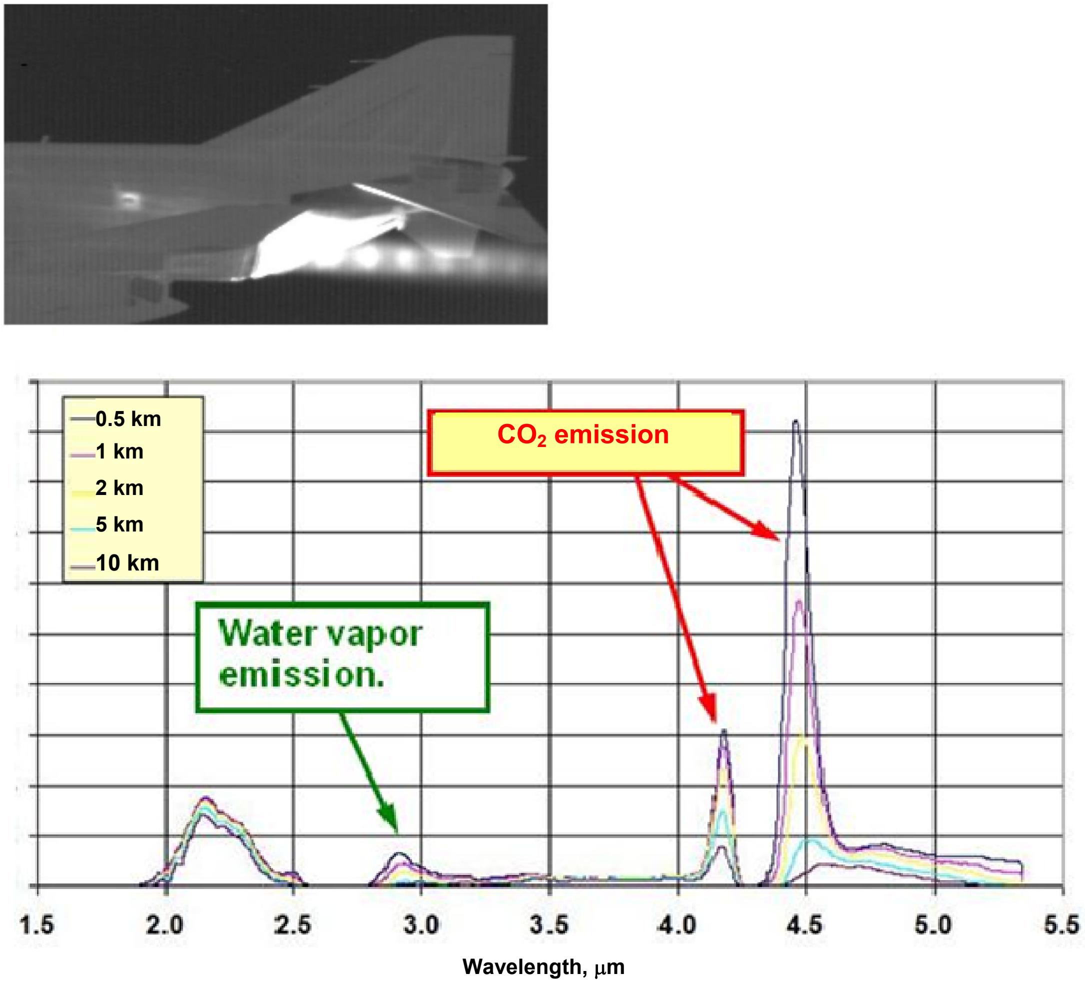


FIGURE 30. Spectrum of Exhaust Plume at Beam. (Spectral distribution of emissions from gases occurs at discrete lines or spikes.)

All exhaust plumes have similar spectral distributions. Differences in gas temperature and mass flow affect the magnitude of gaseous emission but not the location of the spectral lines.

Plume size or spatial extent varies greatly depending upon mass flow, as well as whether the exhaust gases are used to generate thrust. Plume radiance is greatest at the exit nozzle and diminishes with distance as the exhaust gases are cooled by mixing with the air. The plume of a jet aircraft engine may be 50 feet or more in length. The plume of a helicopter or turboprop engine may be only 4 or 5 feet in length, as shown in Figure 31.

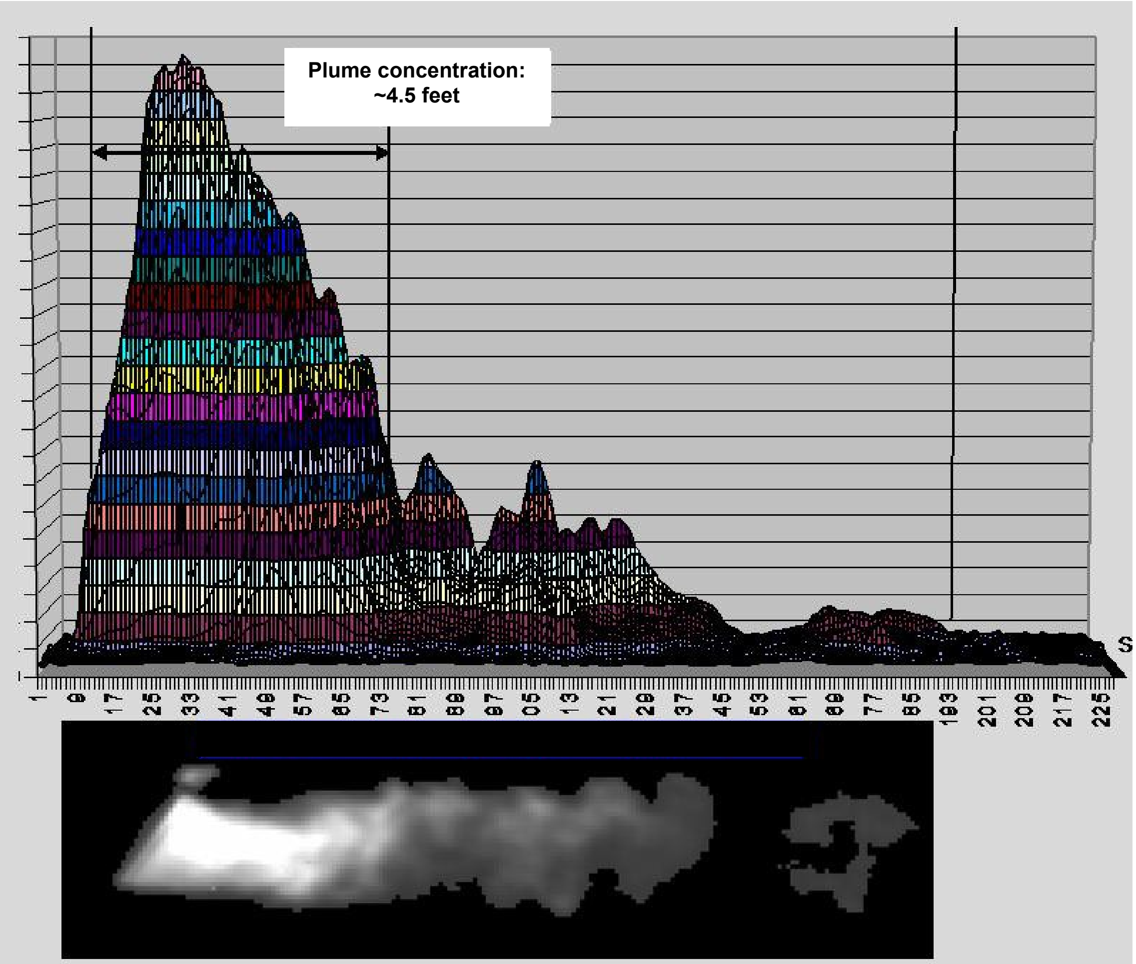


FIGURE 31. Radiance Map of Exhaust Plume at Beam. (Plume radiance diminishes after exiting the exhaust nozzle as the hot gases are mixed with surrounding air.)

Hot Parts and Plume Emissions

Some of the complexity of aircraft signatures is illustrated in Figure 32. The image at the left is of helicopter engine hot parts and plume. These two components are distributed in the spatial domain as shown in the radiance contour map.

The same components each have different spectral distributions. Hot parts have a distribution in accordance with Planck's law. The plume emissions are at discrete lines for CO_2 and water vapor.

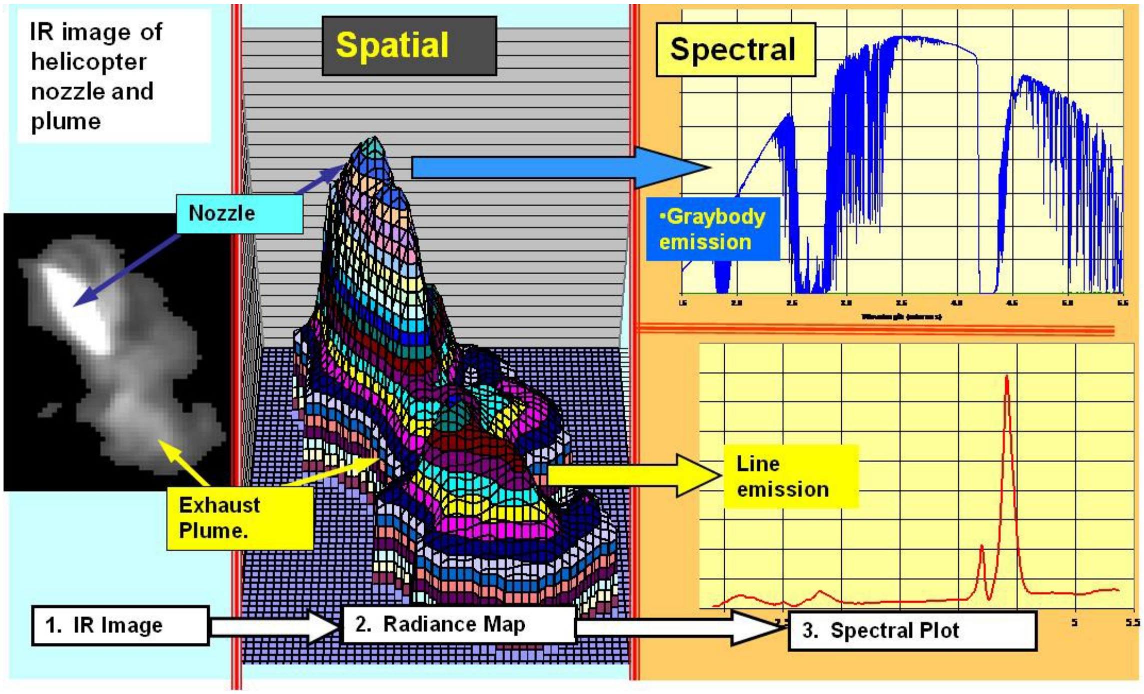


FIGURE 32. IR Image (1), Radiance Map (2), and Spectral Plot (3) of Helicopter Nozzle and Plume.

Airframe

Absolute and Contrast Signature

The terms *absolute* and *contrast* have very specific meanings, especially when applied to the airframe.

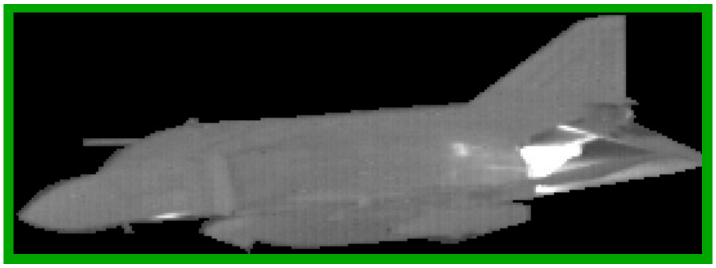
Absolute is the target signature without background radiation. Absolute signature values are obtained by extracting the aircraft from the background by using highly resolved IR imagery. Because a resolved condition is required, absolute quantities are limited to the two source quantities of intensity and radiance.

Contrast is the difference between absolute target and absolute background radiance. Contrast can be applied to the three main IR quantities: radiance, radiant intensity, and irradiance.

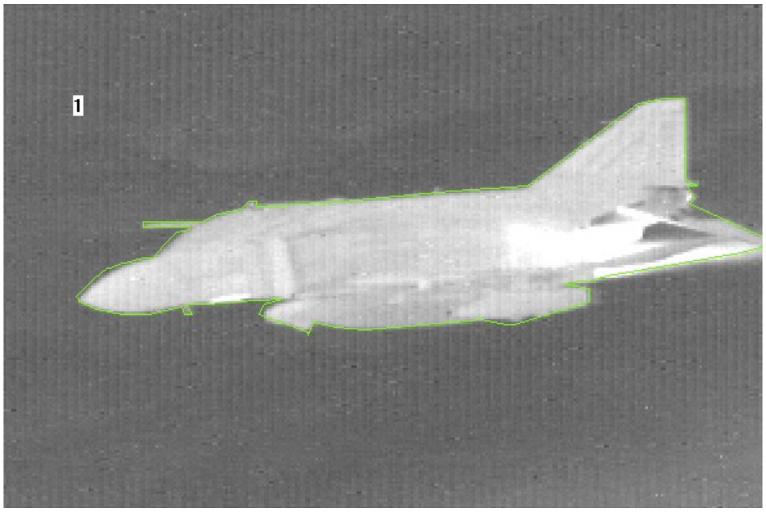
Contrast irradiance is the quantity detected by any remote sensor or missile. Contrast varies greatly with background conditions. There is an inverse relationship between background and the contrast signature—generally, the higher the background, the lower the contrast signature.

Airframe Contrast Variability

Usually, the largest variability in airframe contrast signature comes from the background. Contrast can change rapidly from a strong positive contrast against the sky, through nearly zero, to strong negative contrast against warm terrain (see Figure 33).



(a) Absolute signature.



(b) Contrast signature.

FIGURE 33. Absolute and Contrast Signatures. (Absolute is the target signature in isolation from background sources. Absolute signature values can only be positive. Contrast is derived from the difference between the target and the background. Contrast values can be positive or negative.

Contrast Signature Factors

Of the three aircraft signature components, the airframe is the most condition dependent and consequently the most variable. Three of the main factors affecting airframe contrast signature are the following.

1. Background radiance level. Usually, the lowest background radiance occurs against a clear sky and, consequently, results in the greatest contrast and highest detectability. Airframe contrast against a clear sky is also variable and depends upon elevation above the horizon. Figure 34 shows an aircraft at long range in the MWIR. The green figure shows a vertical profile of radiance through the scene. Radiance of the sky has a gradient that increases toward the horizon. The target radiance indicated is greater than that of the sky, thus giving a positive contrast.
2. Airframe temperature and emissivity. These properties determine direct emissions in accordance with Planck's law. As Figure 35, an IR image of an F-4 aircraft at high subsonic speeds, shows, the canopy has similar temperature and emissivity as standard paint. Temperature is affected by air ambient and aerodynamic heating (described in the following subsection).
3. Solar and terrestrial illumination. The airframe signature is a mixture of direct emissions and reflections of the environment. The intensity of these reflections depend upon the reflectivity of the airframe surface (complement of emissivity), on the irradiance of the illumination, and on the projected area.

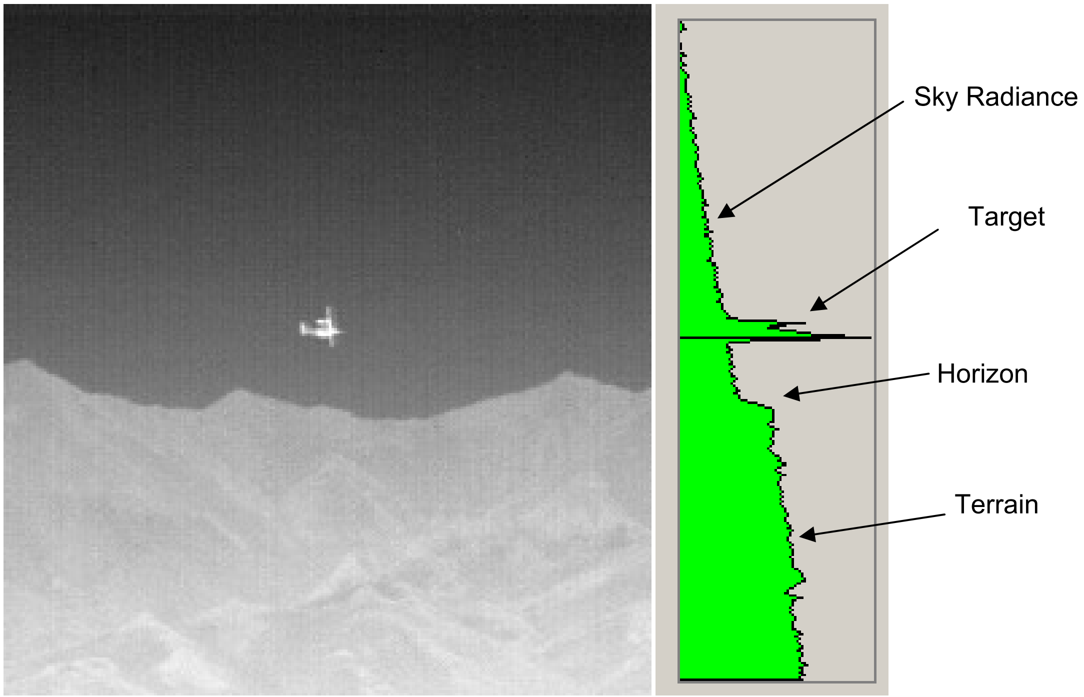


FIGURE 34. Aircraft at Long Range in MWIR. (This image shows an aircraft in contrast against sky radiance gradient. The clear sky is a worst-case background for the aircraft. Background level varies with elevation above the horizon, as the image at right shows.)

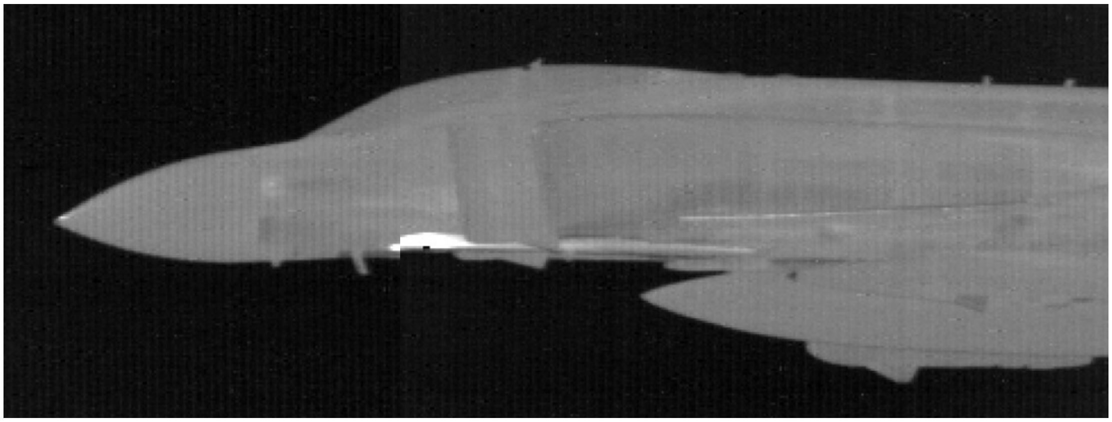


FIGURE 35. IR Image of F-4 Airframe at High Subsonic Speed.

Airframe Aerodynamic Heating

The temperature of the airframe is warmer than ambient by the amount of aerodynamic heating. A good estimate of airframe temperature is given by the formula for the recovery temperature given below. Note that the temperature units are Kelvin.

The temperature of the skin of an aircraft stabilizes at the ambient air temperature plus aerodynamic heating. Aero heating increases as the square of Mach number. The formula below gives a good approximation for most uses.

$$T_R = T_0(1 + 0.17M^2)$$

where:

T_R = recovery temperature, K
T_0 = ambient air temperature, K
M = Mach number (assumption is recovery factor = 0.85 approximately midway between laminar and turbulent flow)

Illumination Sources, Reflections, and Surface Orientation

The effects of illumination from the sun, sky, and terrain on airframe contrast seen by a ground-based sensor or missile are illustrated in Figure 36. A sensor always sees a mixture of direct and reflected radiation. Airframe surfaces, regardless of orientation, have a direct emission thermal component whose distribution is in accordance with Planck's law.

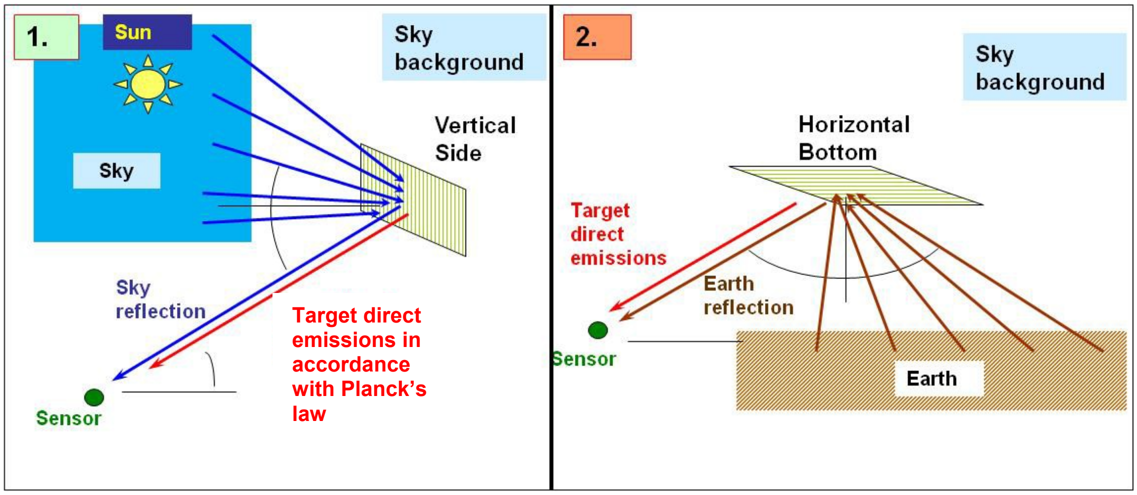


FIGURE 36. Illumination Sources and Reflections. (The effect of different illumination sources on airframe contrast against the background depends on the orientation of the surface.)

Vertically oriented side surfaces reflect the sky and sun if viewed from the sunlit side. These are seen in contrast against sky background. If the sun is not present, contrast can be reduced by making the vertical surfaces more reflective than emissive.

