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**Human Factors and Safety Considerations
of Night Vision Systems Flight Using Thermal
Imaging Systems**

(Reprint)

By

Clarence E. Rash
Sensory Research Division

Robert W. Verona
Office of the Program Manager
for Night Vision and Electro-Optics
Fort Belvoir, Virginia

John S. Crowley
U.S. Army Safety Center

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**United States Army Aeromedical Research Laboratory
Fort Rucker, Alabama 36362-5292**

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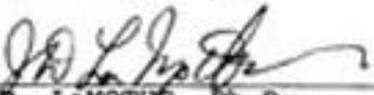
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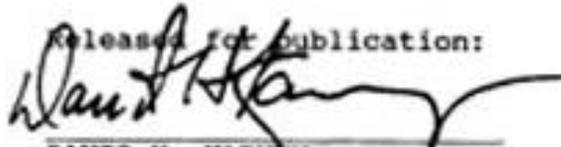


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Director, Sensory Research
Division



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COL, MS
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DAVID H. KARNEY
Colonel, MC
Commanding

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Clarence E. Rash

U.S. Army Aeromedical Research Laboratory Fort Rucker, Alabama 36362-5292

Robert W. Verona

Office of the Program Manager
for
Night Vision and Electro-Optics
Fort Belvoir, Virginia 22060-5677

John S. Crowley

U.S. Army Safety Center
Fort Rucker, Alabama 36362-5363

ABSTRACT

Military aviation night vision systems enhance the aviator's capability to operate effectively during periods of low illumination, adverse weather, and in the presence of obscurants. Current fielded systems allow aviators to conduct terrain flight during conditions which would be extremely dangerous, if not impossible, using only unaided vision. In night vision systems, trade-offs are made that enhance some visual parameters and compromise others. Examples of visual parameters which are traded off include acuity, field-of-view, spectral sensitivity, and depth perception. Cost, weight, and size constraints also lead to compromises between an ideal and a viable system design. Thermal imaging sensors introduce enhanced night vision capabilities along with new problems associated with the interpretation of visual information based on spectral and spatial characteristics differing from those provided by unaided vision. In addition, the mounting of these visual displays onto the aviator's helmet provokes concern regarding fatigue and crash safety, due to increased head-supported weight and shifts in center-of-gravity. Human factors and safety issues related to the use of thermal night vision systems are identified and discussed. The accumulated accident experience with U.S. Army AH-64 helicopters equipped with the thermal Pilot's Night Vision System and the Integrated Helmet and Display Sighting System is briefly reviewed.

1. INTRODUCTION

Army aviation has used night vision systems since 1971. These systems enhance the aviator's capability to operate effectively during periods of low illumination, supporting the Army's doctrine of carrying out missions in darkness and under adverse weather conditions. In the aviation environment, night imaging systems are the sensor and the display, as shown in Figure 1. Currently, the two major technologies used for night vision sensors are image intensification (I²) and thermal imaging (e.g., forward looking infrared-FLIR).

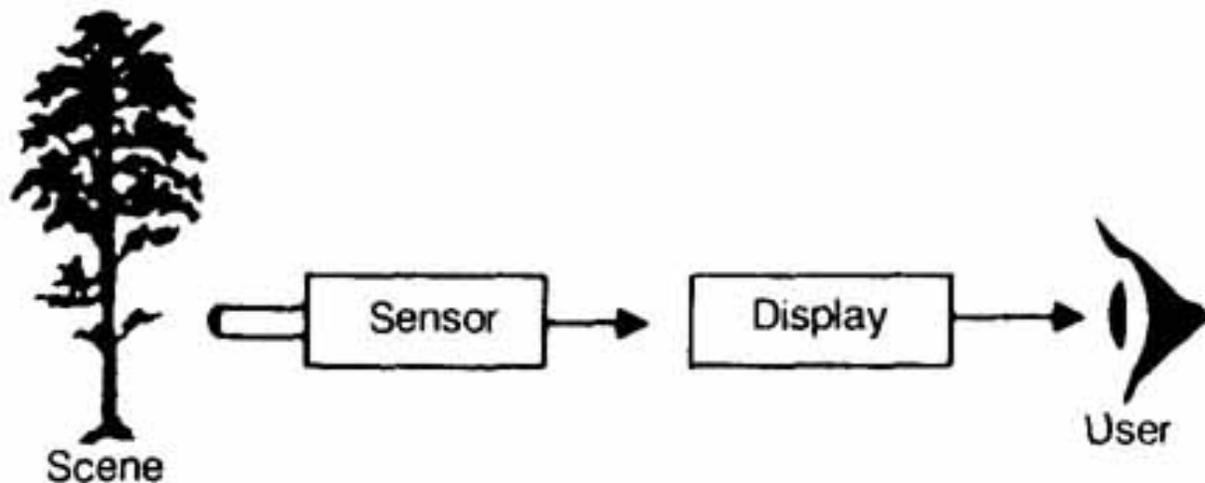


Figure 1. Simplified block diagram for a Night Vision System.

Image intensifiers amplify, or intensify, reflected or emitted light so the eye can more readily see a poorly illuminated scene. They depend on the presence of some minimum amount of light in order to produce a usable image. This is analogous to using a microphone, amplifier, and speaker to allow the ear to more easily hear a faint sound.

The U.S. Army has fielded two night vision systems for aviation use based on I² technology. One is known as the AN/PVS-5 Series Night Vision Goggles (NVG) and is based on second-generation image intensifier tubes. The other, which uses third-generation tubes, is known as the AN/AVS-6 Aviator's Night Vision Imaging System (AN-VIS) (Figure 2). The NVG and ANVIS systems amplify low level ambient light reflected from objects and present an image on a phosphor screen. Both systems use two image intensifier tubes to form a binocular device which is attached to the aviator's helmet. While both of these systems currently are in use, the second generation NVGs are systematically being replaced in aviation by the newer ANVIS.



Figure 2. The Aviator's Night Vision Imaging System (ANVIS).

The second type of night imaging sensor, the topic of this paper, uses thermal imaging. This type of sensor does not depend on ambient light, but rather on infrared (IR) radiation emitted by objects in the scene. The thermal sensor can be designed to “see” radiation in either the 3 to 5-micron or 8 to 12-micron (10^{-6} meters) spectral range. All objects radiate measurable amounts of energy in these spectral ranges. The amount of radiated energy is dependent on temperature and type of material.

In the Army's newest production aircraft, the AH-64 (Apache) attack helicopter, thermal imaging is used for both pilotage and targeting. The targeting sensor system is known as the Target Acquisition and Designation System (TADS) and the pilotage sensor system is known as the Pilot Night Vision System (PNVS). The PNVS provides imagery to a helmet-mounted display (HMD) called the Integrated Helmet and Display Sighting System (IHADSS) (Figure 3). Both the TADS and the PNVS use thermal imaging sensors, mounted on the nose of the aircraft, operating in the 8-12 micron spectral range (Figure 4).



Figure 3. The Integrated Helmet and Display Sighting System (IHADSS).

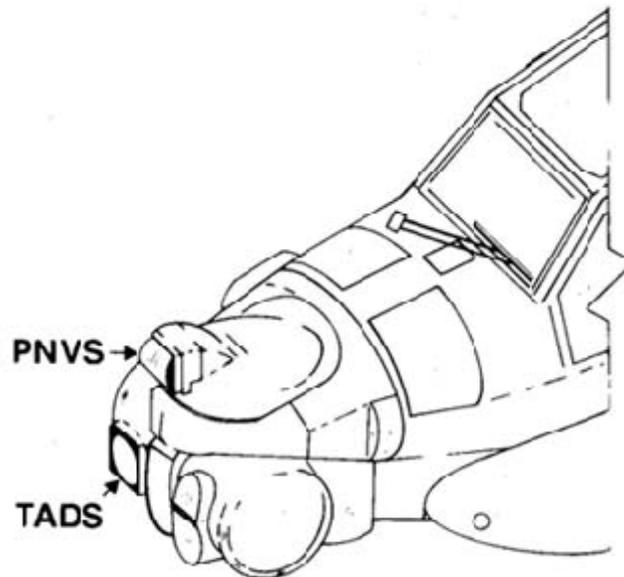


Figure 4. The positions of the PNVS and TADS sensors on the AH-64.

Independent of the technology of the night imaging system (i.e., I² or thermal), some of the “natural fidelity” of the external scene is lost in the imaging process. The specific characteristics of each sensor and display system determine the nature of the presented image, and consequently can affect user performance. Compared to unaided night vision, the image presented to the aviator by modern night imaging systems is bright and contains considerable visual information. However, the aviator flies with far fewer visual cues than are available in daylight—a handicap which may not be obvious to the aviator. Coupled with the more apparent limitations to field-of-view and color vision (among others), successful flight using night imaging systems is a remarkable feat.

Several papers have discussed performance and safety issues relating to night imaging systems based on I² technology.^{2,3} This paper addresses the major characteristics of thermal imaging technology and the performance of the currently fielded PNVIS/IHADSS systems used in the pilotage of the AH-64 attack helicopter. Paramount in this discussion is the possible influence of these characteristics on user performance and safety.

2. THEORY OF THERMAL IMAGING SYSTEMS

Night vision systems based on thermal imaging technology operate by detecting infrared emission of objects in the scene. No universal definition exists for "infrared energy." For imaging, it is generally accepted as thermally emitted radiation in the 1 to 20 micron (10⁻⁶ meters) region of the electromagnetic spectrum (Figure 5). Currently, most thermal imaging is performed in the 3-5 or 8-12 micron regions. These regions are somewhat dictated by the IR transmittance windows of the atmosphere (see Section 10).

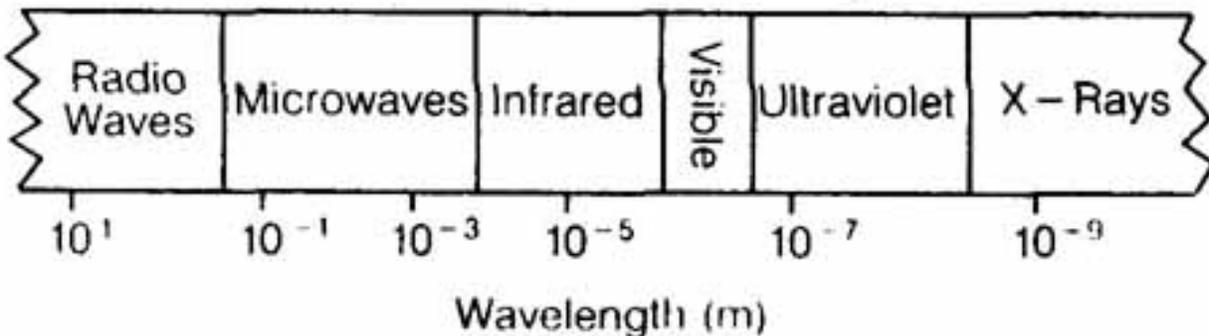


Figure 5. The electromagnetic spectrum.

Thermal imaging theory is based on the fact every object emits radiation. This radiated energy is a direct result of the vibration of the molecules making up the object. An object's temperature is a measure of its vibrational energy. Hence, the higher the temperature of a body, the greater its amount of radiated energy. In turn, the temperature of a body is determined by several factors, including: a) the object's recent thermal history, b) the reflectance and absorbance characteristics of the object, and c) the ambient temperature of the object's surroundings.

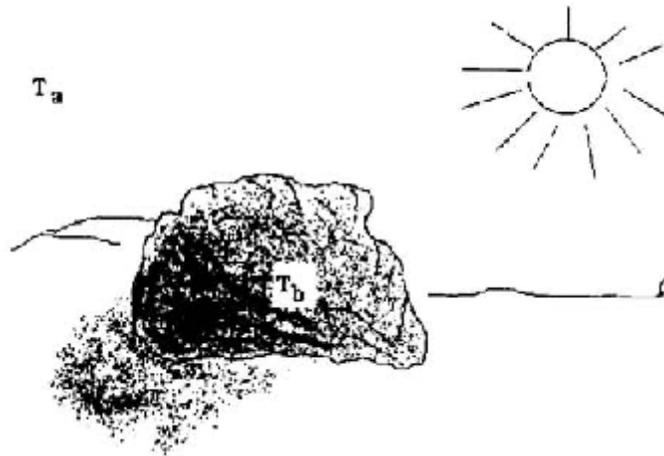


Figure 6. Simplified scenario of boulder (T_b) and surrounding atmosphere (T_a).

An object's recent thermal history includes its exposure to external thermal sources, e.g., direct sunlight and other surrounding objects, and the presence of internal thermal sources, such as engines. Figure 6 depicts a simplified scenario of a boulder sitting in the open under direct sunlight. The boulder is absorbing energy radiated by the sun, the amount being dependent on the reflectance and absorptance characteristics of the boulder's exterior surface. The boulder also is absorbing energy radiated by other objects in the scene, which in this simplified scenario consists only of the surrounding atmosphere and the ground. Energy also may be acquired from the boulder's physical contact with the atmosphere, if the temperature of the atmosphere is higher than the temperature of the boulder. At the same time, the boulder is emitting energy in an amount related to its temperature. If the boulder is at a higher temperature than the atmosphere and ground, it will also be losing energy due to contact with the surrounding atmosphere and ground. If the net effect of all of this energy flux is an increase, then the total molecular vibrational energy (and therefore the temperature of the boulder) will increase. Conversely, if the energy flow results in a net decrease in total energy, then the temperature of the boulder will decrease. For example, at night, when the boulder's primary energy transfer will be negative and its temperature will decrease. However, at any given time, the boulder and the atmosphere can be represented by temperature values T_b and T_a , respectively. These values generally are different and will change as a function of time.

The simple scenario discussed above can be expanded by recognizing the complex nature of real objects. If a more realistic object, such as a tank, is investigated, then several other factors must be considered. A tank has geometric features and is manufactured from several different materials. These materials have different reflectance and absorptance characteristics. This will result in different parts of the tank being at different temperatures. The tank's geometric features, such as sides, front and back, and top, can result in nonuniform solar heating. The tank also has a major internal source of thermal energy, its engine. Our simplified picture of an object at a single uniform temperature must be replaced by one in which the object consists of a multitude of temperature values, resulting in many different levels of energy emission.

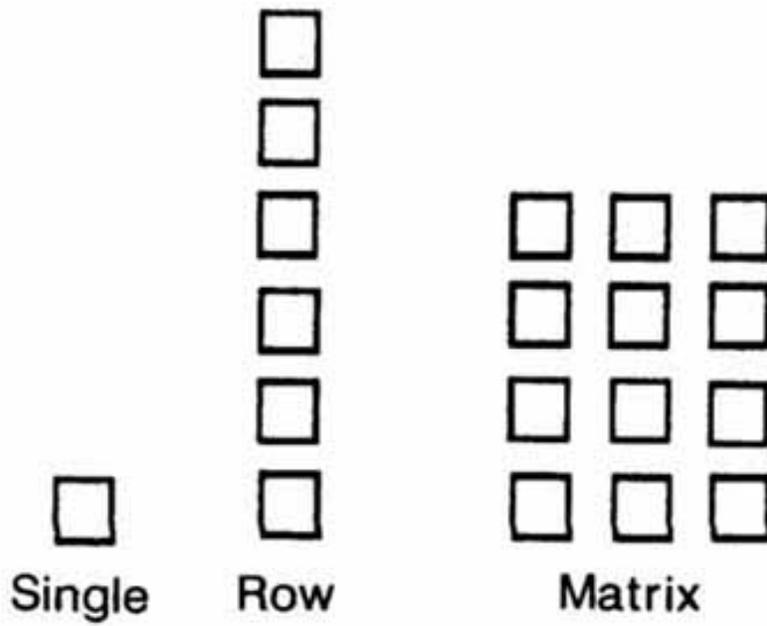


Figure 7. Single, row, or matrix of detectors.

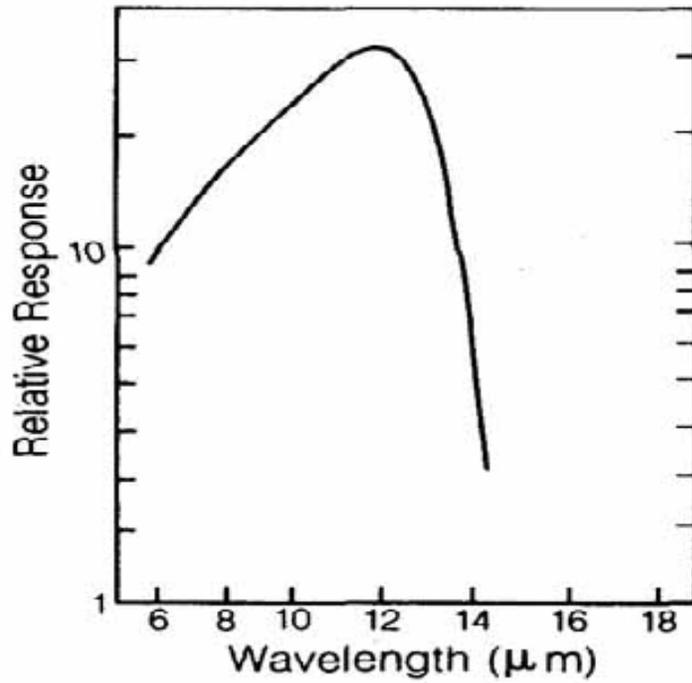


Figure 8. Spectral response of typical HgCdTe detector.

Thermal imaging sensors form their image of the external world by collecting energy from individual segments of the scene. This may be accomplished by using a single detector (or row of detectors) which scan over the scene, building its image one part at a time. An alternate technique is to use a matrix of detectors with each one collecting energy from a different part of the scene (Figure 7). The size of each detector's collection angle defines the smallest area of the scene which can be imaged, i.e., the resolution of the sensor. The output of each detector is related to the amount of energy emitted from a small part of the scene. The overall result is a two-dimensional energy emission profile of the scene. To be able to discriminate between two segments of the scene, or between two objects, the two objects must be at two different emission levels and the sensor must be able to discriminate between the two levels.

The PNVS uses a "common module" design which uses a parallel scan of 180 detectors arranged in a single vertical row. An opto-mechanical system is used to scan the outside scene across the detector array. As implied by the name, the common module FLIR design divides the sensor package into separately functional assemblies. This parallel scan modular imaging approach provides the advantages of higher sensitivity, simpler scan mechanism, and higher reliability, when compared to alternate systems.

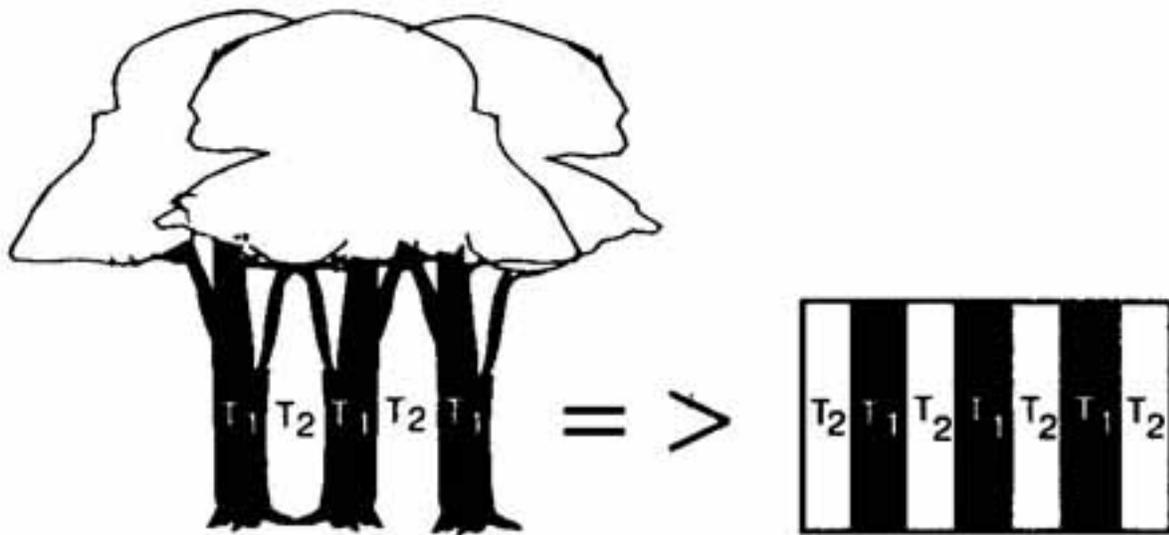


Figure 9. a) A visual and b) thermal representation of a scene consisting of a row of trees.

3. SENSOR PARAMETERS

As depicted in Figure 1, imaging systems can be simplified into two basic sections: the sensor and the display. This section discusses the role of the sensor in the operation and performance of the system. The role of the display is discussed in Section 4, "Display Parameters."

There are several sensor design parameters and user adjustable sensor controls that affect the performance of thermal imaging systems. The design parameters include sensitivity, signal-to-noise ratio, component time constants, spectral response, and resolution. User adjustable sensor controls include gain and bias level. However, many of these parameters are interrelated. In complicated imaging systems such as the common module PNVs, it is difficult to describe individual control operation and effects. What is more important is an overview of how the sensor impacts the quality of the "picture" of the outside world presented to the aviator.

For a sensor to be able to image a scene of the outside world, it must be able to respond to the energy being emitted by objects in the scene. The spectral response of the sensor, or that part of the energy spectrum over which it can collect energy, can be defined as the ratio of the sensor's output signal to the amount of collected energy, as a function of the wavelength. This response is primarily determined by the choice of detector material. One of the most popular detector materials, and the one used in the PNVs, is mercury-cadmium-telluride (HgCdTe). The response for a specific HgCdTe detector varies with the chemical formulation, the mechanism of energy conversion (photoconductive or photovoltaic), and the system's operating temperature. A typical spectral response for the AH-64 PNVs system detector is shown in Figure 8.