Horizontally oriented bottom surfaces reflect illumination by the earth. Bottom surfaces are problematic to lowering airframe signature. Whether contrast will be lower if the surface is more emissive or more reflective depends upon the temperature of the airframe compared with that of the terrain below.

AIRCRAFT IR SIGNATURES: KEY POINTS

Aircraft IR signatures are usually separated into three main components for independent measurement and analysis:

1. Engine hot parts, which usually consist of aft turbine face, engine center body, and interior nozzle sidewalls.
2. Engine exhaust plumes, which are emissions from the combustion constituents of CO_2 and water vapor.
3. Airframe, which includes solar and terrestrial reflections in addition to direct emissions.

Different components dominate the total at different aspects and flight conditions. These components have different spectral and spatial distributions. Figure 37 illustrates the complexity of a typical aircraft IR signature.

FIGURE 37. Aircraft IR Signature Complexity. (MWIR image of F-14A showing engine dominance at tail, solar reflections from the top of the fuselage, and sky reflection from the top of the wing surfaces.)

PROPAGATION AND DETECTION

INTRODUCTION

It is not the IR emissions from an aircraft that ultimately determine its detectability by threat sensors. Detectability is determined by what remains of an aircraft's radiation after it has passed through an atmospheric path and as it is seen in contrast against a natural background.

The atmosphere plays a dual role in aircraft detection, first as a medium of propagation and second as a background source against which aircraft are often contrast. Figure 38 shows how an aircraft appears at missile detection ranges when seen against a thin cloud background.

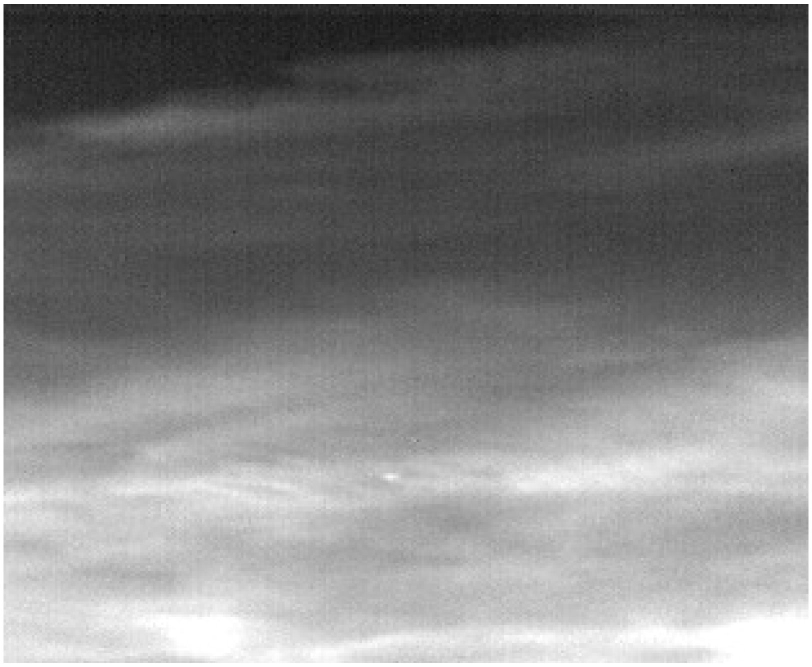


FIGURE 38. Aircraft IR Image at Missile Acquisition Range. (Ground-to-air IR image of an aircraft nose-on against broken cloud background at a range of 7.6 nautical miles taken with a commercial IR camera.)

ATMOSPHERE AS MEDIUM

Atmospheric Transmission

The atmosphere is spectrally selective in its effect on radiation. The MWIR, which is the primary antiaircraft region, is characterized by deep absorption regions separated by regions of relatively high transmission called atmospheric "windows."

Spectral transmission of the atmosphere is made complex as a result of two separate mechanisms: molecular absorption and scattering. In the primary antiaircraft threat bands, molecular absorption is usually the dominant effect.

Molecular Absorption

Of the mixture of gases that make up the atmosphere, only two of the trace gases—water vapor and CO_2—have molecular resonant frequencies that fall within the MWIR, but both have a significant effect on aircraft signature propagation. Molecules absorb and emit radiation at their natural resonant frequencies, and this behavior creates spectral regions in which all or most of the radiation from a source is absorbed.

The depth and spectral width of the absorption regions depend upon the number of molecules in the path, so absorption width is greater for longer path lengths and greater at lower altitude, where air density is higher.

The density of CO_2 is a direct function of pressure. The density of water vapor is a function of both pressure and temperature. As altitude increases, molecules of water vapor in a path decrease more rapidly than those of CO_2 due to the lower saturation density of water vapor with colder temperature. At altitudes above 30,000 feet, absorption by water vapor can usually be eliminated as a factor in propagation. Figure 39 shows the changes in atmospheric transmission in the MWIR with range.

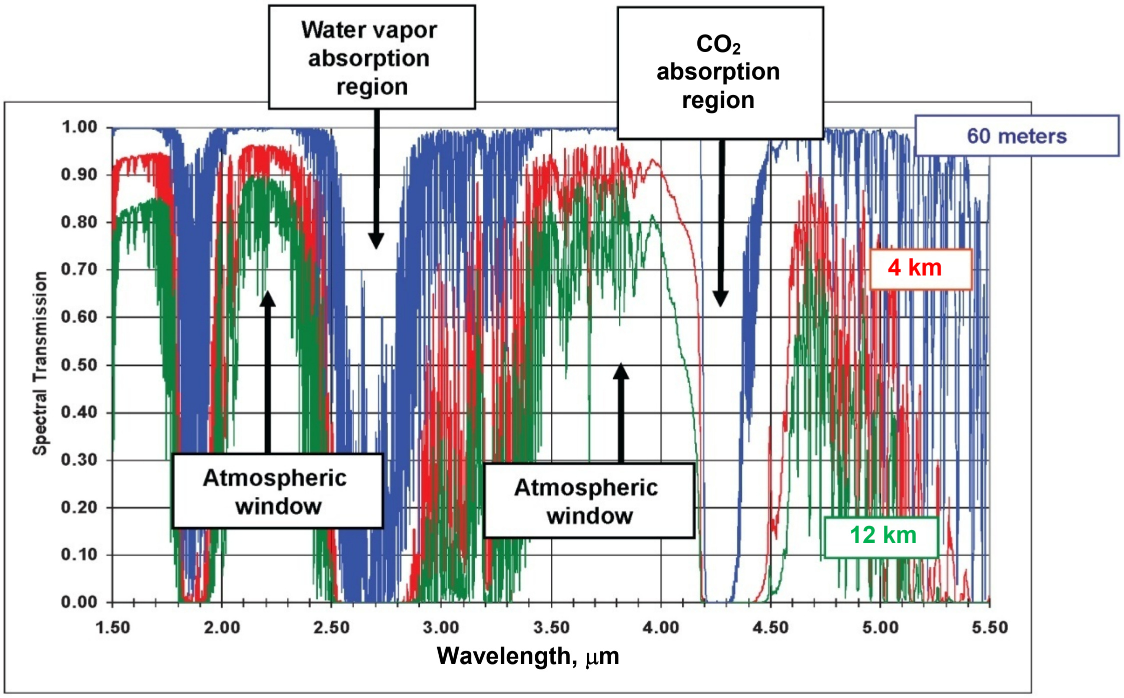


FIGURE 39. Atmospheric Spectral Transmission
in MWIR at Three Ranges.

Effect on Plume Signature Component

Because the three main components of aircraft signature have different spectral distributions, they are affected by propagation through the atmosphere to a different extent. The signature component most attenuated by atmospheric absorption is the engine exhaust gases.

Water vapor and CO_2 are the two main products of combustion in an engine. As hot gases, these emit at discrete spectral lines according to molecular resonances. Absorption by water vapor and CO_2 in the air occurs at these same lines.

The high temperature and pressure of the exhaust gases cause broadening of the emission lines, thus allowing passage through the absorbing atmosphere. Figure 40 presents the effect of pressure broadening most prominently with CO_2, even at the low resolutions shown in that graph. CO_2 emissions viewed through narrower CO_2 absorption result in narrow "spikes," termed "blue" on the short wavelength side of absorption and "red" on the long wavelength side.

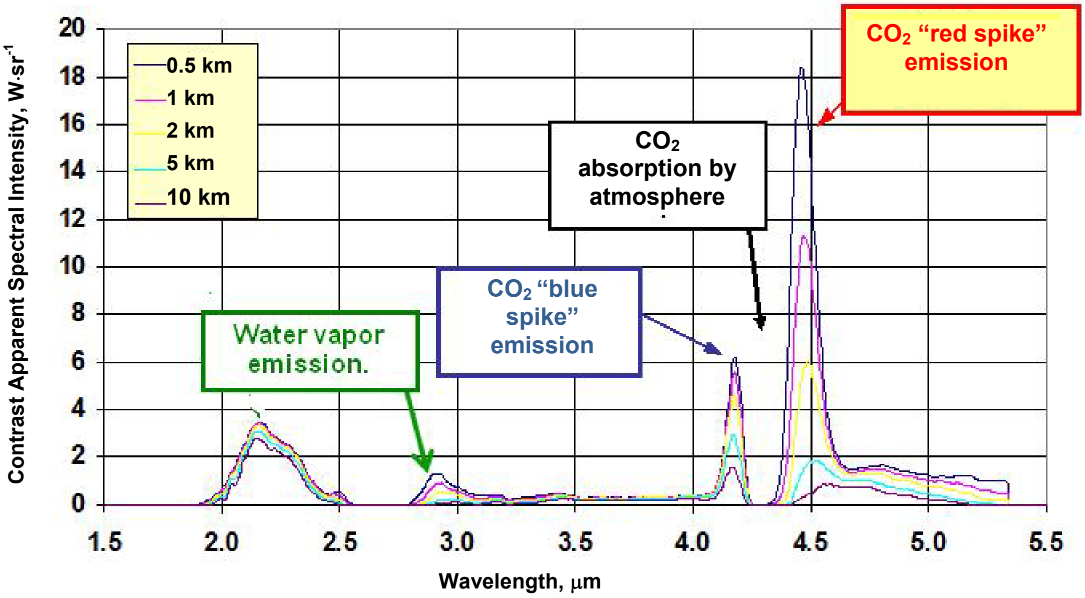


FIGURE 40. Spectrum of Exhaust Plume Through Atmosphere. (Exhaust gases emit at the same spectral lines that the atmosphere absorbs. Spikes of plume emissions are seen on either side of the absorption regions due to pressure broadening of plume emissions.)

IR TERMS: APPARENT AND AT SOURCE

All tactical aircraft are viewed through an atmospheric path of some length. The atmosphere is spectrally selective, totally absorbing some parts of the spectrum while passing other parts with little attenuation. As a result, the effect of the atmosphere on what a distant sensor receives depends on three factors: (1) the spectral distribution of the source, (2) the spectral transmission of the atmosphere, and (3) the wavelength band of the sensor.

Any IR quantity that has atmospheric influence is referred to as "apparent." Almost all IR values are apparent, although the name is frequently omitted.

Mathematically backing out the influence of atmosphere can be done but usually with a high degree of uncertainty. Any apparent value that has had atmosphere artificially removed is referred to as “at source.” Figure 41 provides a graph that illustrates the apparent and at source values.

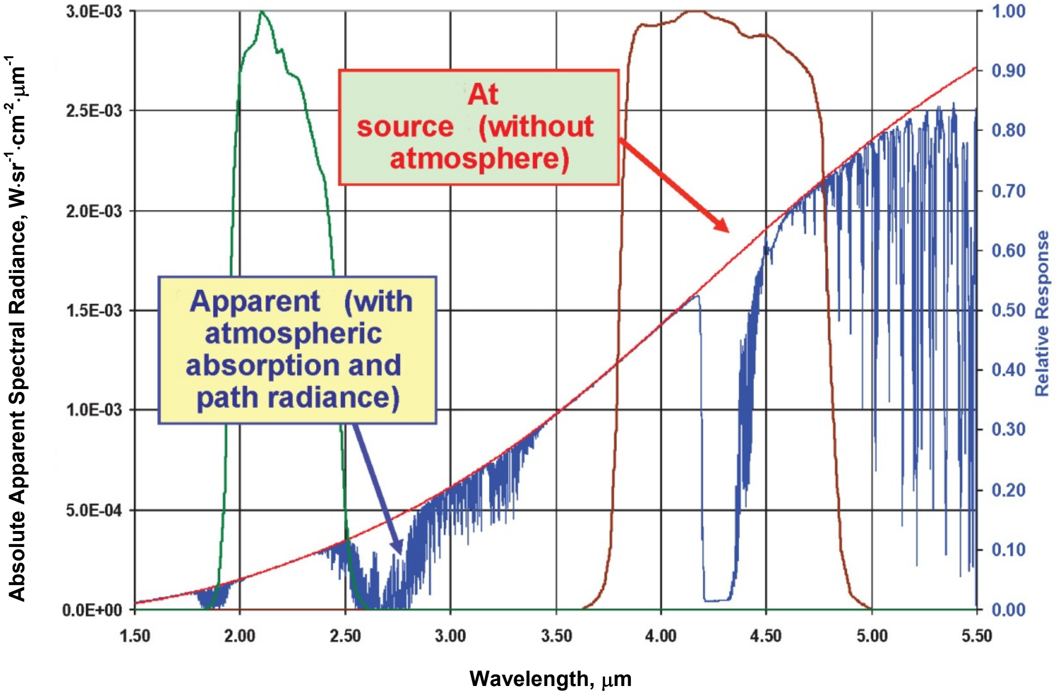


FIGURE 41. Illustration of Apparent and At Source. (The term *apparent* should be applied to any IR quantity that contains the effects of atmospheric absorption and path radiance. A theoretical quantity with no atmosphere is usually referred to as “at source.”)

PATH RADIANCE AND SKY BACKGROUND

Where atmospheric transmission is low, the atmosphere itself becomes a source. The same two mechanisms of molecular resonances and scattering that affect transmission also affect what is referred to as “path radiance.” The curve in Figure 42 shows the spectral radiance of a path to space at low elevation above the horizon. The radiance of an “infinite” path forms the background against which aircraft are contrast.

The scattering of sunlight by aerosols in the air dominates path radiance at wavelengths shorter than about 3 µm. Thermal emission from molecular resonances dominates at longer wavelengths. Thermal emission is chiefly seen in the CO_2 emission/absorption band around 4.25 µm, where absorption is total.

For shorter paths, the radiance between the sensor and target becomes an additive term to the received radiance from a resolved target.

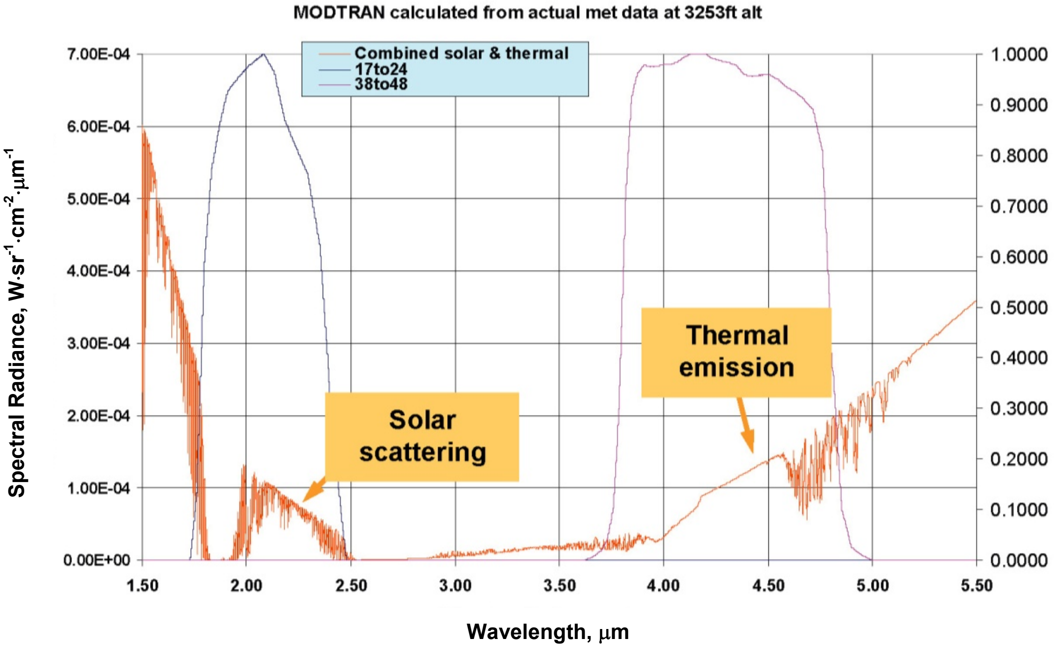


FIGURE 42. Radiance of Long Atmospheric Path. (In addition to transmission, any path through the atmosphere presents a source that is additive to the target and background. In the mid-wave, shown above, two different mechanisms create the path radiance: scattering of sunlight at short wavelengths and direct thermal emissions at longer wavelengths.)

RECEPTION AND DETECTION

IR sensors, missiles, search systems, and measuring instruments have many of the same functional elements (Figure 43). The most common elements are

1. Optics, which collect radiation and, usually, form an image from which information can be extracted.
2. Filters, which may be of two different types operating in two different domains:
   a. Spectral. A spectral filter restricts response to a limited band of wavelengths to help distinguish known target features from natural background.
   b. Spatial. A spatial filter usually is used to (1) determine target direction for tracking and (2) help distinguish a valid target from background.

3. A detector, which converts received radiant power into an electrical signal. The detector may be a single element or, more likely today, may be an array that can determine spatial information in addition to generating a signal.
4. Processing electronics, which amplify and condition the detector signal and perform some action, such as controlling a servo for target tracking.

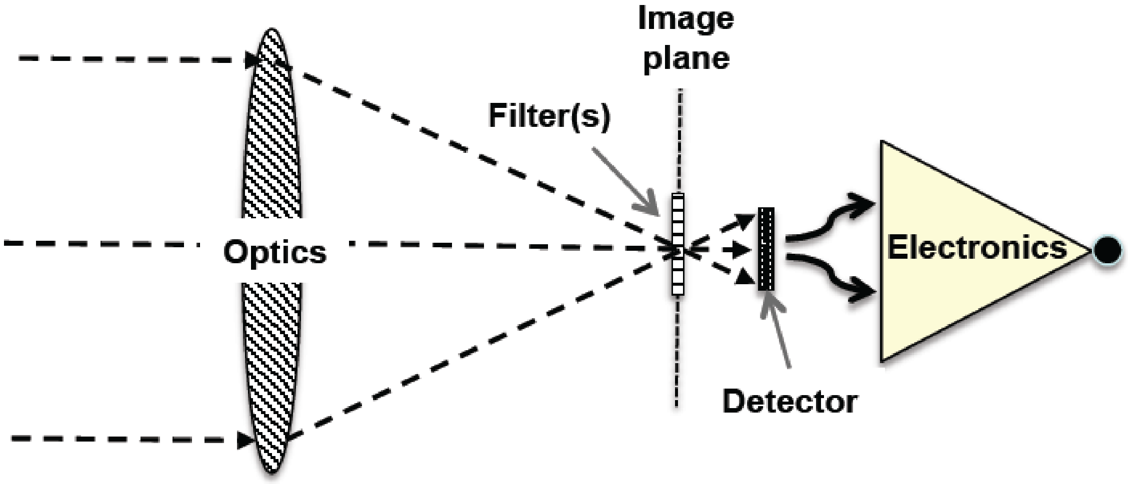


FIGURE 43. Functional Elements in Typical Optical Train.

Optics

Lenses for the IR can be either refractive or reflective. There are advantages and disadvantages to each. Refractive lenses, which can often be made with a lower f-number, afford greater light-gathering power than equivalent reflective lenses but have chromatic aberration that must be corrected with multiple elements of different materials. Chromatic aberration is caused by dispersion that produces differing amounts of refraction and a consequent different focal point at different wavelengths.

Reflective optics, made with curved mirrors, do not have chromatic aberration but are often physically larger for the same focal length and f-number. There are many different designs and configurations of each. Missiles commonly use a Cassegrain, shown in Figure 44. The Cassegrain design is compact in size for its focal length.

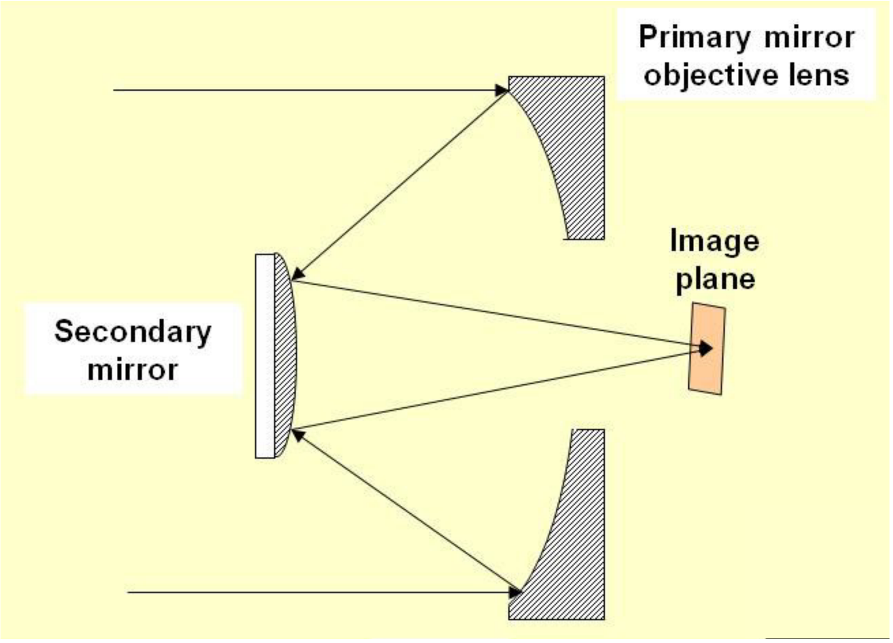


FIGURE 44. Cassegrainian Telescope.

Objective Lens

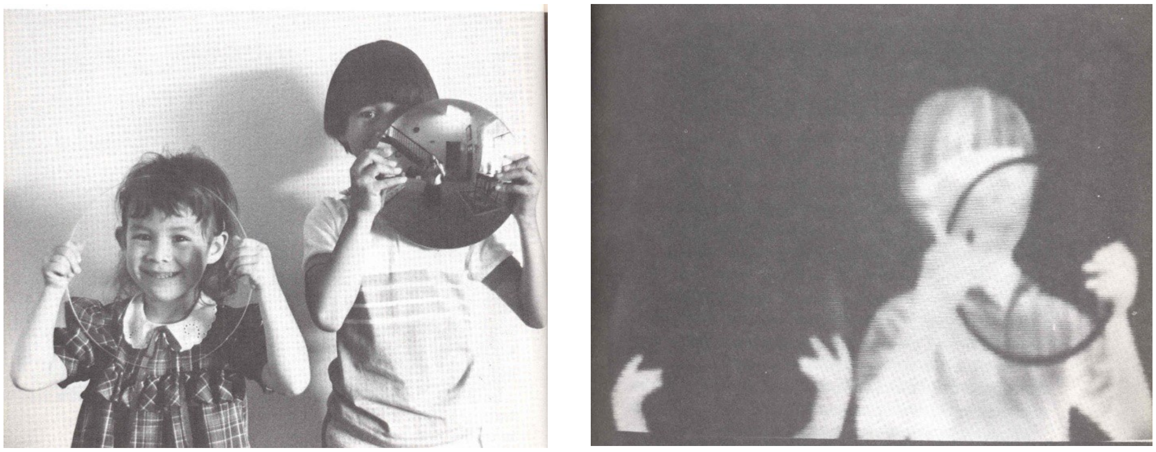
Two main functions of the first optical element (the objective lens) in a typical instrument or missile are the following:

1. Collect radiation (i.e., multiply irradiance [power density] by collecting over a large area and focusing onto a small area).
2. Form an image of the target scene onto a filter and detector array.

Optical Materials for IR

Common optical materials for lenses and windows in the visible part of the spectrum are not transparent in the MWIR and long-wavelength IR (LWIR) (and vice versa). As shown in Figure 45, glass is completely opaque in the IR, while germanium is the opposite.

There are many different materials that are transparent in the IR. The two most common are silicon and germanium. Because of their high indices of refraction, both silicon and germanium must be anti-reflection coated to reduce surface losses.



(a) Visible.

(b) LWIR (8 to 12 μm).

FIGURE 45. Common Materials in Visible and IR. (Photographs were derived from Reference 1). (The little girl is holding a piece of glass, which is transparent in the visible but opaque in the IR. The boy has a piece of germanium, which is opaque in the visible but highly transparent in the IR.)

Spectral Filters

Spectral filters restrict sensitive wavelength range. Reasons for filtering include enhancement of target-to-background contrast, avoidance of unwanted plume emissions and/or atmospheric absorption regions, and extraction and measurement of target spectral features.

Most spectral filters are of the thin-film interference type. Layers of dielectric material are vacuum deposited on a substrate window material. Typical substrate materials in IR are sapphire, silicon, and germanium. The thickness of the deposited layers is designed to have constructive interference to pass desired radiation at desired wavelengths and to have destructive interference to block undesired wavelengths, as shown in Figure 46.

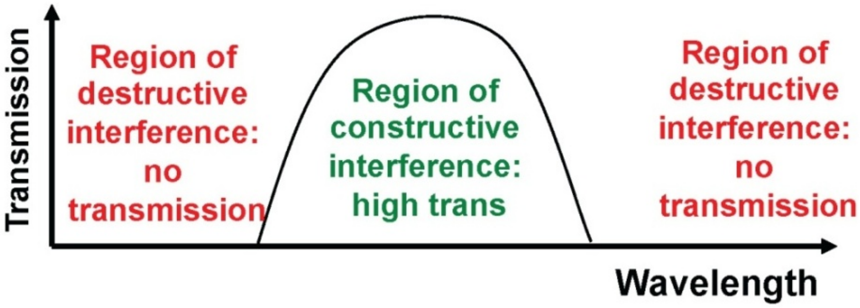


FIGURE 46. Drawing Showing That Most Spectral Filters Work by Interference of Radiation Wave With Itself. (Regions of constructive interference have high transmission. Regions of destructive interference have low or no transmission.)

Spatial Filters

A spatial filter separates information in a scene image by features such as size or position. Spatial filters take a variety of forms. Some common types and their functions include the following:

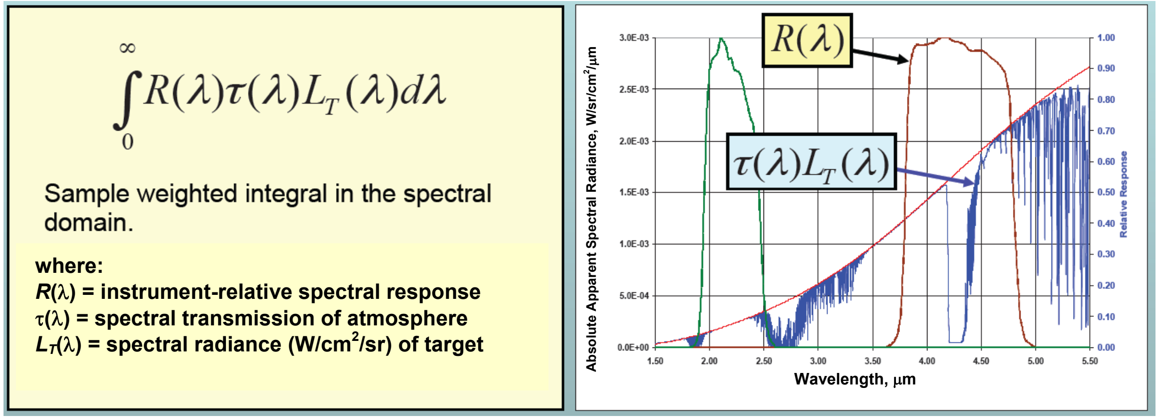
1. Field stop—limits an instrument's FOV; blocks unwanted sources (such as sun) outside nominal FOV.
2. Mechanical modulator, or "chopper"—
    - Partial FOV: performs automatic subtraction of background radiation.
    - Total FOV: alternates between unknown target to be measured and known internal reference source.
    - Reticle (a mechanical modulator used in many missile designs): usually discriminates against extended sources (such as background) in favor of "point" target sources and provides target directional information from modulation phase.

IR Detectors and Detector Response

IR detectors are transducers that convert received radiation into an electrical signal. The two basic detection mechanisms are thermal and photon.

1. Thermal—received radiation causes temperature increase. Electrical signal is created directly or indirectly by temperature rise. Some common examples are
    - Microbolometer arrays—low-cost thermal imaging systems available in some cars.
    - Pyroelectric detectors—change in capacitance with change in radiation. Pyroelectrics are low-cost detectors commonly used in intrusion alarms to turn on outside lights, etc.
2. Photon—received photons free current carriers in semiconductor. These mechanisms usually require cryogenic cooling (typically liquid nitrogen). Two modes of photon detection are
    - Photoconductive—were popular in the 1970s and 1980s. Electrical resistance is indirectly proportional to incident radiation. This mode requires direct current electrical bias.
    - Photovoltaic—are the most common today, especially in arrays. This type is more sensitive with lower noise than photoconductive.

The response of any instrument is a weighted integral of the instrument spectral response, the atmospheric spectral transmission, and the spectral distribution of the target's radiation, as shown in Figure 47.



$$\int_0^\infty R(\lambda)\tau(\lambda)L_T(\lambda)d\lambda$$

Sample weighted integral in the spectral domain.

where:
$R(\lambda)$ = instrument-relative spectral response
$\tau(\lambda)$ = spectral transmission of atmosphere
$L_T(\lambda)$ = spectral radiance (W/cm^2/sr) of target

FIGURE 47. Weighting in Spectral Domain Shown Mathematically and Graphically. (All Instruments and Sensors, Including Missiles, Respond to Multi-Dimensional Integral of Their Responses Convolved With Corresponding Distributions of Received Radiant Power in Different Domains.)

IR Detector Arrays

The greatest advance in IR detectors in the last 10 years has been in detector arrays. Just as silicon detector arrays have transformed photography with a greater number of pixels and lower costs, there have been a steady increase in the number of pixels in IR arrays and a reduction in cost. The availability of larger size and lower cost arrays has changed every aspect of IR sensing, from instruments for measurement to missile seekers.

There are many different IR detector materials, but most of the recent advances have been in two:

- Indium antimonide (InSb)—MWIR of approximately 1.5 to 5.5 µm
- Mercury cadmium telluride (HgCdTe)—LWIR of approximately 2 to 14 µm (photoconductive) and of approximately 2 to 10 µm (photovoltaic)

Detector arrays for the IR will never approach silicon for density and uniformity, but commercial arrays now come in a range of formats, from 128 × 128 to 1,280 × 1,024 pixels. InSb array technology is currently more mature and lower in cost than HgCdTe, with a larger array sizes, higher yields (fewer bad pixels), and better pixel-to-pixel uniformity.

TARGET ACQUISITION

Contributing Factors to Acquisition

Acquisition of an aircraft by a threat sensor such as an IR missile or search/tracker depends upon a number of factors:

1. Total contrast signature of the aircraft at the viewing aspect and against its natural background, as shown in Figure 48.
2. Propagation of the aircraft contrast signature through the atmospheric path between the aircraft and potential shooter.
3. Sensitivity threshold (minimum trackable irradiance) of the missile.

The factors involved in acquisition of a target by a ground-to-air sensor are made complex by changes in background radiance with elevation angle and atmospheric transmission over a slant path of varying length and elevation angle. Typical geometry for a surface-to-air missile is shown in Figure 49.

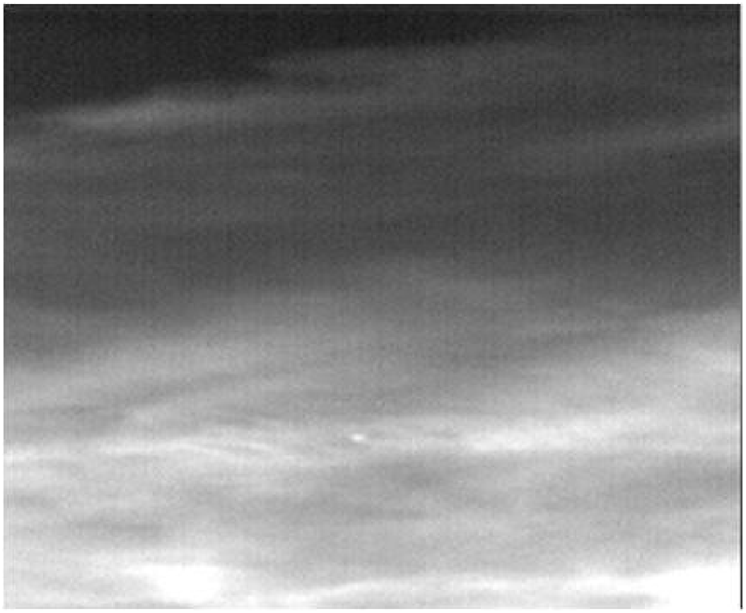


FIGURE 48. IR Image of Aircraft at Missile Acquisition Range. (The aircraft is clearly distinguished against a thin cloud background with a commercial IR camera.)

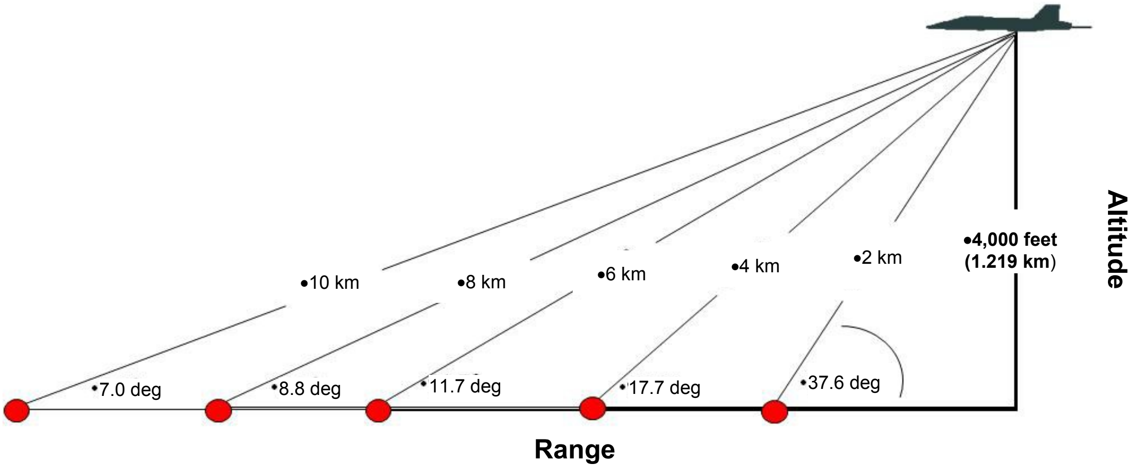


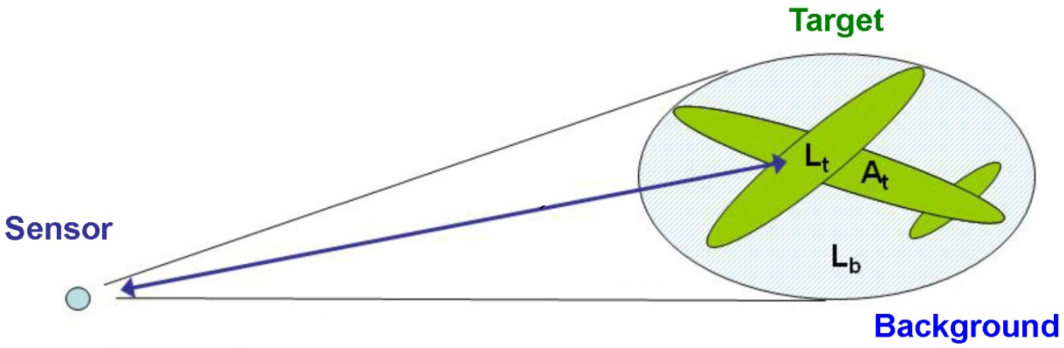
FIGURE 49. Typical Surface-to-Air Missile Acquisition Geometry.

Apparent Contrast Irradiance

The contrast irradiance received by a distant sensor is the difference between the target and background radiances times the atmospheric transmission times the solid angle subtended by the target. Note that background is treated as a source at target range, so path radiance is eliminated. In the equations in Figure 50, the spectral dependence of all terms and the weighting and integration by the sensor response are omitted. These factors are contained in the equation in Figure 51.

Apparent Effective Contrast Irradiance

Radiation is distributed with wavelength. All sensors respond to a weighted integration of the received radiation. The common term for such a weighted integration is *effective*. The equation in Figure 51 shows the apparent effective irradiance received by a sensor.



$$L_c = \tau_p\,(L_t - L_b)$$

$$L_c = \tau_p\,(L_t - L_b)$$

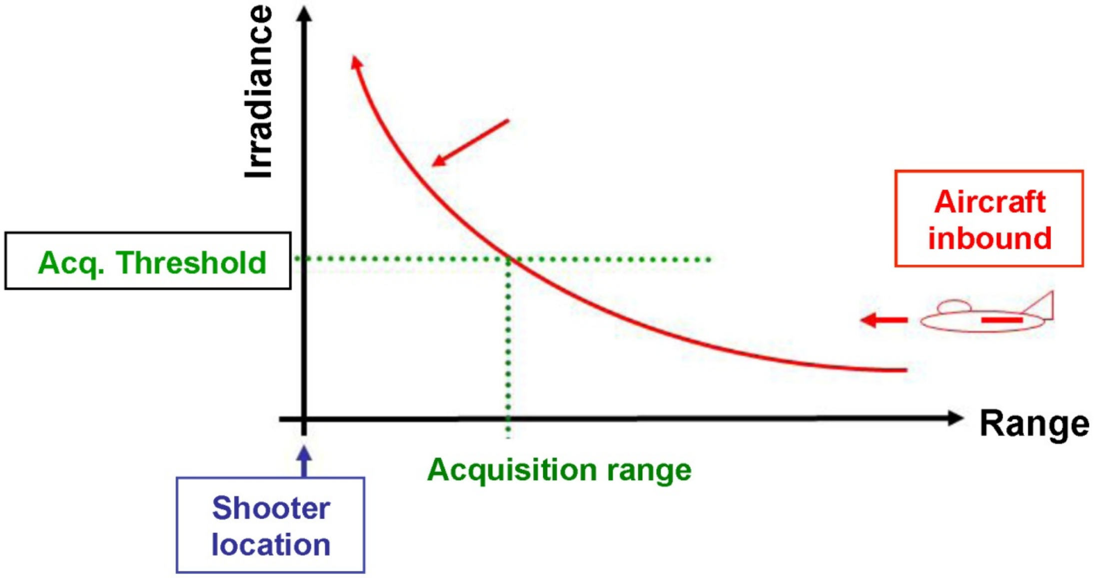
$$E_c = \tau_p\,(L_t - L_b)\frac{A_t}{D^2}$$

$$\boxed{E_c = \tau_p\,(L_t - L_b)\Omega_t}$$

where:

L_c = apparent contrast radiance at sensor ($\mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}}$)
τ_p = atmospheric path transmission
L_t = target absolute radiance ($\mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}}$)
L_b = background absolute radiance ($\mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}}$)
E_c = apparent contrast irradiance at sensor ($\mathrm{W{\cdot}cm^{-2}}$)
A_t = target projected area ($\mathrm{cm^2}$)
D = range (cm)
Ω_t = solid angle subtended by target (sr)

FIGURE 50. Illustration of Target Contrast.



$$E_{ce} = \frac{A_t}{D^2} \int_{\lambda=0}^{\lambda=\infty} R_s\,(\lambda)\,\tau_p(\lambda)[L_t(\lambda) - L_b(\lambda)]d(\lambda)$$

where:
E_{ce} = apparent effective contrast irradiance at sensor (W·cm^{-2})
A_t = target projected area (cm^2)
D = range (cm)
$R_s(\lambda)$ = normalized spectral response of sensor
$\tau_p(\lambda)$ = atmospheric path spectral transmission
$L_t(\lambda)$ = target absolute spectral radiance (W·cm^{-2}·sr^{-1}·μm^{-1})
$L_b(\lambda)$ = background absolute spectral radiance (W·cm^{-2}·sr^{-1}·μm^{-1})

FIGURE 51. Equation for Apparent Effective Contrast Irradiance.

THREAT ENGAGEMENT AREA

Mapping maximum acquisition range around an aircraft forms the missile acquisition envelope for that particular missile sensitivity, aircraft signature, flight, and background condition.

Another envelope, called kinematic, is formed by the maximum distance the missile is able to fly to reach a target flying at that aircraft's speed and altitude. The curve in Figure 52 shows the nearly circular kinematic envelope of a missile around a helicopter. The kinematic envelope around a jet at faster speed will elongate with greater range at the nose, where the aircraft is flying toward the missile.

The engagement envelope is the inner of the acquisition and kinematic envelopes. This envelope defines the area within which a missile is able to both acquire the target and has sufficient propulsion to reach the target at that speed and altitude.

The size of the engagement area is determined by aircraft intensity, contrast against background, atmospheric propagation, and missile sensitivity. Reducing engagement area is the ultimate measure of aircraft signature reduction.

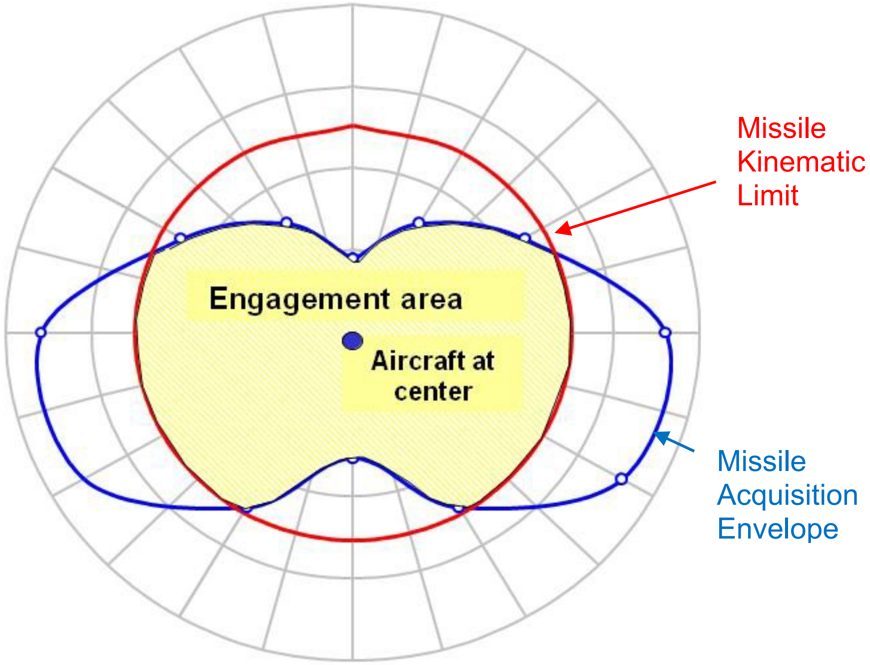


FIGURE 52. Engagement Area. (The engagement area around an aircraft is bounded by the inner of two envelopes: missile acquisition and missile kinematic.)

IR-GUIDED MISSILE PRINCIPLES

SIDEWINDER

The IR-guided missile (the Sidewinder) made its debut as part of an antiaircraft weapon on 24 September 1958. The Nationalist Chinese on Taiwan (then known as Formosa) were engaged in ongoing air and artillery skirmishes with the mainland Communist Chinese over control of two small islands. Armed only with 50-caliber machine guns, the American F-86 Sabrejets flown by the Nationalist Air Force did not have the speed or maneuverability of the Russian MiG-17s flown by the Communists. In this first encounter, the Sidewinders were used to ambush and defeat the MiG-17s as they flew past the Sabrejets.

Because of this success, the Sidewinder quickly became one of the most copied weapons in modern history. The first example was the Soviet Atoll, which was an almost carbon copy. Modern IR missile designs no longer copy Sidewinder directly, but all are designed with an intimate knowledge of the original Sidewinder. Figure 53 shows a Sidewinder launch from an F/A-18.