A sensor's ability to "see" (or resolve) detail often is presented as the dominant parameter in determining the quality of the "picture" obtained. The smallest segment of the scene which can be imaged is a measure of the spatial resolution of the sensor. This may be defined by the solid angle over which the detector can collect energy. For a single detector, usually this is expressed as the subtended angle representing the detector's instantaneous field-of-view (IFOV). However, in the more complex common module PNVs, the spatial resolution obtained is determined by the interrelationship of the single detector IFOV, the number of detectors and their geometry, the scan method, and the scheme for digital sampling of the detector's analog output. Also, in scan-type thermal imaging systems, the vertical resolution and the horizontal resolutions are different.

Finer features of a scene can be detected if they are of sufficient size and there is adequate contrast. The threshold contrast depends on size. Hence, resolution, by itself, does not guarantee preservation of detail. Contrast transfer is another important parameter. Figure 9a shows a scene containing a horizontal row of trees. Assume these trees are of the same width and are separated by a distance which is equal to their width. Also assume that each tree is identical in its emitted energy and is viewed by the detector as an object of temperature T_1 . Let the background of the scene be at temperature T_2 . This leads to a simplified representation of the scene, as presented in Figure 9b.

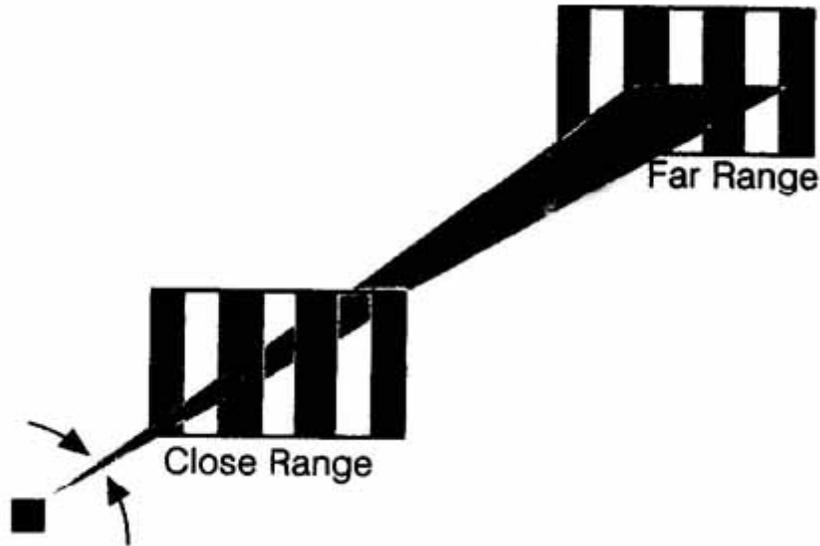


Figure 10. The intersection of the detector's instantaneous field-of-view with the scene at different ranges.

To understand how resolution affects scene imaging, allow the detector to be placed at different ranges from the transformed scene (Figure 10). As the range decreases, the amount of the scene from which the detector collects energy, i.e., scene area within the detector's IFOV, becomes smaller. At the greatest range, the detector is collecting energy from a large part of the scene. At the closest range, the detector is collecting energy from only a portion of one of the bars representing a single tree. At the farthest range, the detector is collecting energy from multiple bars (trees). Consider the detector's output at these two extreme ranges as the detector scans across the scene. As the detector scans at closest range, the detector's output will be at its maximum value when its IFOV is filled fully with a target bar (Figure 11a), a lesser value when the IFOV is filled partially by a target bar and a background bar (Figure 11b), and its minimum value when the IFOV is filled fully with a background bar (Figure 11c). The representative output of the detector is shown in Figure 11d.

Two important concepts are demonstrated in Figure 11. First, the output signal undergoes a modulation (a change in amplitude) which generally follows the increasing and decreasing temperatures (emitted energy) of the scene pattern. The frequencies of the bars in the scene and the maximum and minimum values (which determine contrast) are retained in the output signal. Second, the sharp transition in the scene between a target and background bar is deemphasized in the detector's output. This deviation from a completely faithful representation of the scene occurs as the detector's IFOV simultaneously is collecting energy from both a target and a background bar. During this period, the detector's output value falls somewhere between the values obtained for target or background bars alone.

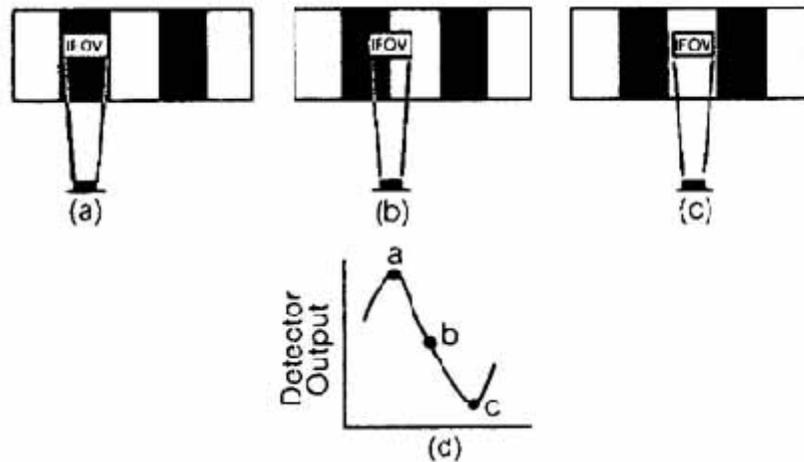


Figure 11. Detector scanning of a close range scene and its representative output.

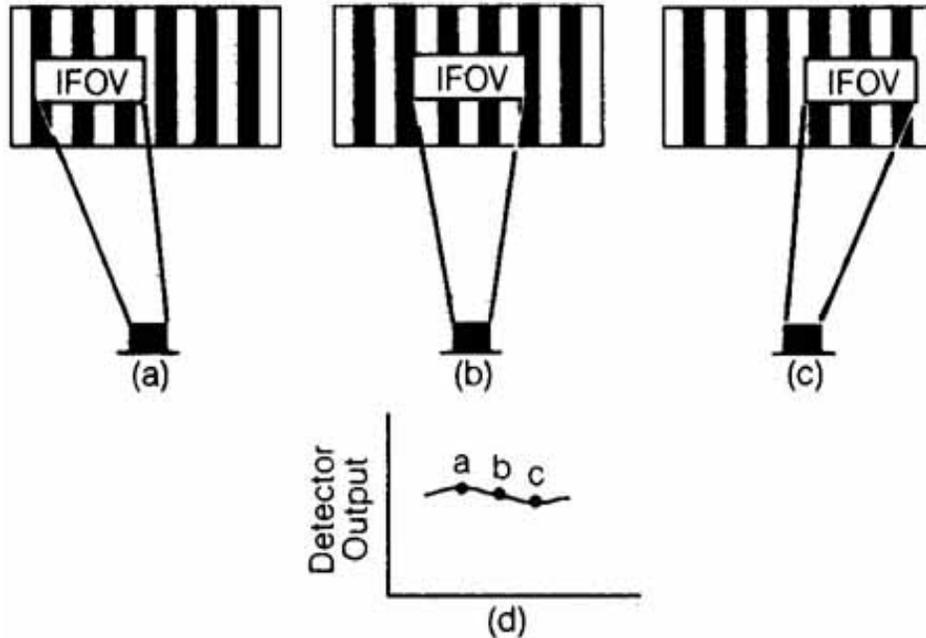


Figure 12. Detector scanning of a far range scene and its representative output.

At the farthest range, the IFOV is collecting energy from a part of the scene containing several target and background bars during the entire scan (Figure 12a-c). As the detector scans, the output signal (Figure 12d) varies little in amplitude and does not undergo a modulation at the frequency in the scene. Neither the scene frequency nor the contrast is accurately reproduced; the individual trees may not be distinguishable on the display.

In the explanation above, as the scene is placed at increasing ranges, the number of bars within the IFOV (target spatial frequency) increases. As this spatial frequency increases, the modulation of the scene, as reproduced in the image, decreases. If the modulation of the image, as compared to the actual scene modulation, is graphed as a function of increasing spatial frequency, a curve similar to Figure 13 would be obtained. This curve is known as the "modulation transfer function (MTF)" and is a figure-of-merit for comparing detectors.

Complex real world scenes are a composite of varying spatial frequencies and contrasts, unlike the single frequency, high contrast scene discussed in the above example. Therefore, the image formed by the detector will not reproduce faithfully all scene information. The contrast of the higher spatial frequencies may be degraded particularly, causing lost in scene detail. Unfortunately, the detector is not the only system component which has a MTF. Further degradation of the scene may result from the MTF of the optics and the display. These component MTFs are cascaded to provide an end-to-end system MTF. A component MTF value (for a given spatial frequency) is always less than one and a system MTF value is always less than any of the component values.

Another figure-of-merit used to compare the performance of thermal sensors is "minimum resolvable temperature (MRT). MRT is a measure of sensitivity. Often, it is defined incorrectly as the minimum temperature difference the sensor can resolve. Actually, it is not a measure of temperature sensitivity, but of energy sensitivity (relating to the material and its temperature). The concept of MRT, while an important laboratory parameter, has no practical significance to the user, except for system comparison. In general, the lower the MRT, the better the sensor can discriminate between objects in a scene.

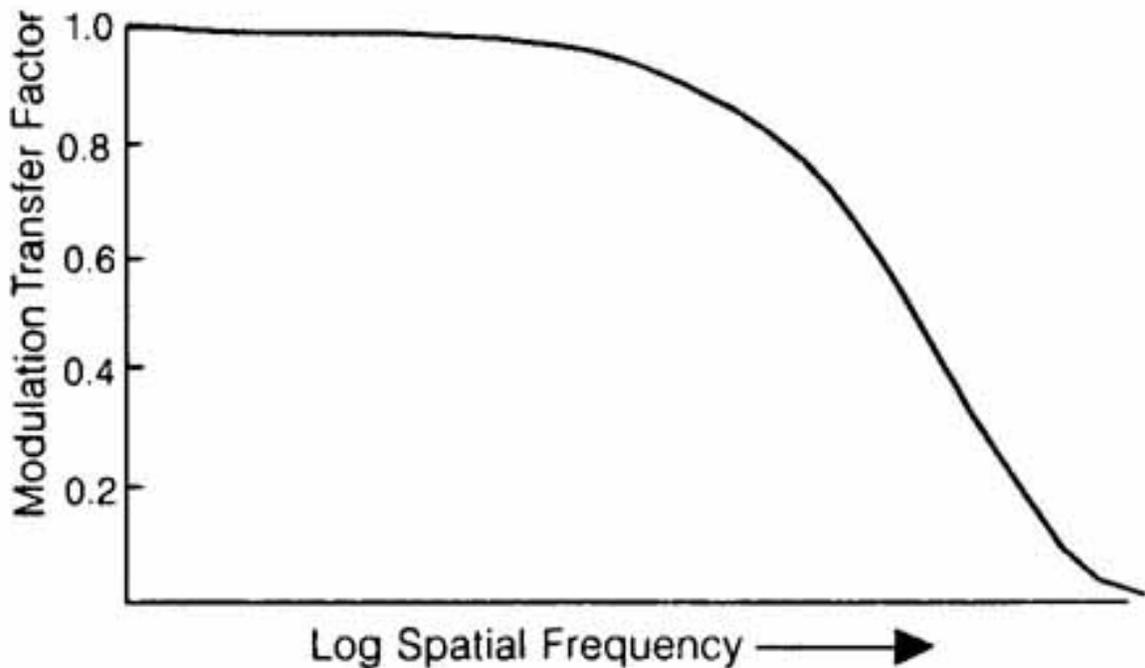


Figure 13. Typical modulation transfer function (MTF) curve.