DOD public domain release.

FIGURE 53. F/A-18 Hornet From Marine VMFA-314
Firing AIM-9 Sidewinder Air-to-Air Missile.

PROPORTIONAL NAVIGATION

Intercept Course

To intercept a target in the shortest time and distance traveled, a missile must navigate toward a point in space ahead of the target aircraft and must time its arrival to be there at the exact instant as the target. Such a course involves calculations of bearing to the target and relative speed of closure between the missile and target. The calculations must be made continuously throughout the missile flight because the intercept point will change with any change in closure rate or with any target maneuvers.

Such an intercept course requires a guidance method known as proportional navigation. A theoretical proportional navigation course for a constant closure rate and a non-maneuvering target is shown in Figure 54. For a constant-closure, non-maneuvering condition, the angle between the bearing to the target and the missile body will be a constant. If the relative closure speed is faster, then the angle will be smaller. Long before guided missiles were developed, such a course was well known to ships. If the relative bearing to another vessel is constant, then the two ships are on a collision course.

Relative bearing in this case is the angle between the longitudinal axis of the missile body and the target. In missile terminology, this angle is known as the line of sight and herein is assigned the Greek letter *lambda* (λ).

A constant bearing has a zero line-of-sight rate. Maintaining a zero line-of-sight rate requires that a missile have two separate and independent control loops: (1) a target tracker and (2) a wing control servo.

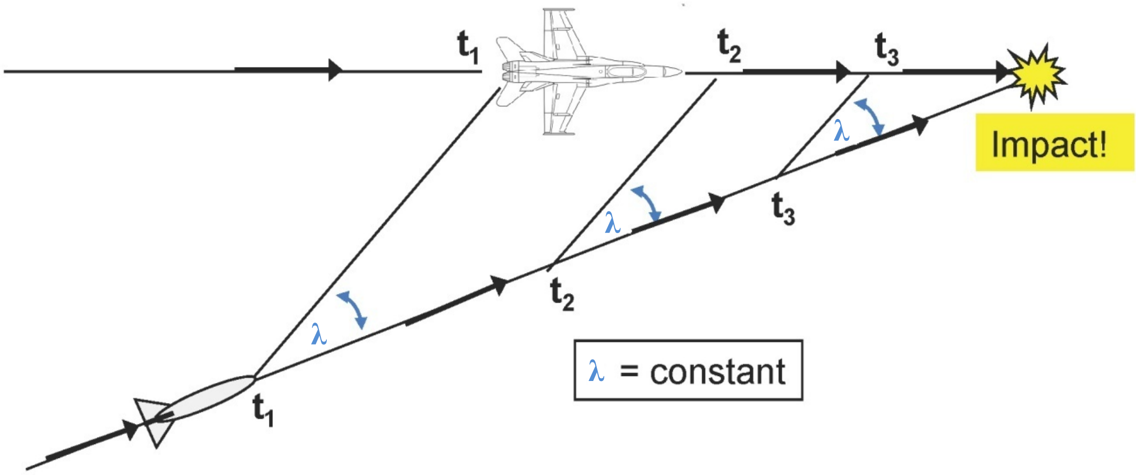


FIGURE 54. Geometry for Proportional Navigation Course for Constant Closure Rate and Non-maneuvering Target. (Note that, therein, t_1, t_2, and t_3 indicate points in time.)

Target Tracker Servo

A closed servo loop controls position by using feedback to zero out any difference, or error, between the actual and desired positions. In the case of a target tracker, a servo drives the pointing direction of the missile optics to keep the target centered in the FOV. If the target moves off center, that movement is sensed, and an error signal is generated that causes the servo to move the optics to null the error to zero.

To do so, a target tracker requires a number of functional elements, some of which may be combined within the same component. These elements are

1. Optics to collect radiation and focus the target scene to an image for extraction of direction information.
2. Gimbals to support the optics and allow free movement in azimuth and elevation independent of the missile body.
3. Gyro to provide an inertial plane of reference for the tracker that is isolated from the missile body.
4. Spectral filter to restrict pass band to a part of the spectrum with high target emissions and, if possible, low background radiation.
5. Spatial filter to transform target spatial information (direction) into a time domain signal. The spatial filter is also usually used to distinguish the target from the background on the basis of image size.
6. Detector to convert received radiation to an electrical signal. Early missiles used a single detector. New missile designs use a detector array. If the detector is an array, it will be located at an image plane, and target direction will be determined by image position on the array rather than with a separate spatial filter. The detector and conditioning electronics provide a signal that contains information on target angular direction from the optical axis.
7. Servo loop to drive the optics to keep the target centered in the optical FOV. The target angular direction signal from the detector is injected as an error signal into a closed loop servo. The servo controls the pointing direction of the missile optics and moves the optics to null out the error.

Target Tracker Window

From a countermeasure standpoint, the target tracker provides a window through which false information can be injected into the missile guidance. A target tracker may be mechanized in many different ways, and tracker designs have evolved considerably over the years. Evolution in tracker design has had a dramatic impact on the countermeasures needed to defeat a missile.

Designing an effective countermeasure to defeat a missile requires detailed knowledge of the specific missile, especially of the target tracker. Examination of the functional components in a generic spin-scan tracker can help one understand the general principles involved in all missile designs.

Optics

The most common telescope for missiles incorporates reflective optics in a Cassegrain design. Figure 55 is a cross-sectional drawing of a typical Cassegrain. The design uses a donut-shaped objective mirror, which collects radiation and directs it to a secondary mirror in the center. From the secondary, radiation converges to form a real image centered on the optical axis. This image contains the target information that will be used for tracking.

For missiles, a Cassegrain has advantages over other telescope designs because it is compact for a given focal length and because the focal point is located on the optical axis, unlike a Newtonian telescope, for example, in which the focus is located to the side. The whole telescope assembly is protected by a curved window called an IR dome.

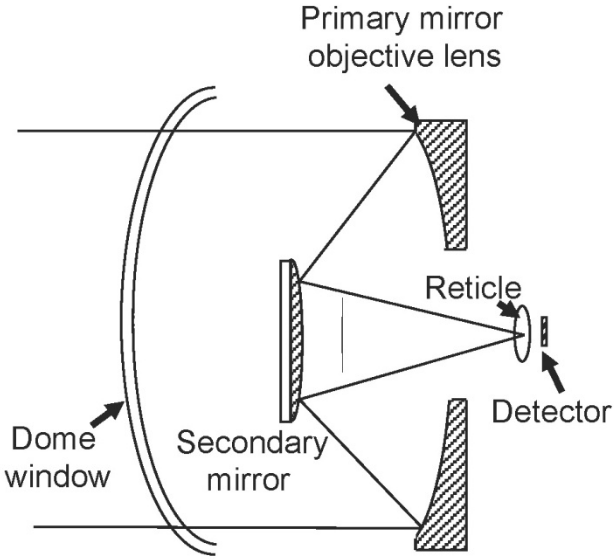


FIGURE 55. Typical Missile Cassegrain Optics. (The target tracker, consisting of collecting optics, spatial filtering to determine target direction, and detector, forms the "window" through which countermeasures can introduce false target information.)

Gimbals

To be free to move independently of the missile body, the telescope must be supported with a system of gimbals. These may be separate azimuth and elevation gimbals; or, as is more common, the gimbal may be a single post in the center with a ring of bearings to allow free movement.

The maximum angle (α_m) that the optics need to move is determined by the direction of approach and relative closure. Most IR missiles have a maximum gimbal angle greater than about 45 degrees.

Gyro

The missile optics are isolated from motions of the missile body and are given what is referred to as an "inertial plane of reference" through gyro stabilization. The gyro may be located in a housing that is separate from the optics; or, as is commonly done, the missile optics themselves may be spun to form their own gyro.

A missile body may undergo large gyrations in flight, but the gyro-stabilized optics will maintain the same pointing direction in space. To change pointing direction in response to tracking error, the servo loop causes a torque to be applied to precess the gyro.

In the free gyro design, the whole telescope spins. A large permanent magnet is mounted to the back of the primary mirror. The optical assembly is driven as an electric motor with an alternating current through surrounding coils.

The telescope assembly is gimbaled about the center with a single support post and bearing, as shown in Figure 56. The detector is fixed to the missile body, and the telescope spins around it.

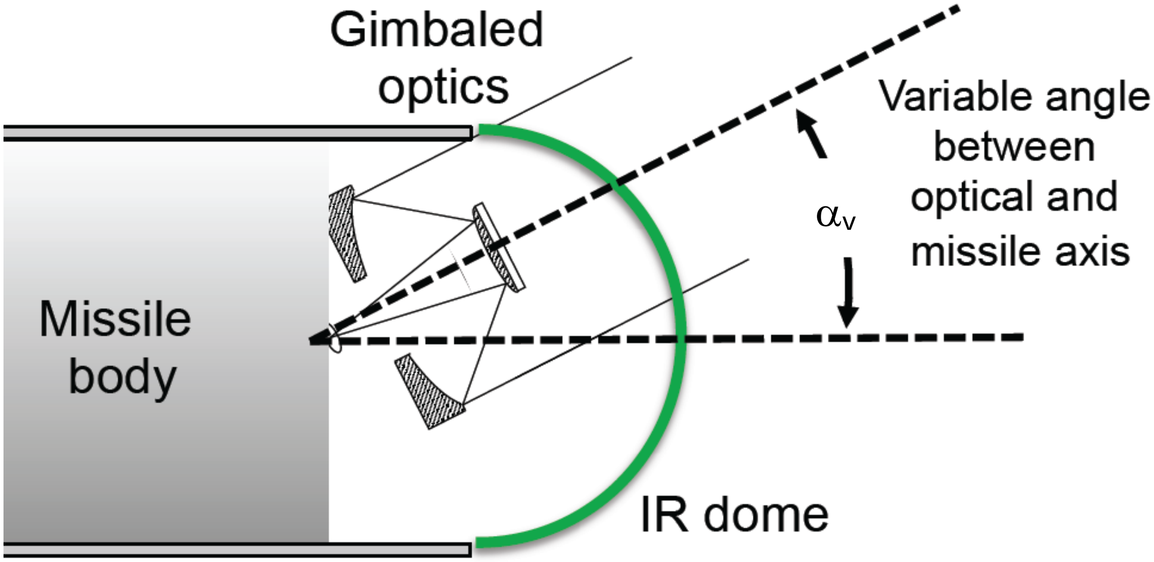


FIGURE 56. Gimbaled Optics. (Missile optics are free to move over a large angular range. Optics are gyro stabilized for isolation from the missile body and for tracking relative to an inertial reference plane.)

Target Emissions and Spectral Response

The location of a missile's wavelength band has a large effect on its range and operational usage. Figure 57 shows spectral curves of two engine signature components, hot parts (upper, blue curve) and exhaust plume (lower, red curve), with the short wavelength band used by early missiles. As the curves show, aircraft engine hot parts have strong emissions in this band but minimal plume and airframe emissions.

Almost all antiaircraft missiles operate in the MWIR, which lies from about 1.5 to 6.0 µm. Due to limitations in the detectors available, most early missiles used detectors with peak sensitivity in the region shown. In most jet aircraft, engine hot parts are only visible around the tail. Consequently, early missiles were primarily tail-aspect weapons and were of limited use from beam to nose-on.

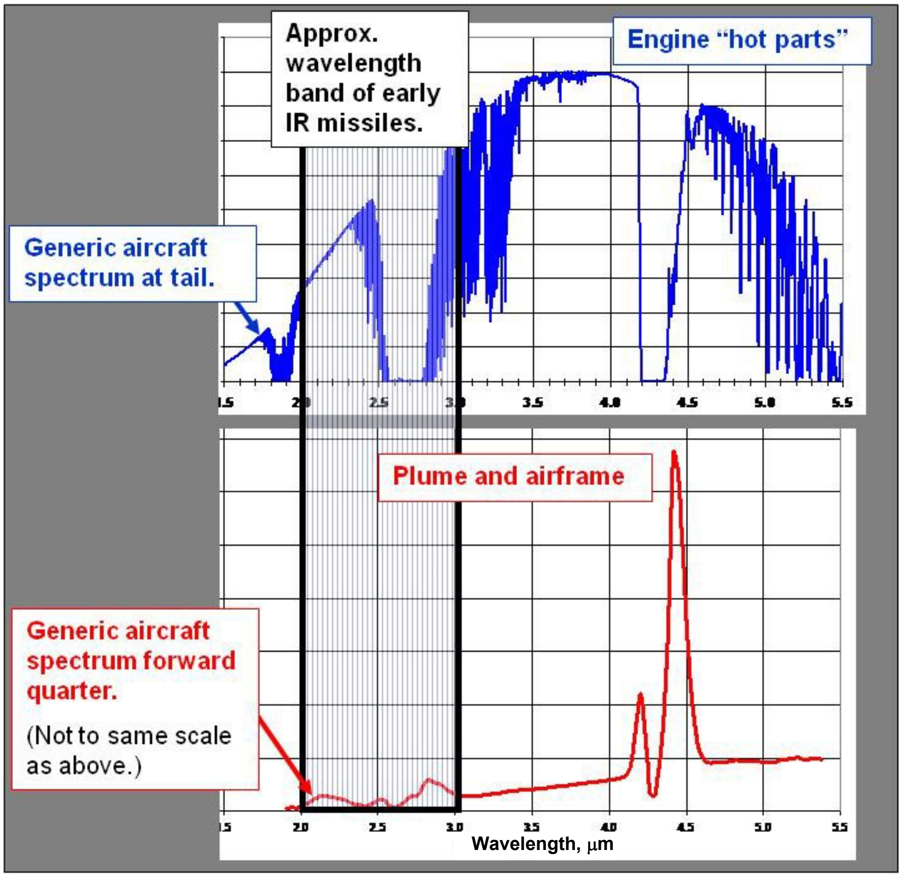


FIGURE 57. Aircraft Emissions and Missile Spectral Response. (Early IR missiles were limited to the short wavelength side of the mid-wave, a factor that made them primarily tail-aspect weapons.)

Countermeasure Implications

Knowledge of a missile's spectral response is the first piece of information needed to design an effective countermeasure. Both decoy and jammer countermeasures require an intensity in the missile's wavelength band that is at least several times greater than the intensity of the aircraft emissions in that band.

Spatial Filter: Target Direction

The tracker must have a means of determining target direction. Direction is a spatial feature, along with size, shape, orientation, etc. There are a number of methods of converting spatial information into an electronic signal for processing and tracking. One of the simplest used in many missile designs is a small spinning disk referred to as a "reticle," which is located at an image plane in the optics. The reticle often also contains the spectral filter on the same disk.

Radiation from the target and scene passes through the reticle on its way to the detector. As it does, a pattern of transparent and opaque segments on the reticle impresses a modulation on the radiation by acting as a kind of shutter. A reticle can be as simple as a disk with half transparent and half opaque, as shown in Figure 58. As the reticle spins, radiation is alternately passed and blocked.

The result is an alternating current signal from the detector whose amplitude is proportional to the target irradiance and whose phase with respect to the spin drive can be used to determine target direction from the optical center.

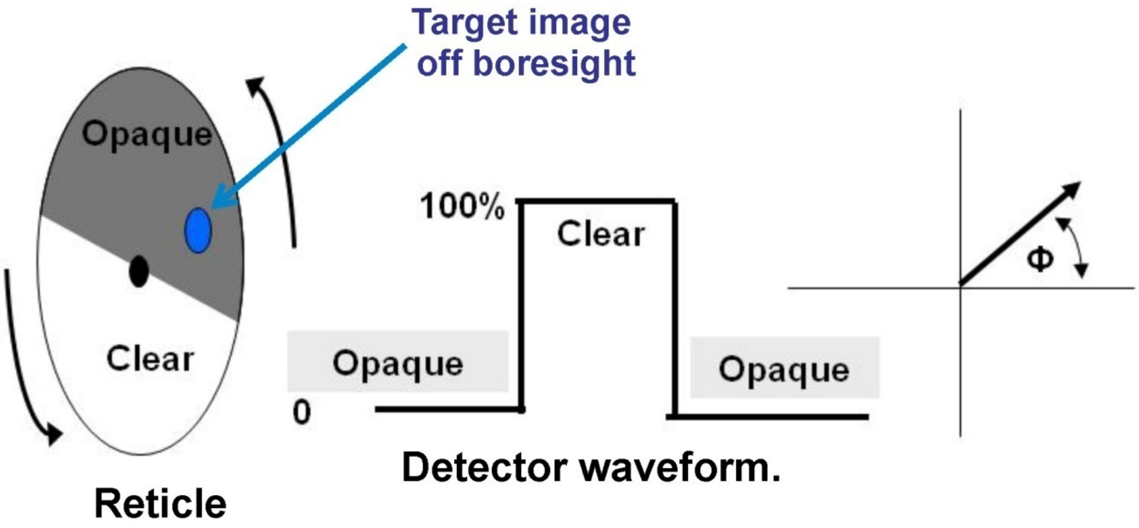


FIGURE 58. Drawing Showing That Target Direction Information Is Contained in Timing or Phase of Detector Waveform From Reference Signal.

Background Rejection

A problem with any tracker is distinguishing the valid aircraft target from the natural background sources, such as sunlit clouds and terrain, which often have much higher intensity than the target. Background sources usually have much greater area than the target, and this spatial difference can be exploited. A common method is to replace the transparent segment of the reticle with "spokes," as shown in Figure 59.

The width of a spoke is designed to be around the size of an image from a distant target so that, as the reticle turns, the target radiation is fully modulated. The image of a large area background source will spill over several spokes and, consequently, not be completely modulated.

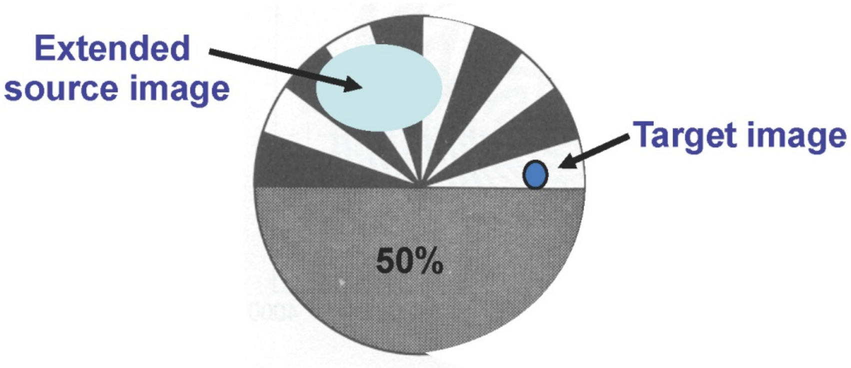


FIGURE 59. Background Rejection With "Rising Sun" Reticle Design. (Radiation from a small target is 100% modulated, while that from an extended source is only partially modulated, a factor that results in rejection of a large percentage of background radiation.)

This spatial filtering does not completely eliminate problems with tracking a target against high background radiance sources. Some signal will still be generated from a background source, but the signal will be much lower than if the background radiation were concentrated into a point source image like the target.

Spin-Scan Waveforms

The basic two-part reticle produces a detector signal with a frequency at the reticle spin rate. Replacing the transparent sector with spokes increases the modulation frequency to a multiple of the spin frequency. The reticle shown in Figure 60 has five spokes in a half disk (or ten spoke cycles if the full disk is covered). If the disk is spun at 100 revolutions per second, the modulation frequency of a target signal would be 1,000 hertz.

The other half of a reticle is often given a transmission of 50% rather than made completely opaque to produce a more balanced modulation envelope. The result is an amplitude-modulated (AM) carrier frequency, as illustrated (Figure 60). An electronic band-pass filter centered at this carrier frequency improves the signal-to-noise (S/N) ratio and helps reject lower frequency components from background sources.

The result of this filtering is a smooth AM waveform (blue curve), in which target direction information is contained in the phase of the modulation envelope. This envelope is rectified and filtered to produce an error signal to control the gyro precession.

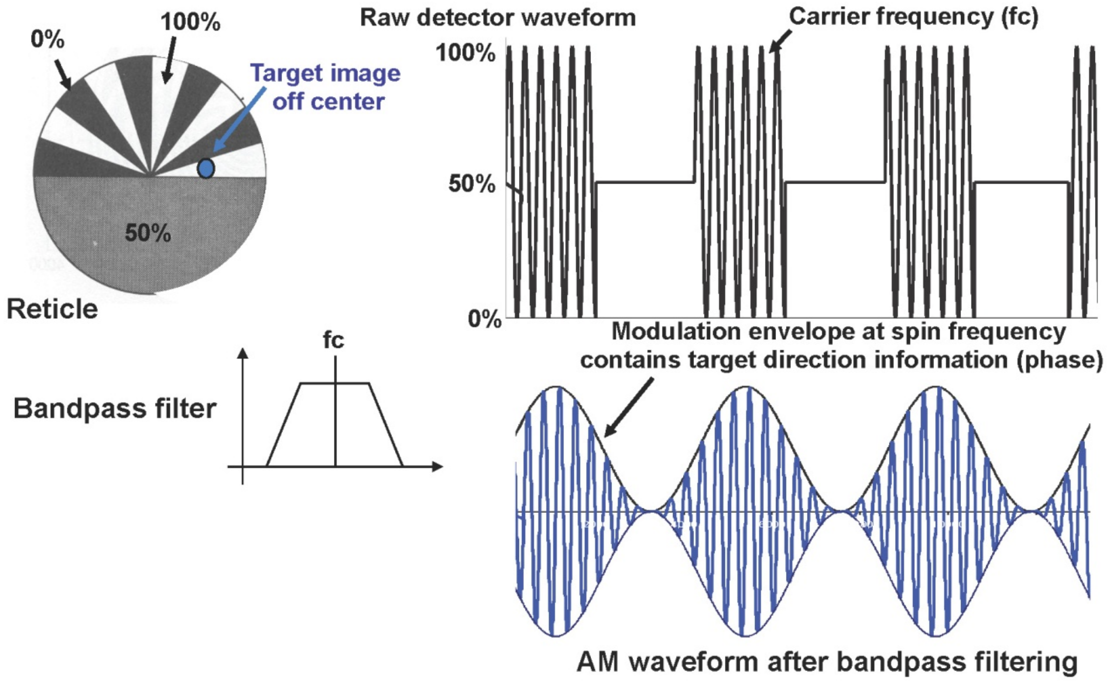


FIGURE 60. Drawing Showing That, After Detector Preamp, Signal Goes Through Narrow Bandpass Filter To Improve S/N. (The AM waveform is then rectified and filtered. Target direction is determined from AM envelope phase.)