Two adjustable sensor controls are available to the user. These are gain and bias level. These controls are intended to allow the user to optimize the sensor's performance. In operation, these adjustments affect the IR detector output signal as it is passed to following sensor stages. Proper settings of these controls, which are highly dependent on environmental conditions, optimize the dynamic range (ratio of maximum to minimum signal levels) of the transferred detector signal. Improper detector settings, for a given scene and environment, will result in loss of scene detail and a degraded image.

A third control over the PNVIS sensor output, but one which does not actually affect sensor operation, is the nFLIR polarity" switch. This switch converts the polarity of the sensor's output from 'white hot' to 'black hot.' This refers to the presentation of the imagery on the display. In the 'white hot' mode, objects emitting the greatest amount of energy appear 'whiter' (actually "greener" for the IHADSS display phosphor) than objects of less emission. Conversely, in the 'black hot' mode, objects emitting the greatest energy appear "blackier." A noticeable difference between these two modes is the appearance of the sky background. In the 'white hot' mode, the sky will appear darker than the horizon. Aviators appear to indiscriminately switch between modes, selecting the "best" image, with no definable criteria for selecting one mode over another. The ability to switch polarity is particularly useful when objects are located under tree cover. In the 'white hot' mode, the objects of interest are bright objects being viewed against the bright trees and ground. For certain gain and level setting, switching to 'black hot' may cause the targets to stand out as dark objects while the background remains relatively bright. AH-64 aviators frequently switch polarity in order to optimize picture quality.

4. DISPLAY PARAMETERS

A video display converts an electrical representation of a scene generated by the sensor into a two-dimensional image that can be viewed by the eye. The video display is typically a cathode-ray-tube and the image is similar to that produced on a black-and-white television. A modulated beam of electrons is scanned very rapidly over a phosphor screen. The beam produces a tiny modulated dot of light that generates the two-dimensional, illuminated visual image.

The quality of the imagery is determined by the scene's characteristics, the sensor's operating parameters, and the display's operating parameters. The role of the sensor's parameters was discussed in Section 3. The characteristics of the scene depend on its spatial frequency content and environmental conditions (see Section 10). Display parameters which impact the quality of CRT images include line rate, screen phosphor, spot size and shape (electronic focus), maximum luminance (brightness), dynamic range, grey scale, resolution, and display MTF. For helmet mounted displays, user adjustable controls often include optical focus, brightness, and contrast. Many of these parameters are interrelated. Additional adjustment controls for electronic focusing, positioning, and sizing of the CRT image are present, but typically are not designed for routine adjustment.

In the United States, a commercial television (TV) picture is generated from 525 horizontal scan lines. Each TV picture or frame is presented every 1/30th of a second. To minimize visual flicker in the display, every other line (1/2 picture or field) is presented every 1/60 of a second. The number of discrete horizontal scan lines determines the maximum vertical resolution of the display. In a 525-line scan system only about 490 lines are active, i.e., present visual information to the viewer. A vertical line from the top to the bottom of the display would consist of 490 vertical dots, one on each scan line. Regardless of size, every display has 490 scan lines. Consequently, there is no more information on a five-foot screen than there is on a five-inch screen. Other common line rates used for special purpose television systems are 875 and 1024.

The PNVs and TADS use the Department of Defense "common module" thermal imaging system and operate at an 875-line horizontal scan rate to improve the apparent vertical resolution with about 817 active lines (information lines). The vertical rates are the same, 1/30 second per vertical frame and 1/60 second per vertical field. Some parameters are traded off for the 875-line system compared to the 525 line system. The electron beam moves faster in a 875-line system compared to a 525-line system, but the faster beam must have higher energy to produce the same luminance.

The phosphor selection for a display is critical and must be optimized for its intended use. Each phosphor exhibits specific physical characteristics. In general, each phosphor emits a unique spectrum of light when activated by an electron beam. The rise-time and persistence are critical parameters that affect how long it takes for the phosphor to radiate light at 90 percent of maximum luminance after being exposed to the electron beam, and how long it takes for the light to fall to 10 percent of its maximum luminance when the electron beam is removed, respectively. The phosphor's luminous efficiency specifies the ratio of luminous energy output for a specified energy input.

The number of grey shades is the number of visually distinct luminous steps from black to white a display can reproduce. To be perceived, one grey scale step must be ordinarily a square root of two (1.414) times brighter than its predecessor. This means the theoretical number of grey scale steps a display can reproduce can be calculated given the luminance values of the darkest and brightest areas of the image. Better displays can reproduce a larger grey scale; ten or more steps are desirable for good image reproduction. Displays that are not very dark in the least brightest areas typically cannot reproduce an acceptable grey scale. Light scatter inside the CRT can reduce significantly the number of grey scale steps available at high luminance levels. Fiber-optic faceplates sometimes are used to reduce light scatter. The larger the grey scale, the smoother the transitions from light to dark areas and the better overall picture contrast.

The maximum operating luminance of a display is critical if the display is going to be used in high ambient light environments. The maximum operating luminance parameter by itself, however, can be misleading. Grey scale and luminance are interrelated parameters and must be specified at the same operating condition. For example, if a display is going to be used only at night, then the number of grey scale steps should be specified at a luminance in the range of 4 to 40 footlamberts at the eye. If the display is to be used in a daylight environment, the number of grey scale steps should be specified in the range of hundreds of footlamberts at the eye.

By definition, the imaging system consists of the display and the sensor. The display works together with the sensor to present the image of the outside scene. The dynamic range parameter exemplifies this relationship. The dynamic range of the video display is limited compared to the dynamic range of the thermal sensor. The sensor is capable of sending about 30 grey scale steps (distinguishable levels of brightness) to the display. However, the display is capable of presenting only about 10 grey scale steps to the eye. To illustrate this concept, allow each of the levels of the sensor's output signal to represent a one degree Celsius difference in the temperature of a simple object. A 30-step grey scale would allow the sensor to produce an output signal representing a range of 1 to 30 degrees Celsius, each degree representing a distinguishably higher signal level. This 30-level signal would be sent to the display, where only 10 levels can be displayed. By adjusting the sensor's gain and level controls and the display's brightness and contrast controls, any 10-degree range could be displayed. If the detail in the object, perhaps represented by the energy levels associated with the temperature range of 5 to 14 degrees, were of interest, then the display could be set up to show the 5 to 14 degree (energy level) range. However, any similar objects with temperatures (energy levels) above 14 degrees would not be discernible, being presented at the maximum luminance level associated with the upper (14 degrees) level. A tank with engine, drive wheels, and exhaust at temperatures between 20 and 30 degrees would look like a white blob; only details that were in the 5 to 14 degree range would be distinguishable as shades of grey on the display. Details represented by energy levels of the 5-degree level and below would be black.

Automatic controls within the sensor are designed to minimize the potentially dangerous effects of the display's limited dynamic range and the resulting "blooming" or whiting out of the display. A problem occurs when the sensor is looking at the relatively warm ground below the horizon and the cold sky above the horizon, a large temperature difference. The pilot needs to see the horizon, but even more important, the pilot needs to see details of the ground and objects around him that are much warmer than the cold sky. The automatic controls work relatively well for large temperature differences that are on different scan lines, but still have difficulty when the large temperature differences are on the same scan line. This situation can occur when the aircraft banks and the sensor sees the cold sky and the warm ground on the same scan line.

Spot size is the size of the electron beam footprint on the phosphor screen, measured at its 50 percent output luminance points. The spot size determines the maximum resolution that can be expected from the CRT. This concept is similar to drawing with a small, thin drafting pencil or a big, thick carpenter's pencil--freer detail can be drawn with the thinner lead. The size of the electron beam increases as its energy increases, and the larger the beam footprint, the poorer the limiting resolution of the display. A general relationship can be defined for line rate, luminance, resolution, and spot size. As the line rate increases from 525 to 875, the electron beam must move approximately 67 percent faster to draw the greater number of lines. The beam has less dwell time to activate the phosphor, thus producing a lower luminance image at 875 than at 525. A higher energy electron beam will increase the luminance, but will result in a larger spot size and decreased resolution.

The modulation transfer function (MTF) is used as a measure of a display's efficiency in presenting information at various spatial frequencies, just as the MTF was described as a measure of the sensor's efficiency. Modulation contrast is measured at several spatial frequencies starting at

about 5 cycles per display width (5 alternating black and white bars across the display) to a spatial frequency with a modulation contrast of less than two percent. The modulation contrast reading at 5 cycles/display width will provide an indication of the number of grey scales the display can present. A display must have approximately 93 percent modulation contrast at 5 cycles/display width to reproduce 10 grey scales. 4 The modulation contrast reading of less than two percent shows the maximum horizontal resolution of the display; that is, the display will not be able to reproduce information above that spatial frequency. The display's maximum vertical resolution is limited by the number of vertical scan lines.

An understanding of the display parameters discussed above is essential to the understanding of the AH-64 IHADSS and panel-mounted head-down displays. The AH-64 has a sophisticated video system with two thermal imagers (PNVS for pilotage and TADS for targeting), a day television sensor, two symbology generators, a video tape recorder, and four video displays (two IHADSS displays and two panel-mounted displays). In the IHADSS, the 1-inch CRT and relay optics, referred to as the Helmet Display Unit (HDU), as shown in Figure 14, are mounted on the right side of the aviator's helmet (Figure 3). The HDU, the helmet, and additional electronics collectively are referred to as the Integrated Helmet and Display Sighting System (IHADSS). The IHADSS display is designed to provide a one-to-one presentation of the 30 degrees vertical by 40 degrees horizontal field-of-view provided by the sensor. The line-of-sight direction for the PNVS or TADS sensor is controlled by the head position of the aviator, which is continuously monitored by infrared detectors mounted in the helmet. Processing electronics of the IHADSS convert this information into drive signals for the PNVS. The result is a visually coupled

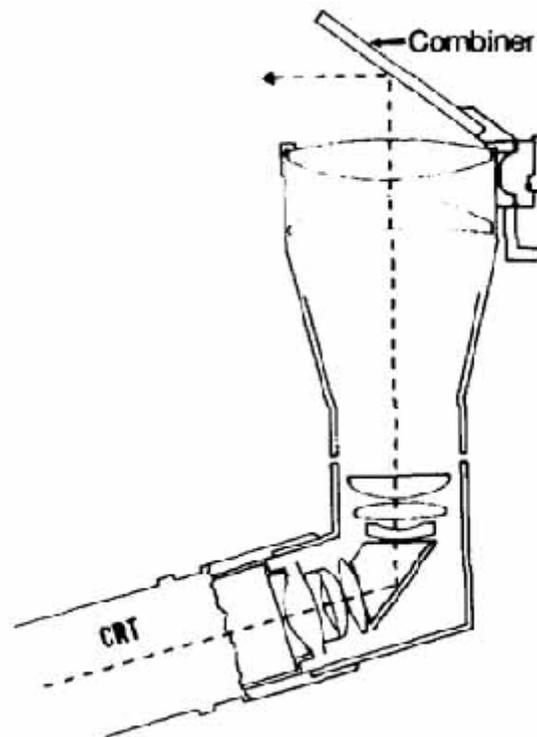


Figure 14. The Helmet Display Unit (HDU), consisting of CRT and relay optics.

system in which the PNVS is slaved to the aviator's head motion. In addition to the PNVS or TADS imagery, symbology representative of various aircraft operating parameters, e.g., altitude, heading, torque, etc., can be presented on the HDU (Figure 15).

The thermal image from the PNVS or TADS can be Presented to the pilot on a miniature (1-inch diameter) cathode ray tube (CRT) in the HDU, shown in Figure 16, or on a 5-inch panel mounted display. The image generated on the helmet mounted 1-inch CRT is viewed through

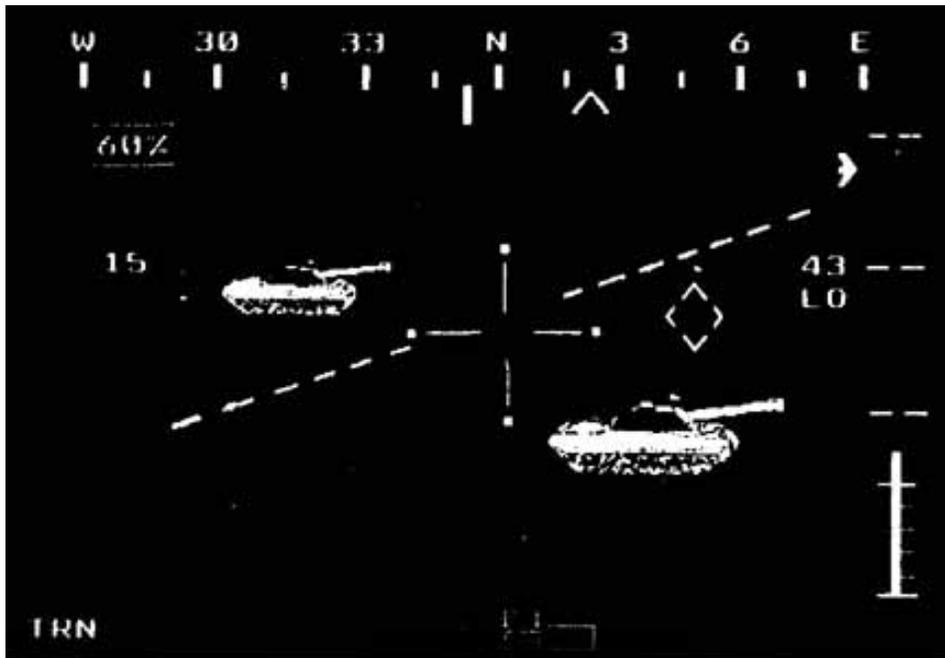


Figure 15. Artist depiction of FLIR imagery and flight symbology.

magnifying relay optics and a see-through beam-splitter (combiner). The magnifying optics increases the 1-inch CRT image to an apparent size equivalent to that of a 21-inch display viewed at a distance of 28 inches. This results in a 40-degree horizontal by 30-degree vertical image which corresponds to the FOV of the sensor and provides a total system magnification of unity. The 5-inch direct view panel mounted display appears as a 7-degree horizontal by 5-degree vertical image. The same information is present on both displays, but the panel display appears to have a better image since it is eye limited (smaller detail than the eye can see) and the HDU is display limited (the eye could see more if the display could present more). In addition, the contrast provided by the panel display will be better since it is a direct view image, not a HDU see-through virtual image.

The optical beamsplitter (combiner) shown in Figure 14 is a delicate and critical component of the HDU; The combiner is made of a 50 percent neutral density filter coated with a dielectric thin-film stack. The dielectric coating reflects 80 percent of the light from the P-43 phosphor to the eye while attenuating 90 percent of light with the same wavelengths as the P-43 phosphor that passes through the neutral density substrate. Smudges, fingerprints, scratches, and other distracting features on the combiner may draw the eye's attention and focus to the combiner rather than to the image projected from the combiner. The combiner must be kept free of

distracting marks. The see-through feature of the combiner is intended to provide a measure of registration between the display image and the outside world. One disadvantage is that bright light sources, when viewed through the combiner, degrade the imagery contrast.

In the IHADSS, an electronically generated grey scale can be displayed to aid the setup of the user's brightness and contrast controls (Figure 17). This setup is valid for the sensor only if the sensor video output matches the same range as the display's grey scale video signal. If the sensor video level is lower than the maximum grey Scale level, the resulting sensor video looks washed out and generally lacks contrast. If the sensor video level is higher than the maximum grey scale level, the resulting sensor video will have too much contrast and will lack detail in the shadows.

The scene information acquired by the sensor is presented as brightness levels on the display. The minimum and maximum brightness levels that can be presented determine the available contrast and shades of grey. The IHADSS is capable of presenting to the eye highlight brightness levels of 4 to 150 footlamberts. At night, FLIR imagery brightness is typically 8 to 10 footlamberts. As the CRT ages, the phosphor becomes less efficient and its brightness drops. If a higher brightness setting is used as compensation, it results in increased electron beam size and lower horizontal resolution. When the CRT no longer can produce adequate luminance to see the flight symbology during daylight periods, it must be replaced, even though it may be more than adequate for night flight.

Among the user adjustments on the HDU is optical focus. This adjustment allows the user to set the semitransparent sensor image at optical infinity so no change in accommodation is necessary when switching attention from distant real objects to the display's virtual image. The user is to look at a distant object and adjust the optical focus so the sensor image is focused at the same point



Figure 16. Miniature 1-inch diameter cathode-ray-tube in the IHADSS.

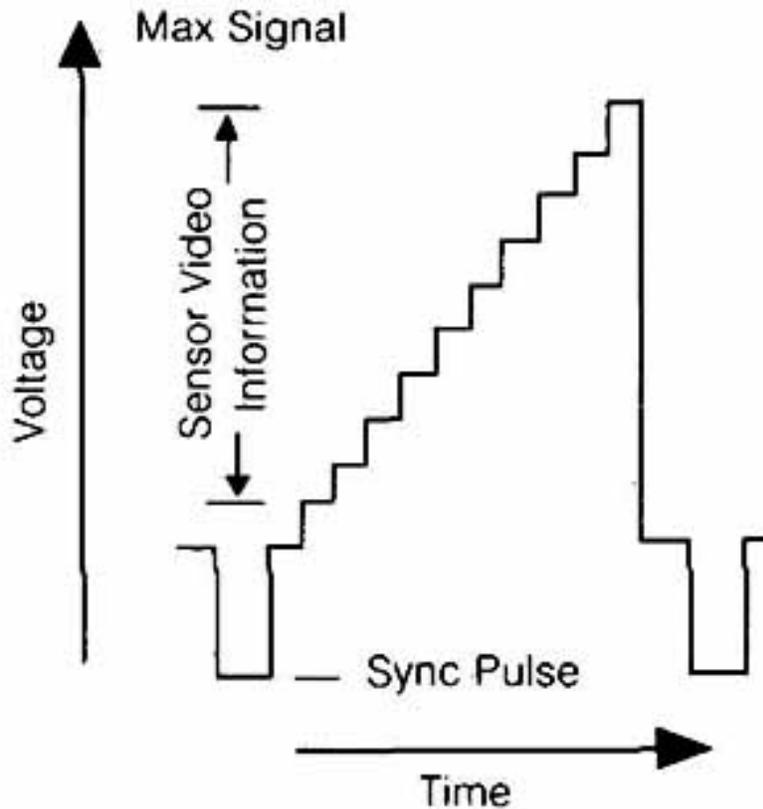


Figure 17. Grey scale video signal used in the setup of the user's brightness and contrast controls.

as the distant object. One apparent disadvantage of this display focus approach is the indication that the display eye tends to focus on the HDU beamsplitter (combiner), rather than at optical infinity. Recent studies have suggested a relationship between this misaccommodation and underestimations of size and distance.⁵ In addition, a 1988 survey of 52 AH-64 aviators identified problems relating to size and distance perception. Sixty-five percent of the survey respondents indicated objects viewed on the HDU as being perceived smaller and farther away than they actually were. During certain phases of flight, such as landing approaches, these misperceptions may affect seriously the aviator's ability to maintain a proper approach angle or avoid obstacles.⁶

The above problem relates to the eye's accommodation, or focusing, point. There is another problem which is associated with the mechanical focusing of the HDU. This focusing is achieved by the rotation of a knurled ring located at the rear of the HDU barrel. The focus can be adjusted over a range of +3 to -6 diopters. In 1989, a study was conducted measuring the HDU focus adjustment settings of 20 AH-64 aviators. Measurements were taken just prior to takeoff. Ninety percent of the aviators were found to have focus settings of 0.5 diopters or greater. The range of focus settings was 0 to -5.25 diopters with a mean of -2.25 diopters. The required positive accommodation by the aviator's eye to offset these negative focus settings is likely a source of headaches and visual discomfort during and after extended periods of flight.⁷ Aviators can increase their accommodation workload inadvertently by misadjusting the optical focus. Then, they

force their visual system to accommodate to a display image that is abnormally close; this is in addition to the normal crewstation and distant real objects accommodation changes.

Additional user adjustments of CRT image orientation, position and size also can significantly impact performance if misadjusted. The orientation of the image is controlled by the rotation of the CRT with respect to the optical axis of the HDU. If the image rotation is improperly adjusted, the pilot may experience a conflict between the symbol-ogy and his otolith-derived sense of gravity. A head tilt may develop to compensate for this mismatch creating a situation analogous to the leans, a common vestibular illusion.^{8,9} Misadjustments of position and size are addressed in Section 9, "Field-of-view and Visual Fields."

5. TEMPORAL CHARACTERISTICS

Discussions in the previous sections have addressed parameters which are related primarily to the spatial characteristics of thermal imaging systems. However, the temporal characteristics of the system also can impact performance, especially in a dynamic environment.¹⁰ Thermal imaging systems have time constants associated with the detector, the scanning mechanism, and the display. The dynamic environment may introduce additional temporal factors, e.g., sensor gimbal jitter, head motion in visually coupled systems, and relative target-sensor motion. An individual detector's time constant determines the detector's speed of response to temperature (energy) changes in a scene segment. In a static environment, where the detector continuously images the same scene segment, the detector time constant's contribution to the temporal characteristics of the sensor is minimal. Rapid temperature changes are not routine events in the real world. However, in a dynamic environment or in a scanning imaging system, the detector is continually imaging different scene segments.