Spin-Scan Tracker

The optical and reticle design of most early missiles used what is called a spin-scan tracker. Spin scan has the following characteristics that are important to countermeasures:

1. The tracker servo loop drives to null the signal to zero. Zero signal occurs when the target is on the optical axis and the target image is at the center of the reticle (green image) (see Figure 61).
2. If the target is off-center, an error occurs. As a consequence, an AM carrier is generated in which the phase of the modulation envelope contains target direction information.
3. With spin scan, the missile is always looking at the target. Always looking at the target has enormous consequences for jammer countermeasures (much more regarding this matter is presented later). This vulnerability to jammers led to the next evolution in target trackers: conical scan.

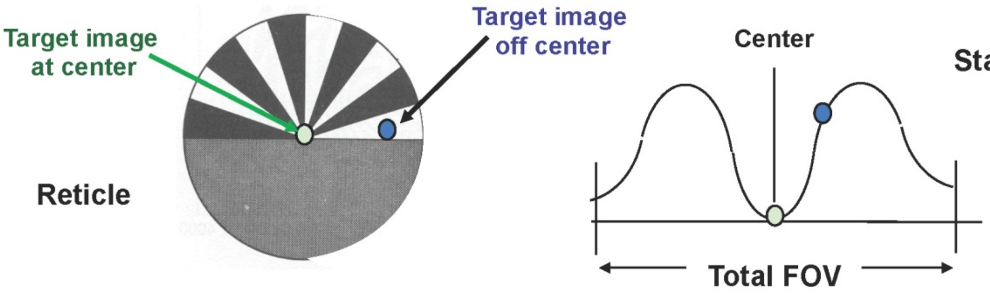


FIGURE 61. Illustration of Spin-Scan Missile Static Gain Curve.

Static Gain Curve

A missile's spatial response to a point source target is referred to as its "static gain curve." The static gain curve for a spin-scan tracker has a null at center where the target image is not modulated by the reticle spokes and consequently generates zero voltage from the detector.

The static gain curve is three-dimensional but, for convenience, is usually presented as a two-dimensional slice across the FOV, as shown in Figure 61. Figure 61 shows the now familiar rising sun reticle with two target images: one at the center of the reticle and one off center.

The voltage from the detector is proportional to the product of the target irradiance and the gain at that position on the reticle. As a target moves off center, the detector output rises to a maximum before falling off as the edge of the FOV is approached. The area within the maxima forms a tracking "well."

Conical-Scan Trackers

The trend in extracting target position and distinguishing a valid target from background is toward ever more detailed spatial information. Target trackers with a single IR detector require mechanical scanning of the target scene. The tracker that has been described is what is known as a spin-scan design. Only a few spin-scan missile designs are still in service worldwide. A spin scan is highly vulnerable to jammers because the tracker optics are always looking at the target; and, consequently, false position information can be injected at any time during the scan rotation. The next step in trackers was the conical-scan design.

Conical-scan trackers borrowed a concept that fire control radars had used for decades. Instead of staring straight ahead, the FOV of a conical scan is offset; and, as it scans, the FOV sweeps out a circular pattern. (In radar, the concept would be called a nutating beam.) A conical scan can be implemented by simply offsetting the secondary mirror in a Cassegrain telescope, as shown in Figure 62.

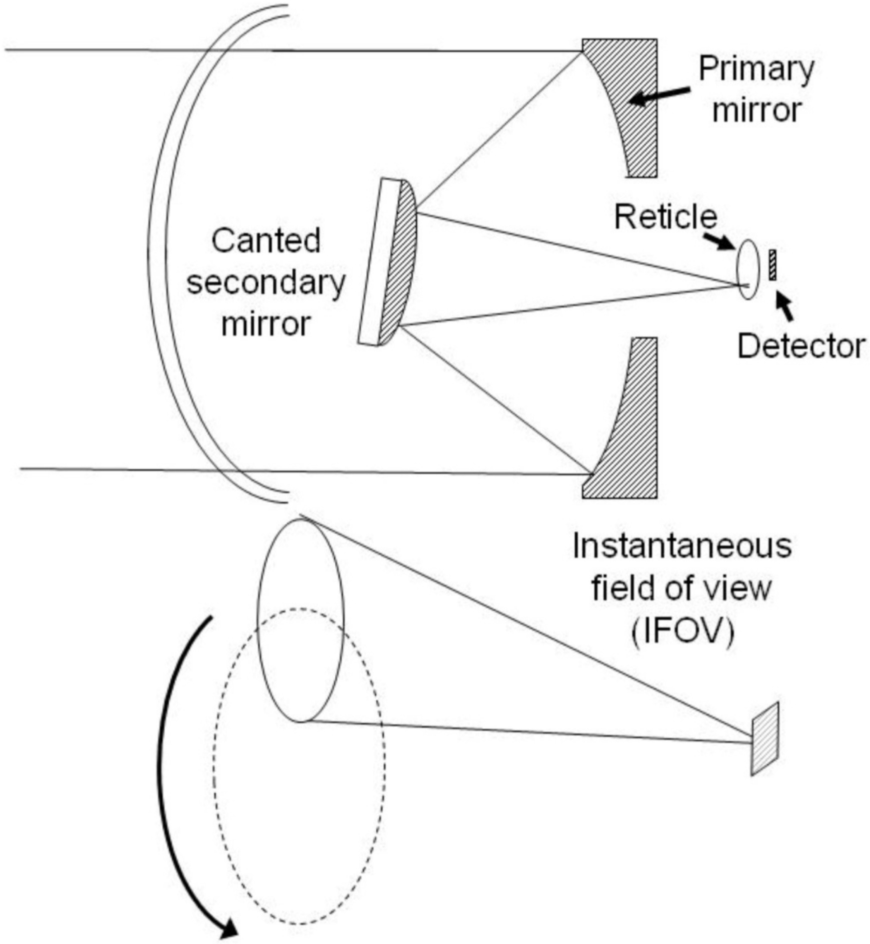


FIGURE 62. Drawing Showing That, With Conical Scan, Instantaneous Field of View (IFOV) of Tracker Sweeps Out a Circular Pattern.

For a target centered on the optical axis, the FOV sweeps out an overlapping circle, as shown in Figure 63. The target image falls on the edge of the reticle rather than in the center. Conical-scan trackers use a different reticle design with spokes all the way around rather than in only one-half of the disk. This configuration produces a detector waveform with constant amplitude.

For tracking near the optical axis, the target image is slightly offset, thus resulting in a frequency change as the image crosses spokes at different distances from the center. For this case, the electronics use frequency modulation (FM) rather than AM, a factor that results in a tighter tracking loop.

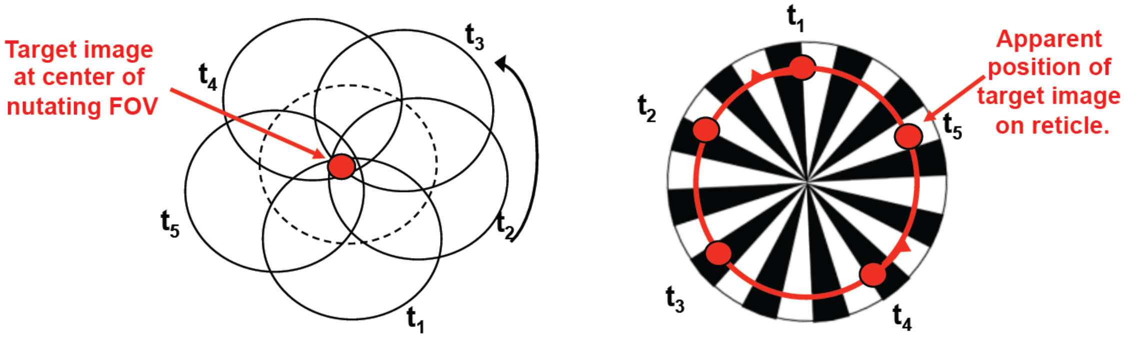


FIGURE 63. Drawings Showing Target Image Position With Conical Scan. (Conical scan tracks, so target image moves around the edge of the reticle. As a result, the amplitude waveform is constant. Any error causes an FM that is detected and drives the servo back to center.)

If the target is farther off center, as illustrated in Figure 64, the image falls off the reticle during part of the scan, shown at times t_2 and t_3. During this time, the target is outside the FOV and no radiation is received from the target. The implication for countermeasures is that no information can be injected into the tracker when it is not viewing the target.

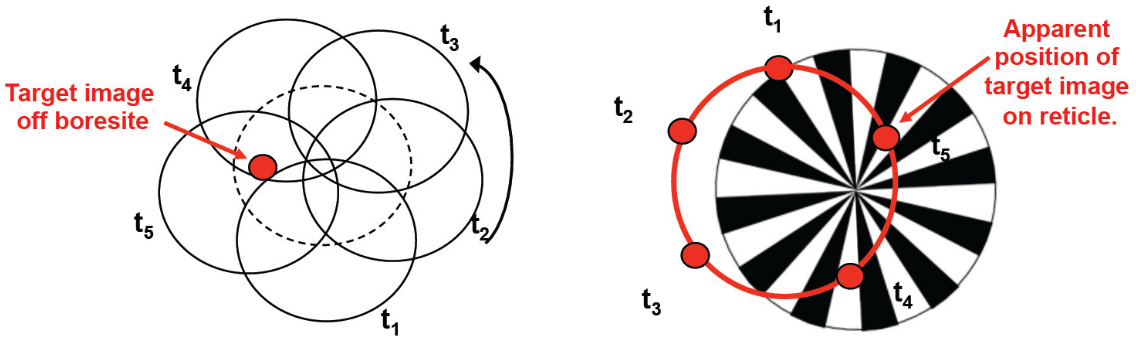


FIGURE 64. Drawings Showing Target Image Off Center. (Larger error in tracking causes the image to fall off the reticle and outside the FOV during part of the scan. Conical-scan trackers greatly increase the intensity requirements of jammers.)

MISSILE EVOLUTION: SPATIAL RESOLUTION

Pseudo Imaging

A variety of other scan techniques are in use in missiles that sweep a detector or detector pair with a small IFOV over the target scene. This action results in greater spatial resolution; and, because the detector spends only a fraction of the scan looking at the target, it has considerable immunity to jammers.

Detector Arrays

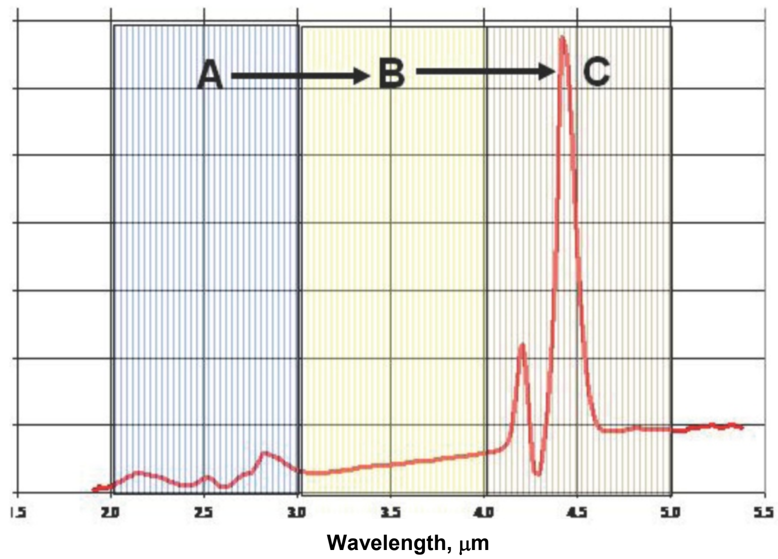
The most recent advance finding its way into missiles is the use of a staring focal plane array (SFPA) rather than a single detector. The electronically scanned array offers target detection and discrimination at greater ranges than possible with mechanically scanned single detectors. Combined with powerful image processors now available, arrays also offer improved CCM discrimination against decoys and the possibly of adaptive response to a changing target scene.

MISSILE EVOLUTION: SPECTRAL

As target trackers have evolved toward scanners with ever more spatial information and resolution (progression from spin scan to conical scan to rosette to cruciform to imaging arrays), there has also been a progression toward longer wavelengths and toward multiple bands.

Progression (wavelengths approximately) through the MWIR has been 2 to 3 µm, 3 to 4 µm, and 4 to 5 µm (exact bands are classified when associated with specific missiles) (see Figure 65). This evolution has impacted the effectiveness of countermeasures because of the difficulty of achieving high intensity from sources at longer wavelengths.

No current antiaircraft missiles operate in the LWIR (8 to 12 µm), but recent advances in HgCdTe arrays will surely change this situation in the future. There are no current countermeasures operating at long wavelengths, and problems countering missiles in that part of the spectrum could be formidable.



A = Uncooled lead (II) sulfide (PbS); B = Cooled PbS, uncooled lead selenide (PbSe); C = Cooled InSb

FIGURE 65. Wavelength Bands of IR Missiles. (Wavelength bands of IR missiles have progressed across MWIR from shorter to longer wavelengths [approximately A to B to C] as IR detectors have been developed with longer wavelength response and higher sensitivity.)

MISSILE EVOLUTION: SHOULDER-LAUNCHED MAN PORTABLE AIR DEFENSE SYSTEM (MANPADS) MISSILES

The next major advance in antiaircraft IR missiles was the development of the shoulder-launched MANPADS. The Army Redeye first entered service in 1967. The severity of the MANPADS threat became apparent at the end of the Vietnam War, when the United States first encountered the Soviet SA-7b.

A typical MANPADS warhead has less than a pound of explosive, but the high accuracy in hitting an engine can bring down almost any aircraft. Helicopters and transport aircraft are especially vulnerable to MANPADS, which accounted for all United States missile losses in Iraq and Afghanistan.

Today, the SA-7b and many later, more advanced MANPADS have proliferated to almost every country in the world through foreign military sales, as well as domestic manufacture. Providing United States Stinger missiles to the Mujahedeen in Afghanistan in 1986 was a significant factor in forcing the Soviets to withdraw, but doing so also resulted in the Stinger finding its way into other countries. Figure 66 shows an FIM-92 Stinger missile being launched at the White Sands Missile Range, and Figure 67 is a photograph of a European Mistral launcher.

FIGURE 66. FIM-92 Stinger MANPADS.

FIGURE 67. Mistral Surface-to-Air Missile.

IR MISSILES: KEY POINTS

All current antiaircraft IR missiles owe much of their design to Sidewinder, which was developed at NOTS China Lake in the late 1940s.

Missiles fly an intercept course to target using proportional navigation. Proportional navigation requires a target tracker that is independent of the missile body. The target tracker is the window through which the missile can be countered.

The earliest target tracker designs used spin scan. Target direction was determined by using a reticle to modulate the received target radiation and to reject background radiation.

Spin-scan trackers view the target at all times, thus making them vulnerable to jammers. Overcoming this vulnerability was one of the reasons missile designs evolved to conical and other types of scan. (Conical scan has other advantages as well.)

Conical-scan trackers view a target near boresight continuously; but, if the target image is off boresight, the target falls outside the FOV for part of the scan.

At the same time that target tracker scan methods were evolving from spin scan, missile wavelength bands were also evolving from short to longer wavelengths.

Sensitivity at longer wavelengths gives IR missiles an all-aspect capability and makes it more difficult for countermeasure sources to achieve high in-band intensity.

IR COUNTERMEASURES: DECOYS

The three basic elements of aircraft defense are (1) suppression of the aircraft's signature to reduce missile acquisition range; (2) warning of a missile launch and cueing of an appropriate countermeasure; and (3) activation of a countermeasure, of which there are two types: decoys and jammers.

Signature suppression can shrink the area around an aircraft from which a missile can acquire and be launched. When a missile can no longer acquire, the effectiveness of suppression as a countermeasure is 100%. However, there is a limit, and suppression alone can rarely eliminate acquisition all together. When the limit of what can be achieved through suppression is reached, a countermeasure must be used. The first countermeasure is the decoy. Figure 68 shows a Marine Corps CH-53D helicopter dispensing flares.


DOD public domain release.
http://www.marines.mil/unit/2ndmaw/2ndmawfwd/PublishingImages/507961.jpg

FIGURE 68. Marine Corps CH-53D Dispenses Pyrotechnic Flares.

DECOY FUNDAMENTALS

Decoys: Off-Board Countermeasures

A decoy is an off-board countermeasure that is ejected from and separates away from the aircraft. As the name implies, a decoy attempts to lure the track of a missile away from the target aircraft. To be effective, the decoy must provide a more attractive source for the missile than the real aircraft target. Most IR missiles are not able to search and reacquire a target after launch; so, once the track has been pulled far enough that the aircraft is no longer in the missile FOV, the missile has been defeated.

Decoy is a general name applied to a variety of off-board devices. The decoy most commonly associated with IR is the pyrotechnic flare, such as the ones shown in Figures 69 and 70 being dispensed from a Navy F/A-18E. All flares are decoys, but not all decoys are flares.

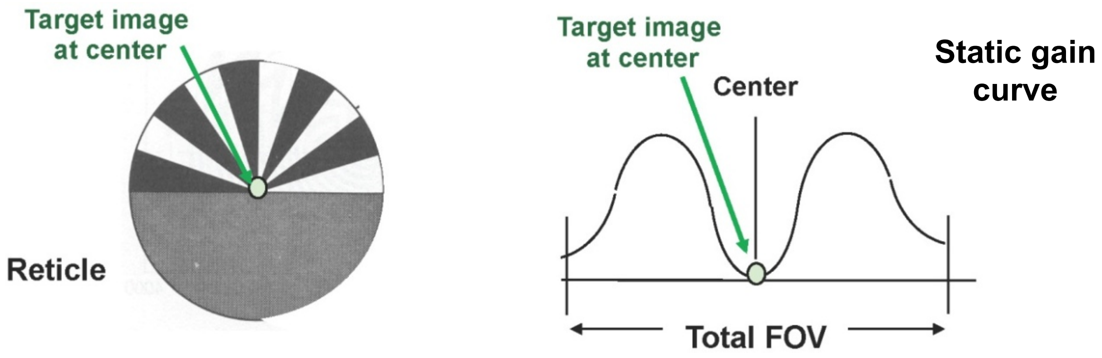
Public domain photo release from www.defenselink.mil.

FIGURE 69. Conventional Pyrotechnic Flare Dispensed by Navy F/A-18E.

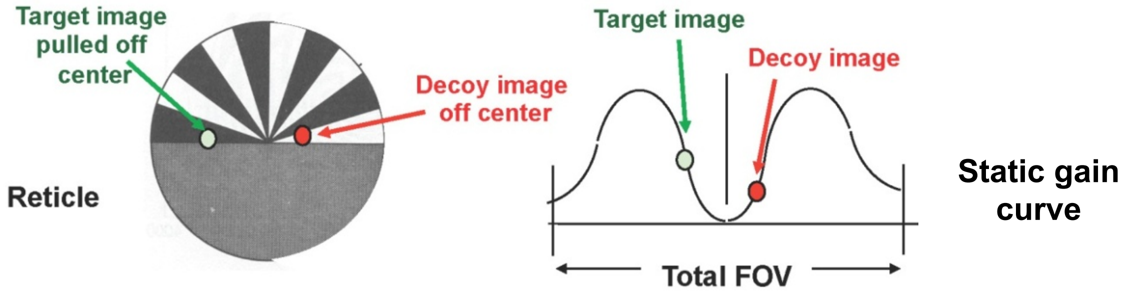
FIGURE 70. Conventional Pyrotechnic Flares Dispensed From F/A-18E.

Missile Response to Decoys

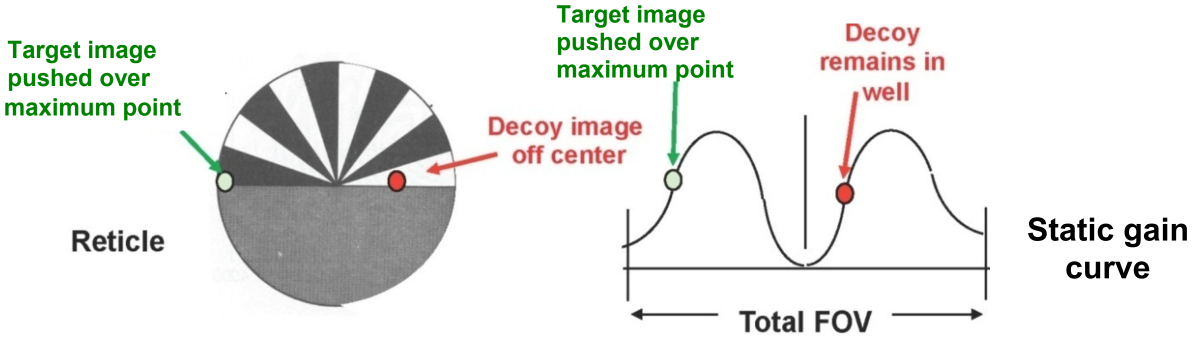
Figure 71 shows the sequence of events that occur with a basic spin-scan tracker to illustrate how a missile responds to multiple target scenes. If the decoy irradiance is greater than that of aircraft target, the track point will bias toward the decoy. As the decoy separates from the aircraft, the target will be pushed over the maximum point of the static gain curve. The decoy will remain within the well. At that point, the decoy has won.



(a) Point before decoy is dispensed—tracker servo holds target at center of FOV.



(b) Point after decoy is dispensed—servo tracks centroid of weight images as decoy separates.



(c) Point at which decoy wins—decoy separated from aircraft until target image moved over maximum point of static gain curve; decoy remains in well.

FIGURE 71. Sequence of Events To Illustrate Response of Spin-Scan Tracker to Decoy.