In visually coupled display systems, the interface between the pilot's head movements and the corresponding sensor movements is an additional potential problem source. Any latency between the movement of the head and the movement of the sensor must be reduced to an imperceptible level. The PNVS gimbal with its 120 degree/second maximum, velocity is responsive and approaches the desired level of imperceptible latency (see Section 12, "Head/System Interface"). However, the communication of the helmet sight command signals to the PNVS gimbal generates a perceptible, but acceptable latency. The TADS with its 60 degree-/second velocity is appreciably slower and although acceptable as a pilotage backup and navigation system, is unacceptable as a primary pilotage system.

Rapid head movements in visually coupled systems generate a rapidly moving scene on the display. The head movement rates greatly exceed the nominal relative movement rates that are observed between an aircraft and a moving ground object. Phosphor persistence is an important display parameter that affects the temporal response of a CRT display. Excessive persistence reduces modulation contrast and causes the reduction of grey scale in a dynamic environment where there is relative motion between the target and the sensor.¹¹ Persistence effects may cause the loss of one or more grey scale steps. This may be of minor concern at low spatial frequencies where there are many grey scale steps. However, where there is only enough modulation contrast to pres-

ent only one or two grey scale steps under the static condition, the loss of one grey scale step at high spatial frequencies, would be significant.

This effect is well demonstrated in the history of the phosphor selection for the IHADSS. A P-1 phosphor initially was selected to satisfy the high luminance daytime symbology requirement. After initial flight tests, the CRT phosphor was changed to the shorter persistence P-43 from the more efficient P-1 because of the image smearing reported. The test pilots reported tree branches seemed to disappear as pilots moved their heads in search of obstacles. It was determined the long persistence of the P-1 phosphor was responsible for the phenomenon.

The electro-optical multiplexer, a Department of Defense common module, used to convert the mechanically scanned thermal detector outputs to a video signal also introduces a significant delay time to the video image. These multiplexers eventually are to be replaced with solid-state multiplexers with improved delay times.

6. HEAD-SUPPORTED WEIGHT AND CENTER-OF-GRAVITY

The addition of display systems to the helmet has increased significantly the amount of weight which must be supported by the head. The head-supported weight of the IHADSS is 4.0 pounds (1.8 kg). This weight includes the helmet (integrated Helmet Unit- IHU), HDU, and miniature CRT.

The effects of increased head-supported weight (HSW) on the aviator can be separated into two categories: crash kinematics and mission effectiveness. The effect of increased HSW on crash kinematics is a direct result of the additional mass. Adding IHADSS (4.0 lbs) to the average male head (weighing 11.7 lbs) results in a 34 percent increase in head/neck weight and a concomitant increase in neck loading during a sudden impact. The force exerted on the skull base during acceleration can be approximated by the product of the mass of the helmeted head and its acceleration. Thus, for a given acceleration, the larger the mass (i.e., head plus HSW), the larger the force, and consequently, the risk of injury. Glaister recently recommended that the total weight of the entire headgear ideally should not exceed 4.4 lbs.¹² To help reduce the hazard of increased head/neck mass in an accident sequence, the HDU has a "break-away" feature, that allows it to drop off the IHADSS helmet when exposed to high accelerative forces.

Increased HSW can affect mission effectiveness either directly (via physical effects) or indirectly (via fatigue). The physical effect of increased inertia alone causes rapid lateral head movements to be slowed and delayed.¹³ These inertial effects are seen at levels of HSW (4.4 lbs.) similar to those added by the H-IADSS. In 1968, research at the U.S. Army Human Engineering Laboratory showed an HSW in excess of 5.3 pounds (2.4 kg) slowed head motions, as well as degraded the performance of complex sighting tasks.¹⁴ In situations where the primary pilotage imagery input is controlled by head movement, these handicaps may reduce maneuvering accuracy and increase the risk of an accident.

Not surprisingly, additional HSW also causes fatigue. Phillips and Petrofsky showed, regardless of CG location, neck isometric endurance time after exercise while wearing a helmet weighing 5.0 lbs was significantly reduced, compared to the no-helmet condition.¹⁵ Even the

relatively low level G-forces encountered in rotary-wing air combat maneuvering, combined with a helmet "much too heavy for this type of flying," can be extremely fatiguing, if not painful, even for experienced test pilots. 9

The HDU is attached to the right side of the IHADSS helmet. This laterally displaces the center-of-gravity (CG) of the head/neck/HMD system, resulting in asymmetric loading of the head and neck. The consequences of this CG shift are similar to those of increased HSW, affecting both crash kinematics and mission effectiveness. The offset HSW CG creates a moment arm producing a torque on the head and neck musculature. During an impact sequence, the magnitude of this torque is a product of the head/HSW mass, the linear acceleration, and the CG offset distance. Thus, for a given combination of HSW and acceleration, the torque, and logically, the risk of injury is directly proportional to the CG offset. Obviously, an increase in either HSW or CG offset will increase the torque or bending forces in the neck due to maneuvering flight loads or crash loads. In the design of future helmet-mounted systems, it is imperative the CG of the system be as close to the head/neck CG as possible.

The offset CG also may cause fatigue of the head/neck musculature. Shifting the head/neck CG forward 10 cm by wearing NVGs has been shown to reduce neck isometric endurance following 5 or 35 minutes of dynamic (lateral) neck exercise.¹⁶ However, using a smaller CG shift (2.5 to 5.0 cm) and lighter HSW (3 lbs), a physiologically optimal CG position was found to be either forward or lateral.¹⁵ These conclusions are in conflict with a more recent study in which aviators preferred rearward and vertical CG shifts to forward or lateral shifts.¹⁷ Although complaints about IHADSS CG asymmetry, do not predominate in surveys of AH-64 pilots,^{6, 18, 19} helmet designers should strive to maintain the head/HSW CG as close as possible to that of the head alone.¹²

7. VISUAL ACUITY

Visual acuity is a measure of the ability to resolve fine detail. Snellen visual acuity commonly is used and is expressed as a comparison of the distance at which a given set of letters is correctly read to the distance at which the letters would be read by someone with clinically normal eyesight. A value of 20/80 indicates an individual reads at 20 feet letters that can normally be read at 80 feet. Normal visual acuity is 20/20. Visual acuity, as measured through imaging systems, is a subjective measure of the operator's visual performance using these systems. The acquisition of targets is a primary performance task. For this task, a reduced acuity value implies the observer would achieve acquisition at closer distances. However, providing an acuity value for thermal systems is difficult since the parameter of target angular subtense is confounded by the emission characteristics of the target. However, for comparison with other systems, Snellen visual acuity with the AH-64 PNVIS/IHADSS is given as 20/60.²⁰ The accepted high contrast acuity value for second- and third-generation I² system is 20/60 and 20/40, respectively.

To enhance imagery contrast against high ambient lighting, the AH-64 aviator is provided with a ten percent luminous transmittance visor. Anecdotal information indicates aviators sometimes use this "relatively dark" visor even at night to decrease the distraction of bright external lights visible to the unaided eye. An investigation into the effect on visual acuity of

wearing spectacles of different luminous transmittances has led to a recommendation that a minimum of 30 percent transmittance is required to achieve the 20/60 high contrast acuity equivalent for the second-generation I² systems under brightness conditions of overcast day, twilight, and full moon.²¹ Therefore, the use of the ten percent visor at night further reduces the aviator's visual acuity through the unaided eye.

8. MONOCULAR PRESENTATION

During the development of the IHADSS, there were two major concerns with the proposed monocular display format: eye dominance and binocular rivalry. Eye, or "sighting" dominance refers to a tendency to use one eye in preference to the other during monocular viewing.²² Critical cost and weight considerations favored a monocular display format for the IHADSS, which logically would be located on the right side of the helmet, since most of the population is right-eye dominant. However, there were serious questions whether a left-eye dominant pilot could learn to attend to a right-eye display. In fact, there is evidence linking sighting dominance with handedness and various facets of cognitive ability, including tracking ability and rifle marksmanship performance.²³ One study addressing head aiming and tracking accuracy with helmet-mounted display systems indicated eye dominance to be a statistically significant factor.²⁴ However, this small amount of research is far from compelling and the IHADSS is produced to fit the right-eyed majority. Since the AH-64 has been fielded, there have been no reports in the literature addressing the influence of eye dominance on IHADSS targeting accuracy or AH-64 pilot proficiency.

Probably a more troublesome phenomenon is binocular rivalry, which occurs when the eyes receive dissimilar input. This ocular conflict apparently is resolved by the brain by suppressing one of the images.²⁵ The IHADSS presents the eyes with a multitude of dissimilar stimuli: color, resolution, field-of-view, motion, and brightness. Aviators report difficulty making the necessary attention switches between the eyes, particularly as a mission progresses.²⁶ For example, the relatively bright green phosphor in front of the right eye can make it difficult to attend to a darker visual scene in front of the left eye. Conversely, if there are bright city lights in view, it may be difficult to shift attention away to the right eye.⁶ AH-64 pilots report occasional difficulty in adjusting to one dark-adapted eye and one light-adapted eye.¹⁹ It may be hard to read instruments or maps inside the cockpit with the unaided eye, since the PNVIS eye "sees" through the instrument panel or floor of the aircraft, continuously presenting the pilot with a conflicting outside view. In addition, attending to the unaided eye may be difficult if the symbology presented to the right eye is changing or jittering.¹⁹ Some pilots resort to flying for very short intervals with one eye closed, an extremely fatiguing endeavor.^{6,26} The published user surveys generally agree the problems of binocular rivalry tend to ease with practice--although under conditions of a long, fatiguing mission, particularly if there are system problems (*e.g.*, display focus or flicker, poor FLIR imagery, etc.), rivalry is a recurrent pilot stressor.^{6,26} It is likely sighting dominance interacts with binocular rivalry, affecting a pilot's ability to attend to one or the other eye.

An apparent disadvantage of a monocular display such as the IHADSS is the complete loss of stereopsis (visual appreciation of three dimensions during binocular vision). Stereopsis is thought to be particularly important in tactical helicopter flying, since the terrain is invariably within the

200-meter limit of effective stereo vision in this mode of flight.²⁷ However, monocular depth cues (e.g. retinal size, motion parallax, interposition, and linear perspective) generally are acknowledged to be more important for routine flying. A 1989 study of visual acuity and stereopsis with Night Vision Goggles (a second-generation binocular 12 system) found stereopsis with this system to be greatly reduced.²⁸ Aviators using monocular pilotage systems can improve their nonstereo depth perception with training, although the degraded acuity inherent in these systems will affect adversely the perception of even monocular depth cues to some extent. This is reflected frequently in aviator surveys.^{6, 19} However, with practice, most AH-64 aviators are able to fly competently throughout the night nap-of-the-earth (NOE) environment.

It is currently in vogue to suggest that the next generation of HMDs should deliver imagery to both eyes, instead of one, as in the IHADSS. This can be accomplished in two ways: binocularly (each eye is presented with a distinct image, two slightly separated sensors are used) or binocularly (both eyes are presented with identical images from the same sensor). The advantages and disadvantages of these display modes are beyond the scope of this paper. However, it should be noted AH-64 aviators report using the unaided eye for a variety of functions, including reading instruments and maps within the cockpit, cross-checking range and size information derived from the PNVs, and maintaining color vision and dark adaptation in one eye.^{6, 19, 29} It would seem advisable at least to allow the aviator the option of selecting a monocular format should it be deemed necessary.

9. FIELD-OF-VIEW AND VISUAL FIELDS

The human eye has an instantaneous field-of-view (FOV) which is roughly oval in shape and typically measures 120 degrees vertically by 150 degrees horizontally. Considering both eyes together, the overall FOV covers approximately 120 degrees vertically by 200 degrees horizontally.³⁰ The size of the FOV provided by an imaging system is determined by trade-offs among various sensor and display parameters including size, weight, and resolution. The IHADSS FOV is rectangular in shape measuring 30 degrees vertically by 40 degrees horizontally (Figure 18).

The 30 x 40 degree IHADSS FOV seems small when compared to that of the unaided eye, but its size is perhaps not as significant considering the multiple visual obstructions (e.g. armor, support structures, glareshield) normally present in military aircraft cockpits. Although the HDU does physically obstruct unaided lateral visibility to the right, the IHADSS provides an unimpeded external View throughout the range of PNVs movement (+/- 90 degrees azimuth and +20 to -45 degrees elevation). However, the AH-04 pilot is trained to use continuous scanning head

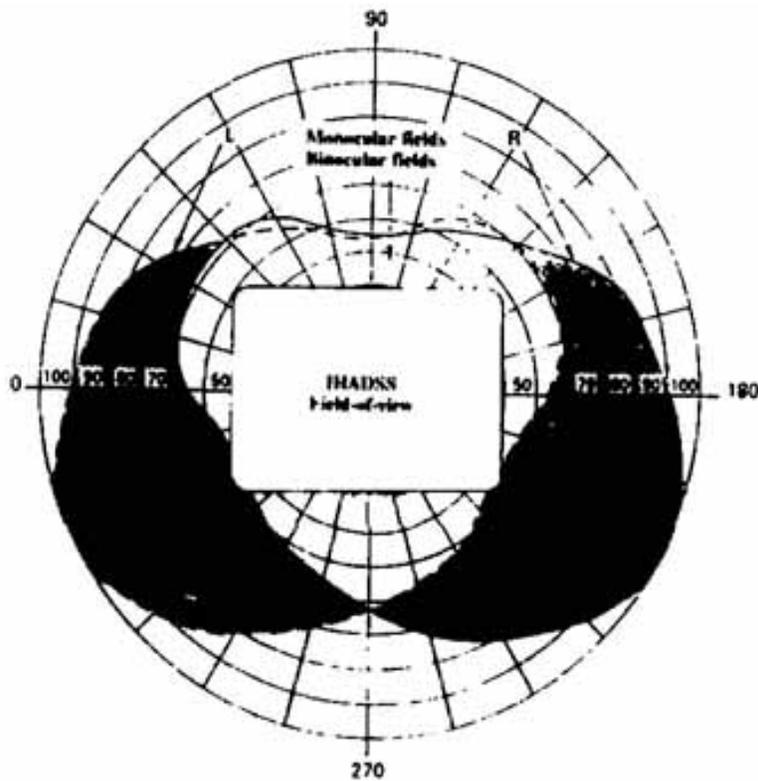


Figure 18. Pictorial representation of IHADSS 30X40 degree field-of-view.

movements to compensate for the limited FOV. A potentially disorienting effect occurs when the pilot's head movements exceed the PNVS range of movement--the image suddenly stops, but head movement continues. This could be misinterpreted by the pilot as a sudden aircraft pitch or yaw in the direction opposite the head movement. If there are lights visible to the unaided eye (or through the combiner), diplopia (double vision) may result.

The IHADSS is designed to present the sensor's FOV in such a manner that the image on the combiner occupies the same area in front of the eye, resulting in a one-to-one representation of the outside world (i.e., no magnification or minification). However, in order to achieve this design goal, the pilot must place his eye within the cdt pupil of the HDU optics. (The exit pupil of an optical system is a small volume in space where the user must place his eye in order to obtain the full available field-of-view.) The major determinant of whether this can be attained is the physical distance between the eye and the combiner. Variations in head and facial anthropometry greatly influence the ability of the aviator to comfortably achieve a full FOV. Some aviators report discomfort due to pressure against the zygomatic arch (cheekbone),¹⁸ and many report difficulty seeing all the provided symbology.⁶ The interposition of chemical protective masks and/or spectacles (either for laser protection or correction of refractive error) increases the eye-combiner distance, further reducing the likelihood the pilot will see the full FLIR image or symbology display.^{31, 32} Improper adjustment of the HDU/helmet attachment bracket also can prevent the aviator from achieving the design FOV.

The effects of reduced FOV on aviator performance are not understood fully. The task of determining a minimum FOV required to fly is not a simple one. First, the minimal FOV required is highly task-dependent. Consider the different sensory cues used for high-speed flight across a desert floor (narrow FOV) versus a confined area hovering turn (wide FOV). Second, the FOV required to maintain orientation depends on workload. A small attitude indicator bar (or cue), occupying only a few degrees of the visual field, does not provide much information to the peripheral retina, which normally mediates visual information regarding orientation in the environment.⁸ Acquiring this orientation information from the central (foveal) vision requires more concentration, and renders the pilot susceptible to disorientation, should his attention be diverted to other cockpit tasks for even a brief period. Third, with helmet-mounted displays such as the IHADSS, any reduction in FOV also may deprive the pilot of critical flight symbology.

To compensate for the FOV problems cited above, some AH-64 pilots resort to using the CRT horizontal and vertical size controls to reduce the overall size of the image.⁶ This allows the aviator to view all of the imagery and symbology, but the sensor's 30 x 40 degree FOV now occupies less area on the combiner than it must in order to provide a one-to-one scene representation. Since this minified image can cause problems with distance and size perception, it is strongly discouraged.

10. ENVIRONMENTAL. CONSIDERATIONS

Thermal imaging systems, such as the PNVIS, are capable of providing acceptable pilotage imagery in a wide range of environments (e.g., deserts, swamps, mountain areas, etc.) and weather conditions (e.g., fog, snow, etc.). However, their effectiveness is limited by the operating environment and prevailing weather. The atmosphere absorbs, emits, and scatters IR radiation and often is the major driver in system performance. The choice of detectors, with respect to their spectral response, is governed to a degree by the transmittance of the atmosphere. A plot of the transmittance of the earth's atmosphere is depicted in Figure 19. This figure demonstrates the effect of three major IR radiation absorbers: water vapor (at 2.7, 3.2, 6.3, and 11.9 microns), ozone (at 4.8, 9.6, and 14.2 microns), and carbon dioxide (at 2.7, 4.3, 12.6, and 15.0 microns). The effectiveness of the 3-5 and 8-12 micron response ranges of the HgCdTe detector becomes obvious.

In addition to absorption of IR radiation by the atmosphere, there is scattering by the various atmospheric molecules. The scattering of the IR radiation further attenuates the IR signal and contributes to the IR background noise. The overall attenuation, a summation of scattering and absorption, is expressed by the extinction coefficient. These coefficients can be used to compare how the atmosphere will transmit IR radiation for various atmospheric conditions. In Table 1, transmissivities for some of these conditions (calculated by Lambert-Beer's law) are presented for ranges of 1 and 10 kilometers (1an). The conditions in Table 1 mostly are related to moisture. However, additional elements such as dust and smokes (obscurants) affect the composition and density of the atmosphere and, therefore, the IR radiation transmission.³³

As discussed above, the atmospheric transmission is affected by the environmental conditions attenuates the IR signal. In addition to this effect, these conditions reduce the solar heating of objects (targets), thereby reducing their thermal signatures.

The role of the sun and existing environmental conditions are responsible for one phenomenon, referred to as "thermal crossover," which is unique to thermal imaging. Figure 20 shows representative 24-hour thermal history curves for four materials: soil, water, vegetation, and concrete. Just after midnight, all are emitting more energy than they are absorbing (due to the absence of the sun). Each material's temperature is different (the vegetation has the lowest temperature and the water has the highest) and all still are slowly decreasing. As sunrise (assumed to be 0600) approaches and occurs, the temperature of each material begins to rise, at a different rate for each substance. By approximately 0900, the temperatures of three of the substances (soil, water, and concrete) nearly reach the same value (point A) and the thermal sensor may be unable to discriminate among them. Point A is a crossover point for these three materials. As the day proceeds, the materials continue to increase in temperature. At point B, the water and the vegetation reach a crossover point. At these crossover points, the relative order of the temperature values reverses. For example, prior to point B, the temperature of the water is higher than that of the vegetation. Following point B, the temperature of the vegetation is higher than that of the water. On the display of the imaging system, where the different temperatures (actually energy levels) are represented by different levels of brightness, the materials undergoing the crossover reverse contrast. Where the water may have been "brighter than" the vegetation, it is now "darker than" the vegetation.

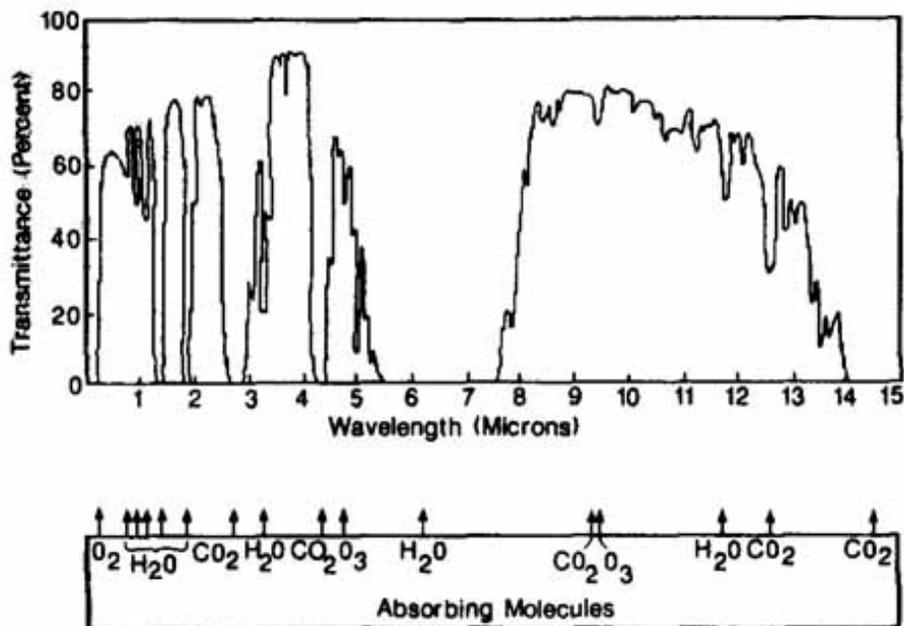


Figure 19. Spectral transmittance of the earth's atmosphere.