Decoy Requirements Against Non-CCM Missiles

The section entitled "Missile Response to Decoys" provides the requirements that a decoy must meet to protect an aircraft from earlier generation missiles that do not have CCM circuitry. These are

1. The decoy must be more intense than the aircraft within the missile spectral response band. For example, the following holds true: the greater the ratio of the in-band flare-to-aircraft intensity, often called the jammer-to-signal (J/S) ratio, the more effective the flare is likely to be against non-CCM missiles.
2. Greater intensity must be reached while the decoy is close to the aircraft and the image is within the capture well of the target tracker. Achieving high intensity while close to the aircraft requires a fast intensity rise time, especially to protect at close range.
3. The burn time of the decoy must be sufficiently long and separation from the aircraft must be sufficiently great so that, when the decoy burns out, the aircraft is outside the missile FOV. Otherwise, the missile will reacquire and resume track on the aircraft.
4. The separation rate of the decoy must not exceed the track rate of the missile, otherwise the decoy will flash through the FOV and be gone before the missile is able to respond.

These conditions must be met at all aspects around an aircraft and at all operational airspeeds and altitudes.

PYROTECHNIC FLARE DEVELOPMENT

Simultaneously with the development of IR-guided missiles, the United States and other governments began developing countermeasures to defeat them. The requirements previously described dictate a decoy with high intensity in IR wavelengths and a fast intensity rise, as well as one whose intensity is not greatly affected by aircraft speed or altitude.

One additional requirement greatly restricts decoy design options: all countermeasure solutions must fit in a small package. Any countermeasure device or system carried on an aircraft has a severe size and weight limitation. Decoys come in a variety of shapes and sizes, but the most common size for Navy decoys is a cylindrical tube 5.81 inches long by 1.43 inches in diameter.

This size constraint limits the IR characteristics available to the decoy designer. The first of these is temperature. To achieve high intensity from a source with a small projected area, the temperature must be high—typically several thousand degrees in

Celsius. The requirements were met with the pyrotechnic flare (see Figure 72), which has become the standard IRCM in all the world's air forces.

- The success and, especially, the compromise of the Sidewinder to the Soviets, spurred United States flare development in the late 1960s. Development was accelerated when the United States begins to encounter MANPADS at the end of the Vietnam War.
- Conventional flares consist of a highly energetic pyrotechnic material that is expended from a casing by an electrically fired impulse cartridge.

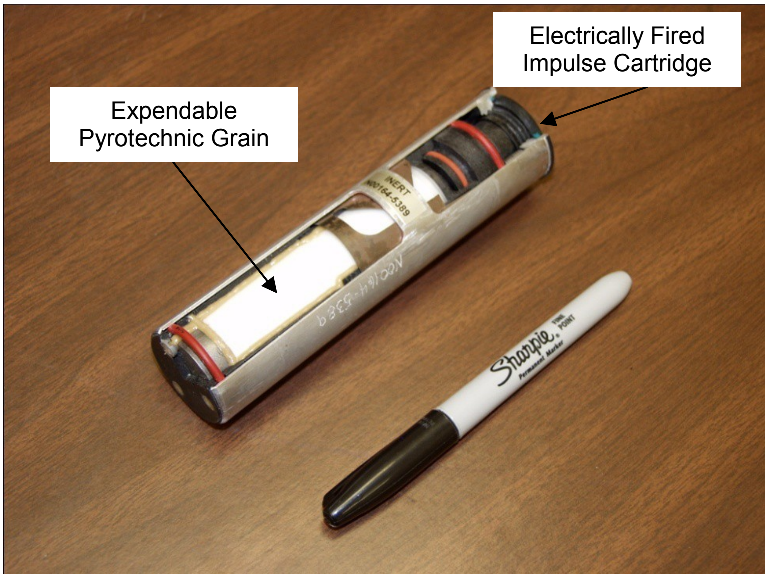


FIGURE 72. Cutaway Model of Conventional Navy Flare
(5.75 Inches Long by 1.38 Inches Diameter).

In the United States, a number of agencies and laboratories were involved in flare development in the early 1950s. The major research and testing were initially done at what was then the NOTS (now NAWCWD), China Lake, California, and, from the late 1960s, were carried on by what was then the Naval Ammunition Depot (now the Naval Surface Warfare Center [NSWC]), Crane, Indiana.

A pyrotechnic does not depend upon external oxygen for reaction; and, consequently, the reaction temperature is not greatly affected by altitude or airspeed. The most energetic composition in terms of IR emissions per mass was found to be a composition of magnesium, Teflon, and Vitron.

The product of a magnesium–Teflon reaction is a stream of particles of amorphous carbon that are heated to incandescence by the chemical reaction. Carbon has a surface emission efficiency (emissivity) of nearly 1. Carbon gives the pyrotechnic flare its characteristic spectral shape, very closely approximating that of Planck's curve.

In the airstream, a burning magnesium–Teflon flare has a comet-like appearance as the hot carbon particles produce a trail behind the flare. Because the reaction temperature is very stable with altitude and airspeed, the intensity is proportional to the number and rate of the carbon particles produced.

The main factors affecting intensity are the physical size of the flare, its rate of burn, and the aspect from which it is viewed. Intensity is greatest side on. As the carbon particles streaming behind the flare cool, they form a dense smoke trail that can partially obscure the flare when viewed from the rear.

A typical Navy dispenser system consists of two or more removable “blocks” that each hold 30 flares (or any combination of flares and chaff cartridges) (see Figure 73). A circuit board on the back of the dispenser block makes electrical contact with the impulse cartridges, which push the pyrotechnic grain out of the tube. A number of different safe and arm devices are in use to prevent the pyrotechnic grain from igniting while still inside the tube.

DOD public domain release.

FIGURE 73. Ordnancemen Inspect and Replace Expended Flares Out of Chaff and Flare Buckets of KC-130, 10 March 2002, in Support of Operation Enduring Freedom.

DISPENSING DIRECTIONS AND STRATEGIES

Dispensing direction is downward on most aircraft; but, because direction is a factor in countermeasure effectiveness, dispensers may also be mounted to dispense sideward, especially on helicopters and transport. After being dispensed into the airstream, flares slow rapidly and fall away from the aircraft in a ballistic trajectory (see Figure 74).

FIGURE 74. Marine Corps KC-130 Dispensing in Three Directions. (A U.S. Marine Corps KC-130 Hercules aircraft assigned to VMGR-234 launches a display of flares while flying formation with a second aircraft during Operation Iraqi Freedom.)

Dispenser payloads are limited, especially on tactical aircraft. Two basic dispensing strategies are

1. Preemptive. Decoys are dispensed continuously during target area ingress and egress to prevent a missile acquiring lock. Preemptive dispensing is highly effective against all IR missiles but requires a very large number of decoys.
2. Reactive. Decoys are dispensed only in response to a declared missile launch. Reactive dispensing conserves decoys but is less effective and depends on reliable missile warning.

SOVIET FLARE DEVELOPMENT

Most countermeasure development is done in response to deployed threats rather than anticipation of future capability. Too often, this approach results in losing aircraft before effective devices, systems, and tactics can be developed and deployed. A dramatic historical illustration is provided by the Soviet experience in Afghanistan in the late 1980s.

The rugged Afghan terrain forced the Soviets to use small autonomous ground units and to rely heavily upon helicopter transport and close-air support from helicopter gunships and strike aircraft. The reliance on low-altitude air support made the Soviets vulnerable to MANPADS missiles.

Initially, the United States helped the Mujahedeen obtain Soviet SA-7b missiles, which were abundant on the black market, a scheme that posed no risk of compromising United States technology. The SA-7b has no CCM and can easily be defeated with flares. As Afghan losses mounted, the United States introduced the Stinger into Afghanistan in 1986. The effectiveness of the Stinger resulted in heavy Soviet aircraft losses, a situation that forced aircraft to fly at night or at high altitude, thus negating their bombing accuracy. This denial of close-air support ultimately contributed to the Soviet withdrawal in February 1989. Figure 75 shows a Russian Hind attack helicopter.

The Soviet’s encounter with the Stinger also resulted in an acceleration in that nation’s flare development and the installation of flare dispensers on its aircraft.

DOD public domain release.

FIGURE 75. Russian Mi-24 (Hind) Simulates Attack on McGregor Range, New Mexico, During Roving Sands 1999.

MISSILE CCM AND DECOY COUNTER-CCM (C-CCM) STRATEGIES

Missile Spectral Discrimination

The high temperature of pyrotechnic flare reaction produces sufficient intensity to protect almost any aircraft from almost any IR missile that does not have CCM capability. Unfortunately, the high temperatures of pyrotechnic flares result in a spectral distribution that is very different from that of an aircraft, as the curves in Figure 76 show.

Missiles are able to distinguish which target has the higher temperature and, therefore, is more likely the decoy by viewing the target scene in two wavelength bands rather than just one. Distinguishing valid targets from decoys may be done in several ways. One way is two use two detectors, each with its own band-pass filter. Another is to use a single detector with a reticle having segments filtered for two bands.

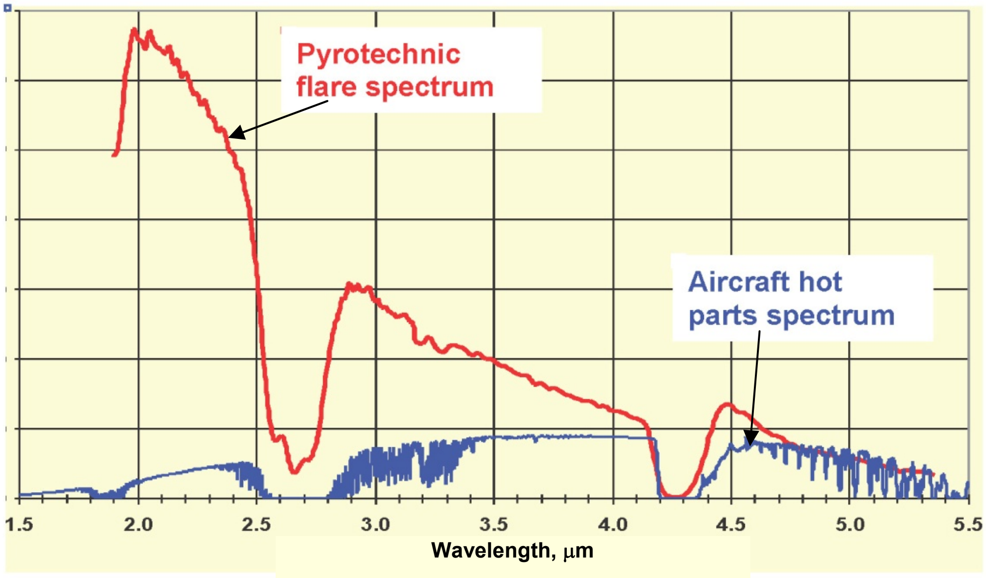


FIGURE 76. Flare and Aircraft Spectra. (The spectral shape of a pyrotechnic flare [red curve] taken near its peak intensity shows a much higher ratio of short-to-long wavelength radiation than an aircraft [blue curve]. This difference can be used as a discriminant by CCM missiles.)

Decoy C-CCM

The counter to a spectral discriminant CCM is a decoy that is a better spectral match to the aircraft. A better spectral match can be achieved with pyrophoric rather than pyrotechnic materials. A pyrophoric material reacts with oxygen in the air; and, consequently, the intensity is affected by altitude and airspeed. Pyrophorics may be either solid or liquid materials.

Pyrophoric materials typically do not have as high intensity as pyrotechnic ones but can be effective for aircraft with lower signatures and may be used in conjunction with pyrotechnics.

Missile Temporal Discrimination

The fast rise needed to increase intensity while the flare is still close to the aircraft is a temporal feature that can be used as a discriminant. By themselves, temporal features are not sufficient to distinguish a decoy from the aircraft but can be used by a missile to trigger other CCM discriminants.

Decoy C-CCM

A decoy with a slow rise time can be effective against some types of missile CCM, especially at longer range. Because rise time is not a strong discriminant by itself, a slower rise decoy is not a dependable counter but may be used in conjunction with other decoys.

MULTIPLE DECOY STRATEGIES

Several factors drive a countermeasure strategy of deploying a number of decoys with different characteristics both simultaneously and in succession.

1. IR missiles are passive, and there is no currently fielded system capable of identifying missile type and, consequently, establishing the most effective decoy.
2. Any multi-target scene presents a problem for a missile tracker. One example is that the more complex and varied the decoys, the more likely it is that one or a combination will pull the track away from the aircraft.
3. As the missile closes on a target, the separation rates and geometry it sees is constantly changing. A decoy or decoy combination that fails at a 10,000-foot range may be the one that saves the aircraft at 2,000 feet.

A major consequence is the need for aircraft to carry larger numbers of decoys, a requirement that adds weight, as well as the challenge of finding the extra space. Decoy effectiveness and efficiency will be improved by more-advanced missile warning systems that can detect and declare a missile at longer range and give an accurate direction of arrival. Better missile warning can enable “smart” dispensing, in which decoys are selected and dispensing is timed for that particular engagement.

With knowledge of how a missile functions, decoys can always be designed that will defeat it. The challenge is the large variety of missile designs in service worldwide and the very real possibility of encountering new designs that have not been exploited.

DECOY TEST METHODS

Captive Missile Seekers

Test Methods

Decoys are tested against instrumented captive missile seekers either on the ground in seeker test vans (see Figure 77) or in the air in the NAWCWD ATIMS (Figure 78). A basic measure of effectiveness is the success or failure to decoy the track of the missiles. The basic test systems and methods are the same for both non-CCM and CCM missiles. The difference is the analysis of missile signals necessary to score effectiveness.

FIGURE 77. Seeker Test Van,
NSWC, Crane, Indiana.

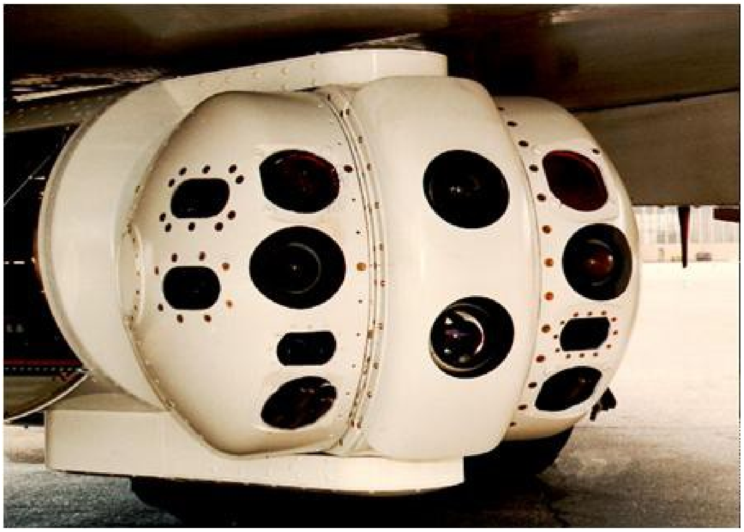


FIGURE 78. ATIMS III Turret With
Captive Air-to-Air Missiles.

With non-CCM missiles, a successful decoy of track is sufficient. With CCM missiles, it is necessary to determine why the missile followed the decoy (or why it did not). Among the critical questions for each category are

- Successful decoy: Was missile CCM triggered? If yes, did track transfer to another decoy in the sequence? If CCM was not triggered, why not?
- Failure to decoy: Was missile CCM triggered? If yes, was missile track initially decoyed but returned to aircraft? How long after dispense did these actions occur? If CCM was not engaged, was J/S in that band simply too low to decoy any missile?

Strengths and Limitations

The strength of captive testing is the viewing of a real aircraft and IRCM scene. The limitation is the nearly static slice in time and range. Captive testing does not replicate the timing and rapid range closure of an actual missile in flight.

Simulations

Testing decoy effectiveness using a fly-out simulation overcomes the lack of range closure inherent in captive missile testing. Simulations incorporate all elements of the missile, target, and countermeasure scenario. Simulations of the missile are of two types: all digital or HIL.

Basic components of a simulation are three models consisting of

1. Target scene:
    - Aircraft IR signature
    - Backgrounds
    - Atmospheric path from missile to target

2. IRCM:
    - Decoys
    - Jammers

3. Missile:
    - Target tracker
    - Guidance
    - Kinematics
    - CCM

Because they are simulations, the results are only as good as the validation against reality. Validation is a difficult, time-consuming, vital, imperfect process. As missiles and countermeasures increase in complexity, rigorous validation is becoming ever more critical.

DECOY COUNTERMEASURES: KEY POINTS

The objective in decoy countermeasures is to pull the track of the missile away from the target until the target is no longer in the missile FOV. Basic parameters in decoy countermeasures are in-band intensity and separation rate versus time.

IR missiles have developed sophisticated CCM that distinguish decoys from the aircraft target by exploiting differences in spectral, spatial, and temporal characteristics.

The decoy counter to missile CCM is to dispense multiple decoys together and in sequence that have a wide variety of characteristics. Figure 79 is a photograph of a salvo of decoy flares.

Developing effective IRCM is a continuous challenge:

- Each successful IRCM advance forces a CCM by missile designers; as a consequence, a new (usually more expensive) countermeasure design is required.
- All missiles can (eventually) be countered.
- All countermeasures can (eventually) be defeated.

The critical parameters are time and cost to develop and place into service.


DOD public domain release.

FIGURE 79. Flare Salvo From F/A-18E and F/A-18F
From USS *John C. Stennis* (22 February 2012).

JAMMER COUNTERMEASURES

Decoys were described as the first of the two basic countermeasure types. The second is jammers. A decoy is an off-board countermeasure that is ejected from the aircraft and pulls the track of the missile away from the aircraft by providing a more attractive target.

A jammer is an onboard countermeasure that stays attached to the aircraft. Through the modulation of an intense IR source, a jammer introduces a false signal into the missile track loop that creates a kind of electronic illusion of a target in another location.

JAMMER STRATEGY

The strategy of a jammer is to inject a signal into the missile track loop that has a phase opposite that of the aircraft target. To the missile, the initial effect of a jammer is the same as the multiple target scenario that is created by a decoy. The difference is that a decoy is a real IR target, while the jammer creates a fictitious one.

This difference becomes critical when sufficient error is generated to move the aircraft target to the edge of the missile FOV. At that position and beyond, a decoy continues to offer an attractive target. For a jammer, however, the edge of the FOV marks the theoretical limit of its influence.

JAMMER EVOLUTION: THERMAL SOURCES

Development of jammers began in late 1960s as IR threats started to proliferate. The hope for jammers was that they would solve the problem inherent with decoys: the need for a reliable missile warning to cue the dispense and the limited quantity available in aircraft dispensers. A jammer could be turned on all the time.

The first challenge was a search for high-intensity modulated sources in MWIR with (ideally) long life and high reliability. Two different types of thermal sources evolved and eventually made their way into operational systems:

1. Pulsed cesium vapor arc lamp
2. Mechanically modulated element heated to incandescence

Older thermal jammers, such as the ALQ-144 shown in the 1983 photograph provided as Figure 80, were highly effective against early IR missiles and had the great advantage of not requiring a missile warning. The thermal jammers are highly effective against early threat missiles and still have utility today because of the wide proliferation of older missiles.

FIGURE 80. ALQ-144 on OV-10D.

TARGET TRACKER SIGNAL REVIEW

A missile's target tracker is the window through which false target information can be introduced, either by a decoy or by a jammer. The tracker converts target scene information in the spatial domain into the temporal domain. Target direction (spatial domain) is converted into an electrical signal whose phase or timing (temporal domain) is used in a closed-loop servo to keep the missile optics centered on the target.

The spin-scan tracker that was used to describe target tracking and response to decoys is also useful in describing missile response to a jammer. Spin scan is also the easiest tracker type to deceive with a jammer. Understanding why provides insight into the challenges of jamming more-advanced tracker types.

Figure 81 shows the signal generated by a target located off optical center. The reticle modulates the target irradiance with two frequencies to create an AM signal. When the target image falls on the spokes of the reticle, a higher frequency carrier is impressed on the target. An electronic band-pass filter that is centered about the carrier frequency improves target S/N ratio and helps reject signals from extended background sources with image sizes that spill over multiple spokes of the reticle.

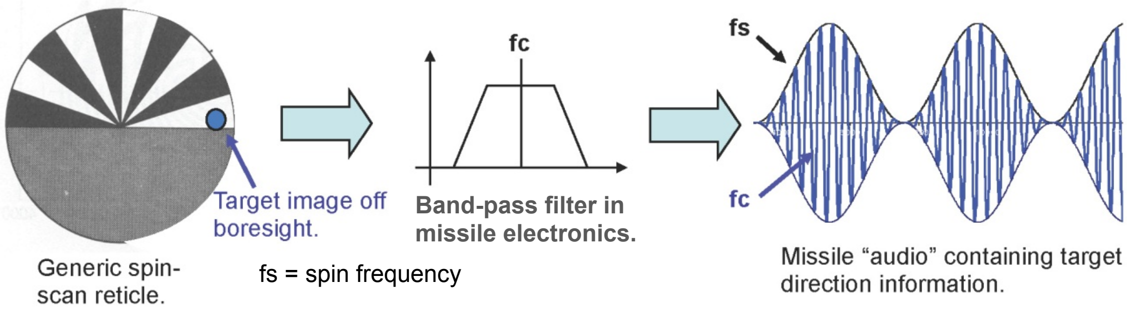


FIGURE 81. Review of Tracking Signal Generated by Spin-Scan Tracker.

When the target image falls in the phasing sector of the reticle where there are no spokes, no modulation occurs, and the signal amplitude that is passed by the electronic filter drops to zero. The resulting waveform is an AM envelope at a spin frequency that is impressed on the carrier.

After the signal is rectified and filtered, the carrier is removed and the remaining signal is a sine wave at the spin frequency. The timing or phase of this signal with respect to a spin reference signal tells target direction. Target direction is always in relation to the inertial reference established by the gyro, not the missile body. The tracker servo causes the gyro to precess in a direction to null out the signal and put the target in the center.

JAMMER WAVEFORMS

Basic jammer strategy is to inject a signal into the target tracker that resembles that of a valid target aircraft. The waveform created by the jammer must pass through the missile's electronic filtering, just as a target signal does. Jammers may have different waveform shapes, depending upon the method used to create the IR source, but the most efficient waveform in terms of jamming influence for the amount of irradiance received is one that resembles the waveform created by the reticle modulation of a real target. Figure 82 illustrates the jammer waveform.

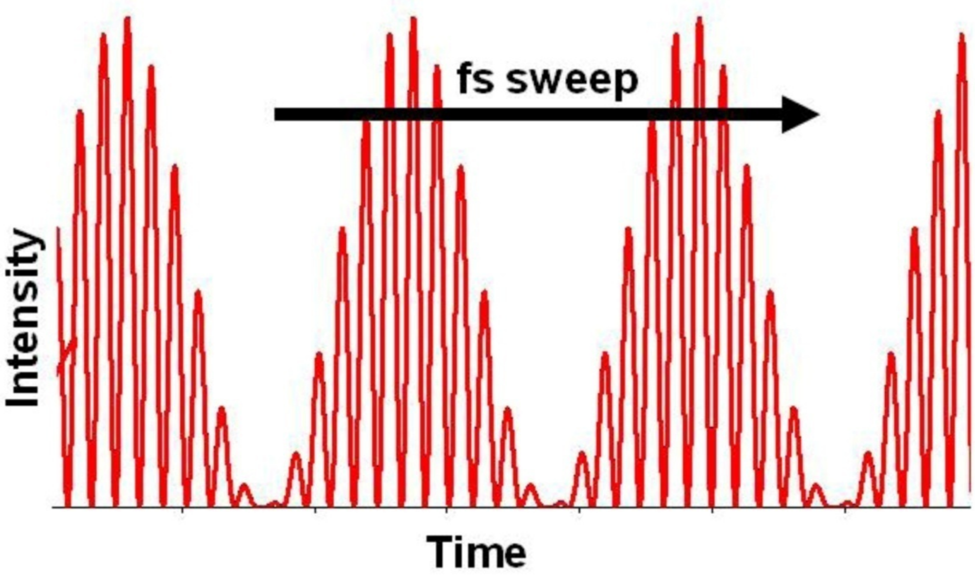


FIGURE 82. Generic Jammer Waveform for Spin Scan.

Because IR missiles are passive and there is no present operational method of getting feedback from the missile, jamming must be done "open loop." The jammer modulation envelope must be swept through the known frequency range of the missile. During part of the cycle, when the jammer signal is in phase with that of the target, the jammer will add to the target's irradiance. As a result, a jammer will usually expand the range at which a target can be detected.

Whether this increased detection range is fatal depends mainly upon the intensity of the jammer relative to the aircraft, or the J/S ratio. A jammer with a low or marginal J/S ratio may be worse for aircraft survivability than no jammer at all. A jammer with a high J/S ratio will still increase detection range, but the jammer signal will override the target sufficiently to deny a stable and sustainable track.

COMBINED TARGET AND JAMMER WAVEFORMS

The jammer is located onboard the target aircraft; but, when the phase of the jammer modulation is opposite that of the target, the net envelope of the combined jammer and target waveform makes the target appear as if it were in the opposite direction from the boresight. If the jammer J/S ratio is sufficient, the result is to push the tracker toward the false target and away from the real target.

Deception occurs only when the jammer phase is opposite that of the target. A signal will be created that is opposite in phase and apparent direction from the aircraft target when the jammer pulses occur in the phasing sector of the reticle. Because the phasing sectors of early spin-scan missiles usually had 50% transmission, the irradiance of the jammer must be two times that of the target to achieve an effective J/S ratio of 1. Figure 83 shows waveforms when jammer phasing is optimum.

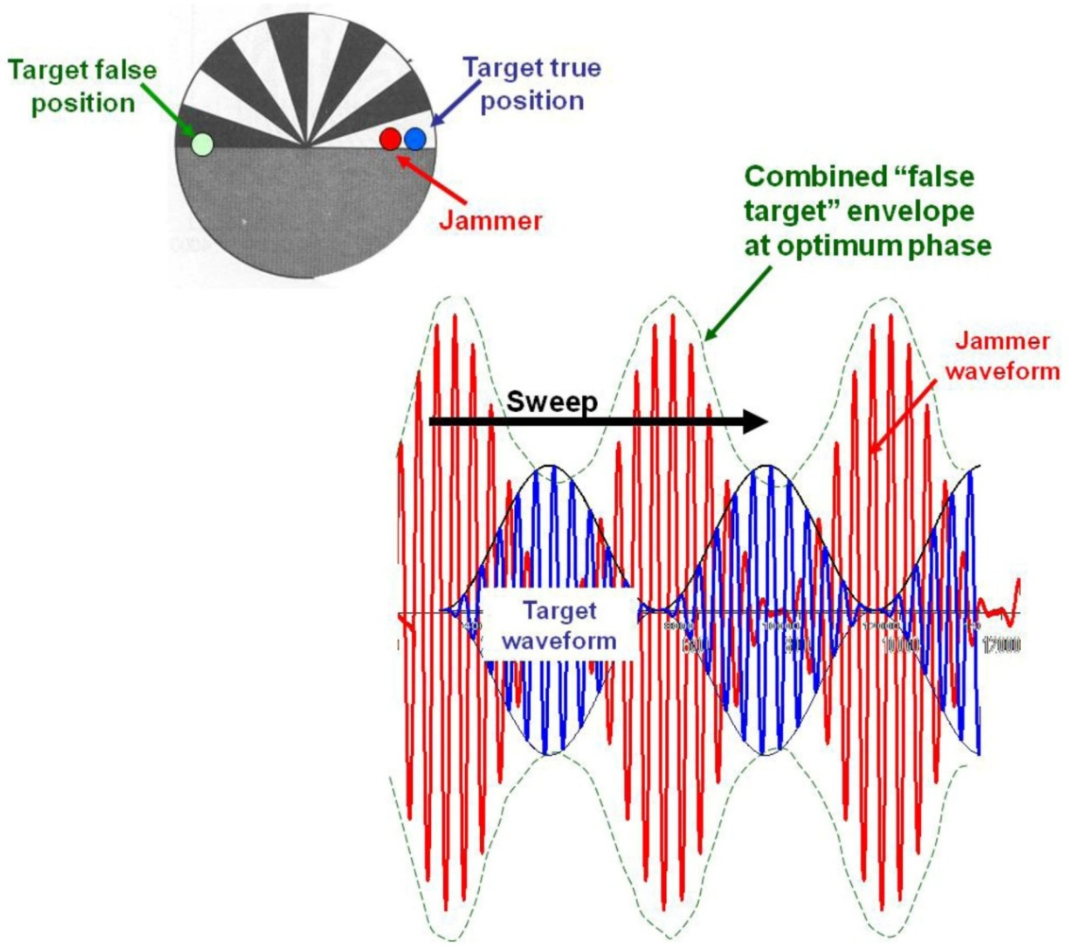


FIGURE 83. Typical Jammer Waveform for Spin-Scan Tracker.

NUTATION AND OPTICAL BREAK LOCK (OBL)

The apparent target position is the vector sum of the target and jammer signals, just as it is for a multiple target scenario with decoys. As a jammer is swept in frequency and consequent phase, the apparent direction to the target rotates, thus causing the missile track point to nutate, or wobble, about the true target position.

As shown in Figure 84, if the jammer intensity is sufficiently intense relative to the aircraft, the nutation will cause an outward spiral that can “walk” the track point and missile FOV off the target and achieve what is known as an OBL.

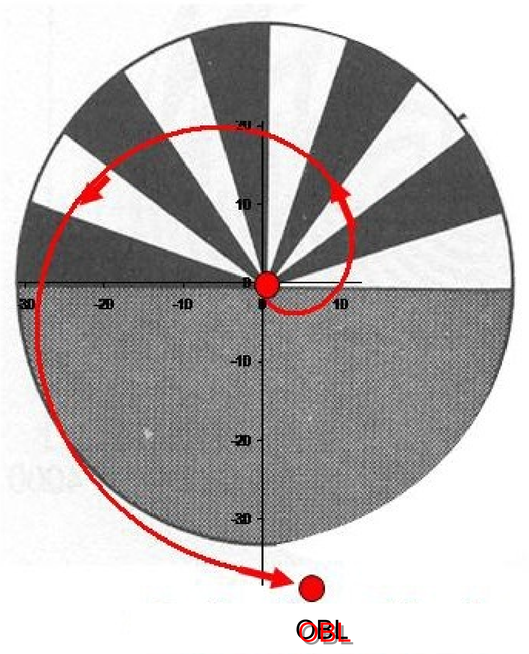


FIGURE 84. Apparent Target Motion on Reticle During Jamming. (Actually, the target is stationary and missile optics sweep out a spiral pattern.)

If an OBL can be achieved, the jammer has won the engagement because most IR missiles do not have the ability to search and reacquire a target once the missile is in flight.

Nutation of the track loop also introduces a signal into the missile control loop that will cause the wings or canards to move and induce a spiral perturbation in the missile’s flight path. This behavior will scatter the hit pattern at the target and cause some percentage of target misses.

Because most MANPADS missiles do not have a proximity fuse, the warhead will detonate only if the missile impacts the target. For these missiles, even a near miss may be sufficient.

END OF THERMAL JAMMER ERA

Two evolutions in missile design pointed to the end of the thermal jammer area. The first was the move by missiles to sensitivity at longer wavelengths (see Figure 85). Missile designers made this move as new detectors, such as InSb, with a sensitivity in band C became available. The greater sensitivity and longer wavelength gave missiles a longer acquisition range and all-aspect rather than just a tail shot capability. Operation at longer wavelengths did not end jammer effectiveness but made it more difficult to obtain high J/S ratios.

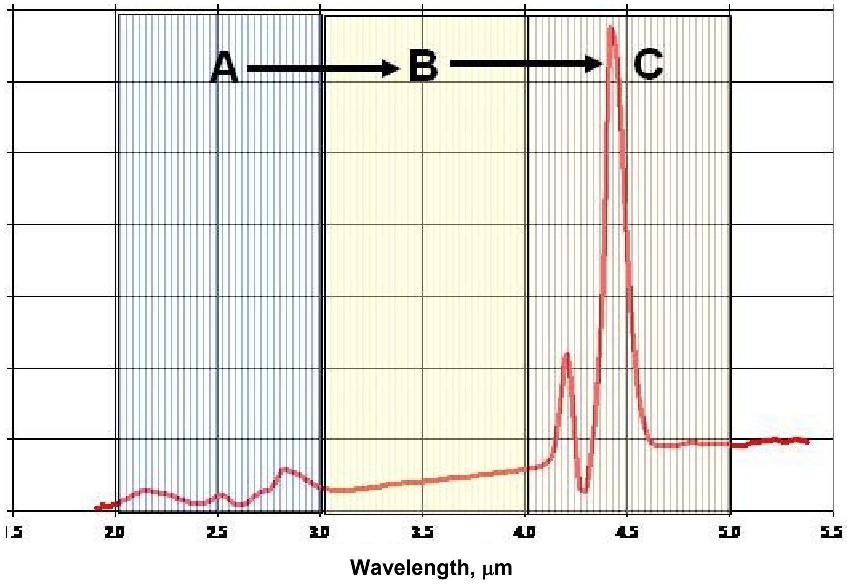


FIGURE 85. Response Moved to Longer Wavelengths.

The second evolution, and the more important one to jammer countermeasures, was the change from spin scan, in which the target is seen through the full scan cycle, to conical or other scan types, in which the missile detector views only the target during part of its scan cycle (Figure 86).

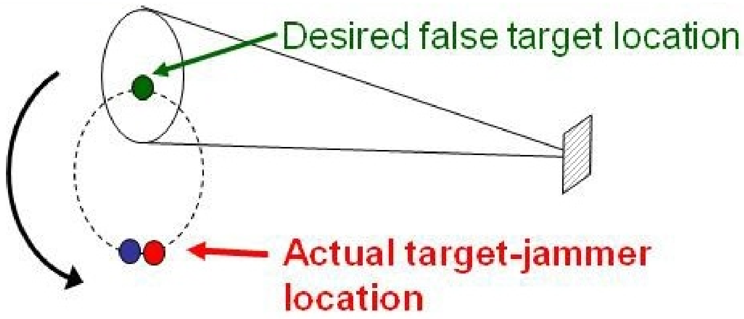


FIGURE 86. Scan Type Moved From Spin to Conical. (With conical scan, the missile views only the target during part of its scan cycle.)

In theory, conical scan would be impossible to defeat with a jammer because the missile does not look at the target during the time the jammer needs to be injecting a signal to push the track away (see Figure 87). In practice, it is possible for a jammer to defeat conical scan because of two effects:

1. Perturbations that are induced in missile flight. Even if there is no OBL, the jammer modulation disturbs missile flight, thus scattering the hit pattern at the target and resulting in a miss by some percentage of shots.
2. Optical scattering and reflections that are present in the missile optics. Optics are not perfect, and a strong enough source from outside the nominal missile FOV can still get through.

The consequences of conical scan and coarse imaging scans (rosette, cruciform, etc.) for jammers are a requirement for J/S ratios that are higher than possible with a wide beamwidth thermal source.

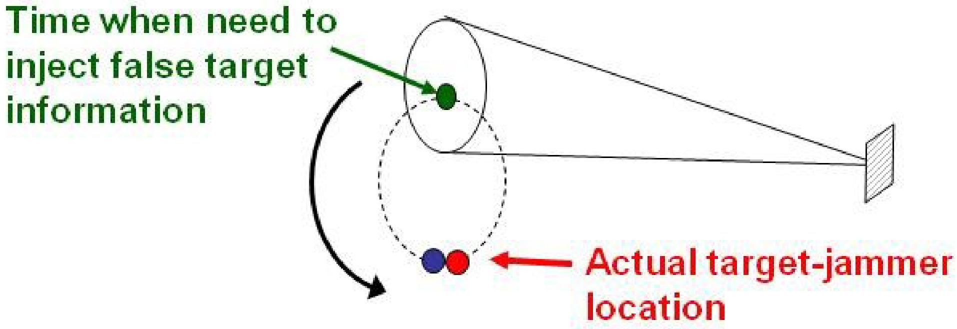


FIGURE 87. Drawing Depicting Missile IFOV at Time When Jammer Needs To Be Injecting Push-Away Signal.

CONSEQUENCES TO TESTING WITH CAPTIVE MISSILES

The advent of conical-scan missiles also had an impact on jammer effectiveness testing with captive missiles. Unless a jammer has a sufficient J/S ratio to force a rapid OBL, then the effectiveness of the jammer cannot be determined from a captive missile test alone. The role of captive seeker testing is evolving toward greater use in validation of simulations rather than as a stand-alone test of effectiveness.

Signals from highly instrumented missiles are recorded in response to countermeasure events. These signals are compared with and used to validate the missile simulation at an identical fixed-range condition. Side-by-side radiometric measurements are made of the target and countermeasure to validate the signature model.

A live fire test is always better, but live fire opportunities are rare because of their greater cost; and, even then, detailed signal analysis is necessary to correctly interpret the results. Live fire testing in the early 1970s against the conical-scan Redeye missile raised hope that jammers could cause a miss even if OBL could not be achieved. In one test program, a target drone equipped with a jammer caused 17 shots with the Redeye to miss. For the 18th shot, the jammer was turned off and the missile scored a hit.

Live fire tests seem conclusive, but the Redeye was a poor test case because (1) it was for a shorter wavelength, in which higher J/S ratios could be achieved and (2) the wide misses were caused by saturation of a stage in the electronics unique to the Redeye. Jamming tests with other later conical-scan missiles showed some percentage of misses but not as wide and not as high a percentage.

OBL achieved early in a missile’s flight causes a certain, wide miss. Against longer-wavelength, conical or other types of scan missiles, OBLs can be achieved only with the very high J/S ratios that can be obtained with laser jammers.

LASER JAMMERS

Laser jamming of missiles was tested in laboratories in the mid-1970s and found to work well, but lasers have two problems that were not solvable then and are still difficult today:

1. Low in-band power—no laser materials have natural molecular resonances in threat IR bands. In-band emission requires frequency multiplication, which yields low power. Laser jammers achieve high irradiance with a very narrow beam (see Figure 88).
2. Need for reliable missile warning with accurate direction of arrival to hand off to a tracker and an accurate pointer tracker to follow the inbound missile and direct the laser beam onto the missile optics.

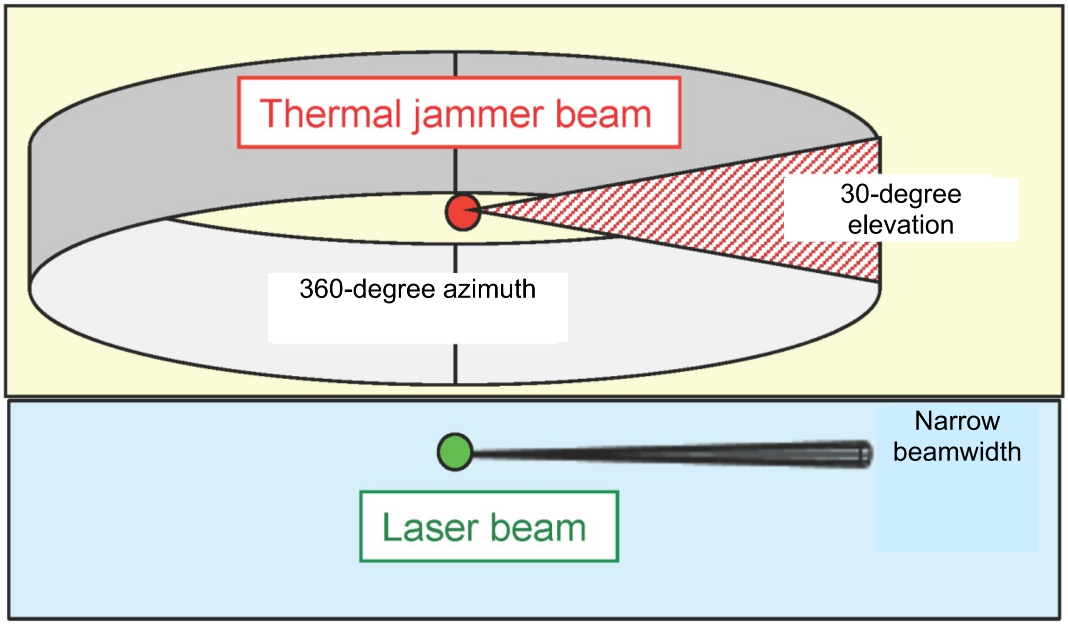


FIGURE 88. Dramatic Increases in Irradiance Can Be Achieved by Narrowing Jammer Beam. (Thermal jammer beamwidths can be narrowed with reflectors, but narrower beams can be achieved with a laser. The problem with a narrow beam is the need for accurate pointing.)

JAMMER COUNTERMEASURES: KEY POINTS

The objective of jammer countermeasures is to inject a signal into the missile target tracker that causes the tracker to push away from the real target aircraft.

If the jammer intensity is sufficiently greater than that of the aircraft (high J/S ratio), the jammer can force an OBL and a certain miss.

Evolution in missile design toward longer wavelengths and, especially, to conical and other scan types from spin has made the jammer requirements more difficult.

Older thermal jammers have inadequate intensity to force OBL. The new directional infrared countermeasure (DIRCM) jammers have extremely high J/S ratios, achieved by narrowing the beamwidth. Having a narrow beam requires a reliable warning receiver and accurate pointer/tracker.

Much testing will be required, but DIRCM systems may offer greater effectiveness against the next-generation advanced imaging missiles, especially as more powerful in-band lasers are developed. Figure 89 shows a laser jammer installation on a Marine Corps CH-53E.

FIGURE 89. Close-up of LAIRCM System Installed on CH-53E.

MISSILE WARNING RECEIVERS (MWRs)

WARNING RECEIVER TRADE-OFF

The classical warning receiver trade-off is to find an acceptable compromise between (1) a high probability of detection and (2) a low false alarm rate.

The warning receiver challenge is to distinguish the missile from natural background sources. Passive tracking by IR missiles eliminates RF illumination warnings.

The basic design strategy is to look for and exploit differences between missile and background radiation distributions in the spectral, spatial, and temporal domains. Figure 90 shows the launch of a Stinger missile,

IR and ultraviolet (UV) warning receiver development programs go back to the late 1960s, with many serious efforts, but few of the systems made it into service.

Advances in technology of high-speed processors and large sensor arrays will afford the next generation of warning receivers greater performance and reliability in all environments.

FIGURE 90. Stinger Launch From Marine Corps Avenger Vehicle. (Missiles have features that make them distinguishable from natural background sources, but reliable detection with a low false alarm rate remains a significant challenge.)

Distinguishable Missile Features

The basic approach to any target detection problem is to

1. List all the features that can distinguish the target from natural background sources.
2. Separate those features into categories according to their spectral, spatial, and temporal domain distributions.
3. Design methods of screening or discrimination for each.
4. Where possible, use multiple discriminants to reduce false alarm rate.

Missiles and natural backgrounds have many differences that can be exploited:

1. Missiles are small (spatial).
2. Missiles have a rocket motor (spectral).
3. Missiles close rapidly on intercept course (temporal and spatial) and are also detectable by Doppler using RF.
4. Body of the missile is hot from aerodynamic heating (spectral) so still may be detectable after motor burnout.

Figure 91 shows a Stinger MANPADS launch.


DOD public domain release.
(www.defenselink.mil/multimedia.)

FIGURE 91. Stinger Shoulder Launch.

Warning Receiver Problems and Constraints

Balanced against the many differences that make missiles distinguishable are a number of requirements that make the warning receiver problem difficult to achieve:

1. False alarm rate must be low. Urban areas have many false sources that must be rejected.
2. Declaration must be very quick for short-range shots. (In Iraq, MANPADS shots were observed from less than 1 to 2 km.) System must declare in sufficient time to employ countermeasures.
3. For air-to-air missiles, motor burnout may occur miles away. As a result, only the hot missile hard body can be detected and tracked.
4. A wide field of regard is required: 360-degree azimuth and large enough elevation coverage not to have blind zones when banking.
5. System must not be blinded or degraded by own ship countermeasures, engine exhaust, or rotor/propeller blockage.
6. When the warning receiver is used with a DIRCM system, the direction of approach must be accurate for handoff to tracker.

Figure 92 shows a full IR countermeasure suite on an AH-1W Cobra.

FIGURE 92. IRCM Suite on AH-1W Super Cobra. (IRCM installations on an AH-1W, 17 October 2008, over flight deck of USS *Peleliu*.)

Detectable Spatial Features

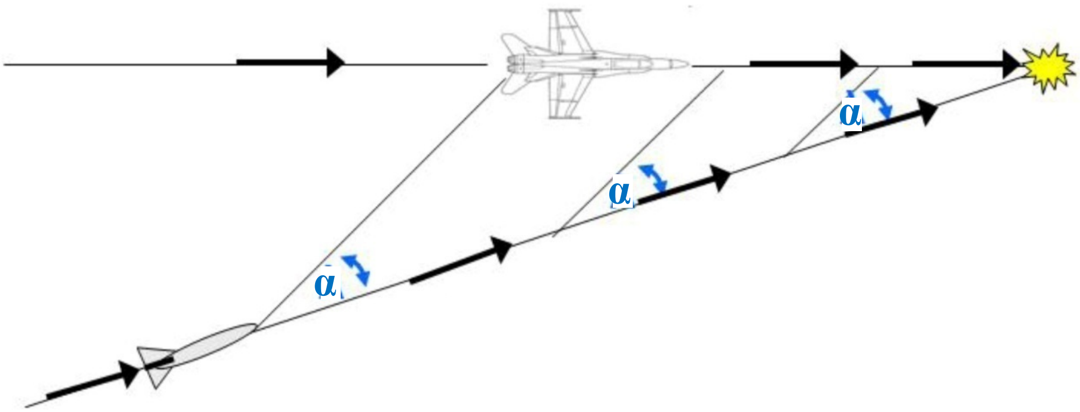
Two spatial characteristics make a missile distinguishable from background sources:

1. The motor is small, while most natural backgrounds are large. Size discrimination is even easier with imaging than with missile reticle trackers.
2. A missile on an intercept course with a target will be at a nearly constant relative bearing, while the background will be moving.

Detectable Temporal Features

The profile of increasing irradiance versus time received from a rocket motor is an important discriminant that is usually used together with spectral and/or spatial discriminants.

Irradiance is proportional to the inverse of the square of the range from a source. An approaching missile has a rapidly increasing irradiance curve that can also be used to estimate time to impact. Figure 93 shows the nearly constant approach geometry of a missile after the proportional navigation equation has been solved.



Missiles try to keep the bearing to the target constant to put the missile on an intercept course. From the aircraft, the constant bearing of the missile is a feature distinguishable from the moving background, and this factor can be exploited by warning receivers to help reduce the false alarm rate.

FIGURE 93. Proportional Navigation Geometry.

DETECTABLE SPECTRAL FEATURES

Ultraviolet (UV)

A burning rocket motor is an open flame with emissions across the spectrum from the UV through MWIR. A small part of the UV region referred to as the "solar blind" is attractive because almost all sources there are man-made, i.e., no natural background. The sun has strong emissions into the UV; but, in this region, almost all of the sun's radiation is absorbed by ozone in the upper atmosphere (hence solar blind). Figure 94 shows the burning rocket motor of a Stinger missile launch.

While the solar blind has positive features for warning receivers, there are also limitations:

1. Useful range is relatively short. Transmission of UV is limited by atmospheric scattering because of the short wavelength.
2. Urban areas often have ozone concentrations that limit range.
3. Solar blind warning receivers are not practical on afterburning aircraft because of own ship emissions in the UV.
4. Solar blind is not a useful band at high altitude, where less ozone absorption results in high background from sunlight.

FIGURE 94. U.S. Army Stinger Launch During Live Fire Exercise.
(The open flame of rocket motors emit radiation across the
spectrum from UV through MWIR.)

Infrared (IR)

The mid-wavelength part of the IR has disadvantages because of the large number of background sources, both natural and man-made. However, IR also offers several advantages that can be exploited:

1. Longer range due to higher atmospheric transmission (little or no atmospheric scattering).
2. Possibility of tracking missile hard body after motor burnout.
3. The use of multiple wavelength bands in the IR as a more powerful discriminant.

Figure 95 is a graph of a plume spectrum.

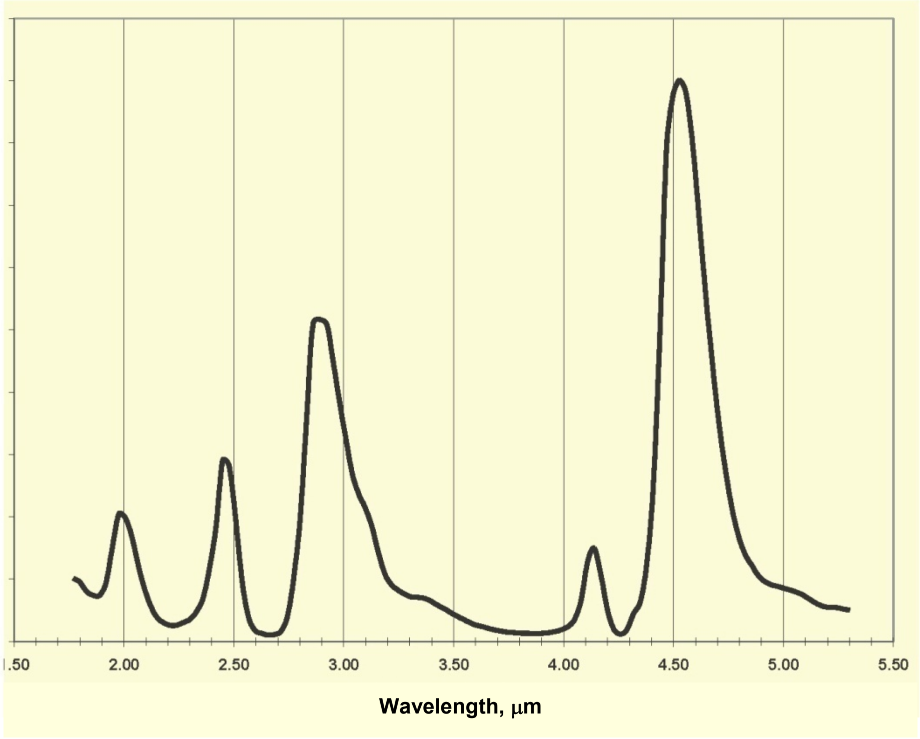


FIGURE 95. Afterburner Plume Spectrum. (Missile rocket motors have very similar spectra to afterburning plumes. The strong CO_2 emission lines make possible discrimination from natural background sources.)

COMBINATIONS

No single one of the spectral, spatial, or temporal features described can provide adequate probability of detection alone but, when used in combination with the powerful embedded processors available today, hold the key to better future missile warning systems.

WARNING RECEIVER TESTING

The complexity of the multiple dimensions and dynamics of the missile and background scene for launch detection and tracking requires validated simulations for testing. The flow of information into the simulation is shown in Figure 96. As the yellow block shows, simulations may be either HIL or all digital.

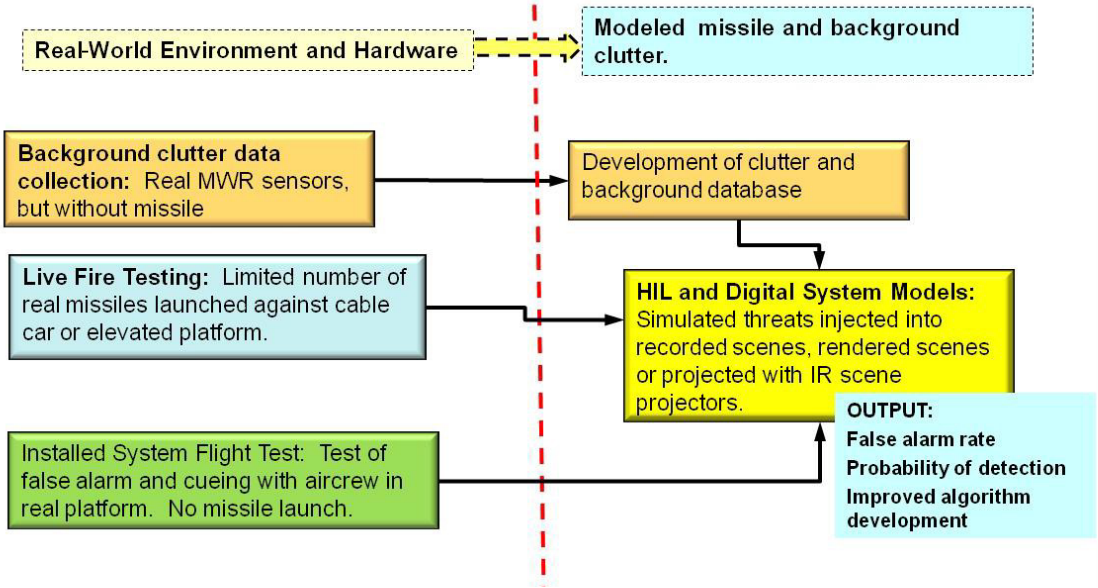


FIGURE 96. Information Flow in Warning Receiver Testing.

Data from the real-world environment and warning receiver hardware feed the modeled missile and background simulation for implementation and validation. The sources for these data include

1. Background clutter data collection: real MWR sensors but without missile.
2. Live fire testing: limited number of real missiles launched against cable car or elevated platform.
3. Installed system flight test: test of false alarm and cueing with aircrew in real platform but with no missile launch.

DIRECTIONS AND CHALLENGES

There are no predicting technological breakthroughs that can change everything in a very short period of time. Processors and the internet are examples in which increasing consumer demand has driven prices down and capability up beyond what even science fiction writers imagined. In the IR, two technologies stand out as having had a major impact in recent years:

1. SFPAs. SFPAs have steadily grown in size and quality, while dropping in price. The revolution they made in the mid-wave (1.5 to 5.0 μm) is now happening in the long wave (7 to 10 μm).
2. Fast, powerful, low-cost embedded processors. The same technology that has changed every other aspect of technology also continues to change IR.

A safe extrapolation is that present trends will continue and probably accelerate, as almost all computer-related technology has been accelerating. The dominant trend in IR is toward greater acquisition of information (spectral, spatial, and temporal) and toward faster processing. The world continues to grow more dangerous, and antiaircraft IR missiles and search/track systems will continue to grow in capability. These challenges must be met with improved IRCM. Figure 97 shows a flare dispensed at transonic speed from an F/A-18.

DOD public domain release.

FIGURE 97. Flare Dispensed in Transonic Flight. (An F/A-18C drops flares during an air power demonstration aboard the USS *Dwight D. Eisenhower* [CVN 69], 27 July 2010. Decoy countermeasures will continue to play a major role in aircraft defense for at least the next decade.)

AIRCRAFT IR SIGNATURES

Research and testing of techniques and materials to reduce aircraft IR signatures are ongoing. Past aircraft were designed exclusively for performance and payload, with IR signature an afterthought and suppression an add-on. In newer aircraft, such as the F-22 (Figure 98), lower IR signature technologies are incorporated into the basic design.


USAF public domain release.

FIGURE 98. Air Force F-22 Shown Over Edwards Air Force Base.

Next-generation aircraft, such as the Boeing Bird of Prey (Figure 99), are likely to have radically different shapes for lower radar RCS and lower IR signature. The biggest gains will continue to come from better engine suppression. Airframe signature can be reduced, but the gains are incremental and will always be condition dependent.

These signature reductions will shorten threat-acquisition ranges and increase countermeasure options and effectiveness.

(www.boeing.com photo release 18 Oct 2002)

FIGURE 99. Boeing Bird of Prey.

IR-GUIDED MISSILES

IR missiles are likely to be the biggest beneficiary of SFPA and processor technology. The expectation is that longer acquisition ranges will be longer and CCM will be more powerful.

The dominant trend in IR missiles is toward imaging, first in a single band and then in multiple bands.

As laser jammers become operational on a larger scale, missiles will incorporate anti-DIRCM CCM. Techniques such as hardening against laser pulses and home-on-jam will be adopted.

If DIRCM systems begin to utilize retro return from missiles in their jamming, the expectation is that a missile counter will be the suppression of the optical cross section.

The countermeasure, CCM, C-CCM game will continue, probably at an accelerated pace. Figure 100 shows the highly advanced Israeli Python-5 missile.

(a) Python-5.

(b) Aircraft. (c) Helicopter.

(Photos: Released by Rafael Advanced Missile Systems, Ltd)

FIGURE 100. Israeli Python-5 (a) and IR Images of Aircraft (b) and Helicopter (c). (This missile is representative of the next-generation of air-to-air IR missiles. The IR images obtained with instrumentation on the Python-5 show very high resolution and sensitivity. [Note warm helicopter rotor blades.])

INFRARED SEARCH AND TRACK (IRST) AND PASSIVE BEYOND VISUAL RANGE (BVR) ATTACK

Focus has been on MANPADS threats in recent years because they have been the cause of most of the U.S. aircraft losses. The MANPADS threat will continue to advance, with improvements in range and more sophisticated CCM capability.

Another growing threat is from air-to-air IR missiles. In combination with advanced IRST systems, these weapons present the likelihood of encountering completely passive BVR attack.

Air forces around the world are equipping their aircraft with IRST systems as a relatively low-cost counter to U.S. aircraft reduction in RCS and to improvements in RF countermeasures and warning receivers. Figure 101 shows the Passive Infrared Airborne Track Equipment (PIRATE) IRST system on a Eurofighter.

Galileo Avionica news release

FIGURE 101. PIRATE IRST System on Italian Eurofighter. (The European PIRATE is one of a new generation of fighter IRST systems. Combined with long-range IR missiles, these devices will allow passive BVR attack.)

DECOY COUNTERMEASURES

Decoys are likely to remain the most effective countermeasure in wide-scale service for the next decade. The expectation is that the trend toward a variety of decoy characteristics and dispensing strategies will continue as new missile CCM designs are encountered.

Improvements to warning receivers will enhance decoy effectiveness by enabling "smarter" dispensing. Changes in dispenser design may also be required to accommodate larger decoys and increased numbers. Figure 102 shows a flare salvo from an HH-60H helicopter.

The coming imaging missiles will present the greatest challenge and may result in combined use of decoys and jammers to defeat.

FIGURE 102. Flare Salvo From HH-60H Sea Hawk. (An HH-60H displays the ability to launch flares and quickly maneuver during an air power demonstration from the USS *Ronald Reagan* [CVN 76].)

Directions in Jammer Countermeasures

In this section, the author discusses the expected direction in jammer countermeasures.

Present thermal jammers on helicopters and transports will be retired from service.

Operational DIRCM systems will increase in numbers, platforms, and variety of configurations. Reliability and service life in operational environments will steadily improve.

In-band laser power will increase. The ultimate goal of laser jammers is to achieve sufficient power to damage sensors. Higher power lasers will force missile designers to utilize laser hardening.

Directions in Warning Receivers

In this section, the author discusses the expected direction in warning receivers.

Present MWRs are designed only for surface-to-air threats and, consequently, are planned only for installation on platforms with the greatest vulnerability: helicopters and transports. Because surface-to-air missiles have a relatively short range with long motor burn times, warning receivers and tracking for DIRCM systems are able to detect and track the burning rocket motor.

Increases in air-to-air threats from China, Russia, and others will create a greater need for air-to-air missile warning. Present and near-term warning receiver technology is inadequate for air-to-air threats. Air-to-air missiles have a much longer range than surface-to-air missiles, and motor burnout may occur miles from the target, thus requiring detection and tracking of the missile body alone.

Advances in IR SFPAs and image processing will be helpful but are unlikely to be adequate alone. Effective air-to-air missile warning is likely to require greater integration of the passive IR warning receiver with aircraft RF warning and fire control radar and, perhaps, the addition of an active warning capability.

Countermeasures Effectiveness Testing

Testing the effectiveness of new, integrated countermeasure and warning receiver systems will almost certainly present the greatest challenges.

These new systems will force greater reliance on simulations, both HIL and all digital. And, this situation in turn will force more rigorous (and expensive) validation work. Figure 103 shows typical information flow in countermeasure effectiveness testing.

The trend toward data from missile testing, both with captive missiles and live missile firings, as well as aircraft and countermeasure measurements being used to feed simulations rather than being used directly, will accelerate.

In every aspect and at every step, there will be judgment calls about what constitutes an adequate test of effectiveness. The need for experienced personnel to make these judgments will continue to grow.

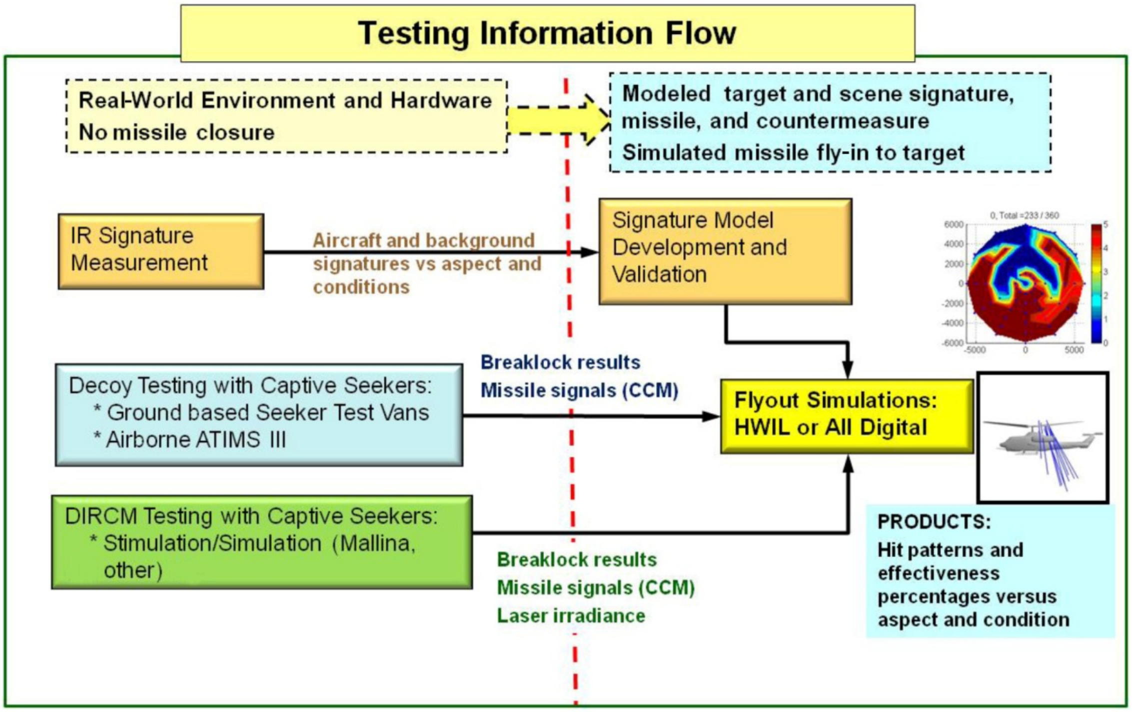


FIGURE 103. Testing Information Flow.

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NOMENCLATURE

α	angle (Figure 93)
α_m	maximum angle
α_v	variable angle (Figure 56)
ε	emissivity or absorbance
λ	wavelength (μm)
τ	transmission
$\tau(\lambda)$	spectral transmission of atmosphere
τ_p	atmospheric path transmission
$\tau_p(\lambda)$	atmospheric path spectral transmission
μm	micrometer
ρ	reflectivity
$\rho\lambda$	spectral reflectivity
Ω	solid angle
Ω_s	solid angle subtended by source (sr)
Ω_t	solid angle subtended by target (sr)
a	$(10^{16})2hc^2$ (1.19042868×10^4 W·cm^{-2}·μm^4)
AM	amplitude modulated
A_N	area normal to surface
A_{ps}	length of vector
A_s	area (Figure 14)
A_s	projected area of source
A_t	target projected area (cm^2)
ATIMS	Airborne Turret Infrared Measurement System
b	$(10^4)\frac{ch}{k}$ (1.43877696×10^4 μm·K)
BVR	beyond visual range

c	speed of light ($2.99792458 \times 10^{10}$ cm·s^{-1})
CCM	counter-countermeasures
C-CCM	counter-counter-countermeasures
CGS	centimeter-gram-second *[system of units]*
cm	centimeter
CO_2	carbon dioxide
D	range (cm)
DC	direct current
DIRCM	directional infrared countermeasures
DOD	Department of Defense
E	irradiance (W·cm^{-2})
E_λ	spectral radiance (W·cm^{-2})
E_c	apparent contrast irradiance at sensor (W·cm^{-2})
E_{ce}	apparent effective contrast irradiance at sensor (W·cm^{2})
E_R	irradiance at receiver (W·cm^{-2})
ERP	effective radiated power
EW	electronic warfare
fc	carrier frequency
FM	frequency modulation
FOV	field of view
fs	spin frequency
h	Planck's constant ($6.62606957 \times 10^{-34}$ W·s^{2})
H_2O	water
HgCdTe	mercury cadmium telluride
HIL	hardware in the loop
I	radiant intensity (W·sr^{-1})
IFOV	instantaneous field of view
InSb	indium antimonide
IR	infrared
IRCM	infrared countermeasures
IRST	infrared search and track
I_S	radiant intensity of source (W·sr^{-1})
J/S	jammer-to-signal *[ratio]*
k	Boltzmann's constant ($1.3806488 \times 10^{-23}$ J·K^{-1})
km	kilometer

L_λ	spectral radiance ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}}$)
LAIRCM	Large Aircraft Infrared Countermeasure *[system]*
$L_b\lambda$	background absolute spectral radiance ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}}$)
L_c	apparent contrast radiance at sensor ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$)
L_b	background absolute radiance ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$)
L_S	radiance of source ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$)
L_t	target absolute radiance ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$)
$L_t(\lambda)$	target absolute spectral radiance ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}}$)
$L_T(\lambda)$	spectral radiance ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$) of target
LWIR	long-wavelength infrared
M	Mach number
MANPADS	man portable air defense system
MWIR	mid-wavelength infrared
MWR	missile warning receiver
NAVAIR	Naval Air Systems Command
NAWCWD	Naval Air Warfare Center Weapons Division
NSWC	Naval Surface Warfare Center, Crane, Indiana
OBL	optical break lock
PbS	lead (II) sulfide
PbSe	lead selenide
PIRATE	Passive Infrared Airborne Track Equipment
R	range or distance
$R(\lambda)$	instrument-relative spectral response
RCS	radar cross section
RF	radio frequency
R_r	distance from receiver to source (cm)
$R_s(\lambda)$	normalized spectral response of sensor
s	second
SFPA	staring focal plane array
SI	International System of Units
S/N	signal-to-noise
sr	steradian
T	absolute temperature (K)
T_0	ambient air temperature (K)
t_1, t_2, etc.	points in time
T_R	recovery temperature (K)

USAF	United States Air Force
UV	ultraviolet
VFA	Strike Fighter Squadron
VMFA	Marine Fighter Attack Squadron
W	watt

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