Table 1.
Atmospheric transmissivities

Condition	Extinction coefficient	Transmissivity at 1 km	Transmissivity at 10 km
Very clear and dry	0.05	95%	61%
Haze	0.11	90%	33%
Light snow	0.51	60%	<1%
Moderate rain	0.69	50%	<1%
Heavy rain	1.39	25%	<1%
Light fog	1.90	15%	<1%
Heavy fog	9.20	<1%	<1%
Heavy snow	9.20	<1%	<1%

Note: Extinction coefficients are expressed in km^{-1} for the 8-12 micron spectral region.

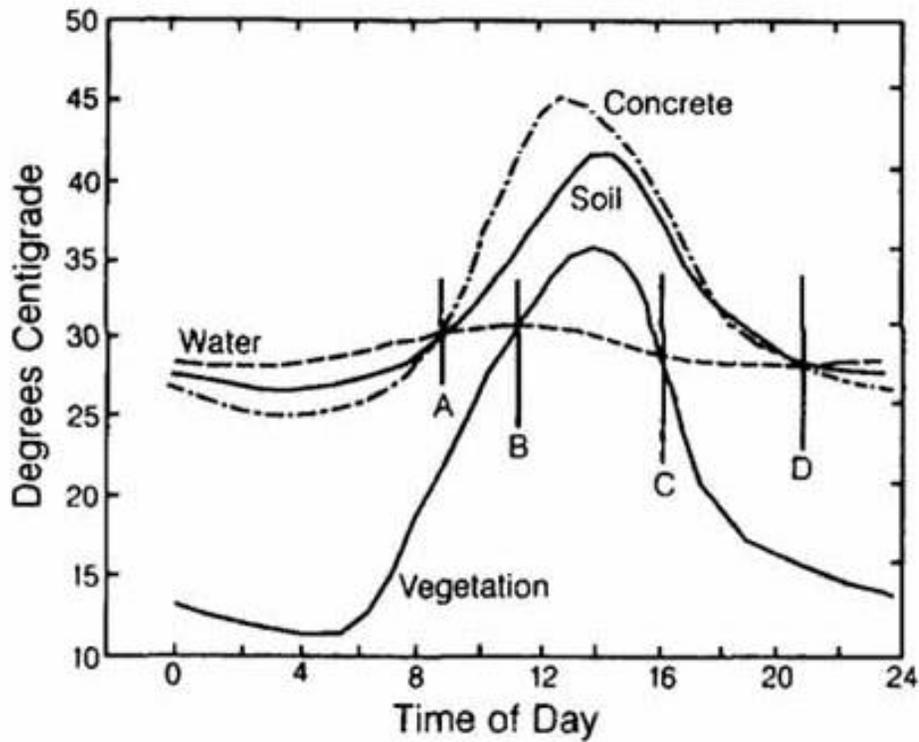


Figure 20. Representative 24-hour thermal history for soil, water, vegetation, and concrete.

Over a 24-hour period, crossover for the representative materials and thermal histories shown occurs twice (points A and D, B and C). However, there is no crossover point for the vegetation with either the soil or the concrete. In the real world, the presence and frequency of crossover points for any two substances is dependent on geographic location, season, weather, and many other factors. In the 1988 AH-64 aviator survey, 98 percent of the respondents reported instances where the FLIR image was degraded to the extent that mission completion was compromised⁶. Most often, this is a result of IR crossover.

11. EFFECTS OF INTERNAL / EXTERNAL SOURCES

Unlike systems using the principle of image intensification, thermal imaging systems are less sensitive to degrading effects of internal crewstation and environmental energy sources.^{2, 34} However, as discussed in the sections above, the performance of thermal systems can be degraded by some sources, most of which occur naturally. Performance degradation also can be induced by man-made sources, including specially designed countermeasures which target thermal imagers. While the effects of internal and external energy sources are associated primarily with the sensor, the display is where these effects are perceived by the aviator.

Physically large areas of very hot or very cold temperatures, which are much hotter or colder than the area of interest and are in the FOV of the sensor, tend to confuse the automatic level and gain controls. In trying to cope with the large temperature range, these controls may mask the area of interest. This may happen naturally with the cold sky region above the horizon. It is more difficult to introduce very cold man-made regions, but it is relatively easy to artificially create large, very hot regions by lighting large area fires. A similar problem may be encountered when viewing a landing zone at a close distance with a thermal sensor, when several aircraft have landed previously and are heating the landing zone with their exhausts. Much of the detail in the scene may be masked by the hot exhaust.

In the air, formation flying can be troublesome to a thermal imager when the hot exhaust of a leading aircraft is viewed against a cold sky background. This effect may be even more troublesome when there are several large, hot exhausts against a cold sky background. The forward aircraft detail may be seriously degraded--enough to mask unexpected or rapid changes in attitude or the initiation of a maneuver by a lead aircraft.

A special group of external sources which is a concern to thermal imaging systems is lasers. Any laser which operates within the spectral response region of the thermal sensor (8-12 microns) potentially can blind or destroy an unprotected sensor. Carbon dioxide (CO₂) lasers operating at 10.6 microns fall within this region. The neodymium-YAG laser used in the AH-64 laser rangefinder operates at 1.06 microns and can not be seen by the PNVIS sensor. Flares are another external source which can degrade sensor performance. Also, flares can affect the display's performance as well. The see-through characteristics of the display permit the bright light from the flare to degrade its contrast to the eye. These effects are most apparent when the flare is in the field-of-view of the sensor. Looking away from the flares will reduce the flare's effects.

The display can be degraded by internal and external visible light sources, particularly high intensity sources in the crewmember's area of interest. Even though the thermal sensor may not "see" the light source, if the light is in the crewmember's line-of-sight, it will degrade the contrast of the display imagery.

12. HEAD/SYSTEM INTERFACE

By Virtue of their design, helmet mounted displays are mounted totally, or in part, on the aviator's helmet. In the IHADSS, the system's display section is helmet mounted. The sensor section is integrated with the helmet in that the direction of the sensor line-of-sight is controlled by head movement. To ensure optimal system performance, proper interfacing of the helmet and its attached display with the aviator's head is critical. The criteria for proper interfacing include the static placement and stability of the eye into the exit pupil of the HDU optics and the dynamic transformation of aviator head movement to sensor movement.

The AH-64 aviator receives his primary sensory data through the HDU to fly the aircraft. To receive the total imagery available on the HDU, he must, adjust the helmet and HDU to match the position of the exit pupil of the HDU optics to his eye. In addition, the helmet must remain stable, maintaining this exit pupil position in the presence of head movements and aircraft vibration. With the advent of the IHADSS helmet, the aviator has moved from an era of the "slap-on, cinch-up" helmet to one where the helmet is a finely-tuned piece of equipment, requiring special considerations and care. One of these special considerations is the fitting process.

The basic fitting process involves numerous steps including, but not limited to, adjustments to suspension system, proper location and alignment of the HDU, and final trimming of the helmet visor to accommodate the HDU when in the operating position. The objectives of the fitting procedure are to: a) obtain a comfortable, stable fit of the IHU (helmet), which will enable the aviator to achieve the maximum field-of-view provided by the HDU and b) achieve boresight, which permits accurate engagement of weapons systems.³⁵ In 1987, Rash et al. evaluated the U. S. Army fitting program for the IHADSS.³⁶ Several important lessons were learned during this evaluation. For the first time, the impact that head anthropometry has on helmet fit was recognized. Not only are there problems associated with one or more extreme head dimensions, but there are additional problems related to head abnormalities, *e.g.*, one ear lower than the other, tapering forehead, bulges, etc. All of these variations increase the detailed attention required to provide the aviator with a comfortable and stable helmet fit.

Aviator facial anatomy also is crucial to optimal HDU interface. If the aviator's eye is not located in the exit pupil, but is some distance behind it, a "knothole effect" is experienced. The field-of-view provided is decreased, in the manner similar to that experienced when a person looking through a knothole begins to move away from the knothole. The presence of a protruding cheekbone or deeply sunken eyes can prevent the HDU from being positioned close enough to obtain the full field-of-view. Even a small displacement can reduce substantially the available field-of-view. If, due to anthropometric and facial anatomic irregularities, the aviator is unable to achieve full field-of-view, he may attempt to position the HDU to select what he considers to be

the critical portion of the imagery and/or symbology for the task at hand. A good indication of poor or difficult fit is the extension of the combiner. A good fit is indicated by a combiner extension distance of a quarter of an inch or less. As previously discussed (Section 9), aviators also may resort to adjusting the size of the CRT image in order to view all of the provided symbology.

Helmet-mounted imaging systems, such as the PNVS/IHADSS, use the aviator's head as a control device. Head position is employed to produce drive signals which slave the sensor's gimballed platform to aviator head movements. As described in Section 4, infrared detectors mounted on the helmet continuously monitor the head position of the aviator. Processing electronics of the IHADSS convert this information into drive signals for the PNVS gimbal. This type of control system is called a visually coupled system. It is a closed-loop servo-system which uses the natural visual and motor skills of the aviator to remotely control the sensor and/or weapon.

One of the most important operating parameters of visually coupled systems is the sensor's maximum slew rate. The inability of the sensor to slew at velocities equal to those exhibited in the aviator's head movements would result in 1) significant errors between where the aviator thinks he is looking and where the sensor is actually looking and 2) time lags between the head and sensor lines-of-sight. Medical studies of head movements have shown that normal adults can rotate their heads +/-90 degrees in azimuth (with neck participation) and -10 to + 25 degrees in elevation without neck participation. These same studies showed peak head velocity is a function of movement displacement, i.e., the greater the displacement, the greater the peak velocity, with an upper limit of 352 degrees per second.^{37,38} However, these studies were laboratory-based and does not reflect the velocities and accelerations indicative of a helmeted head in military flight scenarios. In support of the AH-64 PNVS development, Verona et al. investigated single pilot head movements in an U.S. Army JUH-1M utility helicopter.³⁹ In this study, head position data were collected during a simulated mission where four JUH-1M pilot subjects, fitted with a prototype IHADSS, were tasked with searching for a threat aircraft while flying a contour flight course (50 to 150 feet above ground level). The acquired head position data were used to construct frequency histograms of azimuth and elevation head velocities. Although velocities as high as 160 and 200 degrees per second in elevation and azimuth, respectively, were measured, approximately 97 percent of the velocities were found to fall between a range of 0 to 120 degrees per second. This conclusion supported the PNVS design specification maximum slew rate of 120 degrees per second. It also lends validity to aviator complaints that the TADS sensor (with a maximum slew rate of 60 degrees per second) is too slow to be used for pilotage.

13. EXOCENTRIC SENSOR LOCATION

Before encountering night imaging systems, an aviator's primary visual sensor had been his eyes. His experience in the perception and interpretation of visual input is referenced to the eyes's position on the head. However, when flying the AH-64, the primary visual input for night and foul weather flight is the PNVS sensor. This sensor is located in a nose turret approximately 10 feet forward and 3 feet below the pilot's design eye position. This exocentric positioning of the sensor can introduce problems of apparent motion, parallax, and incorrect distance estimation.³

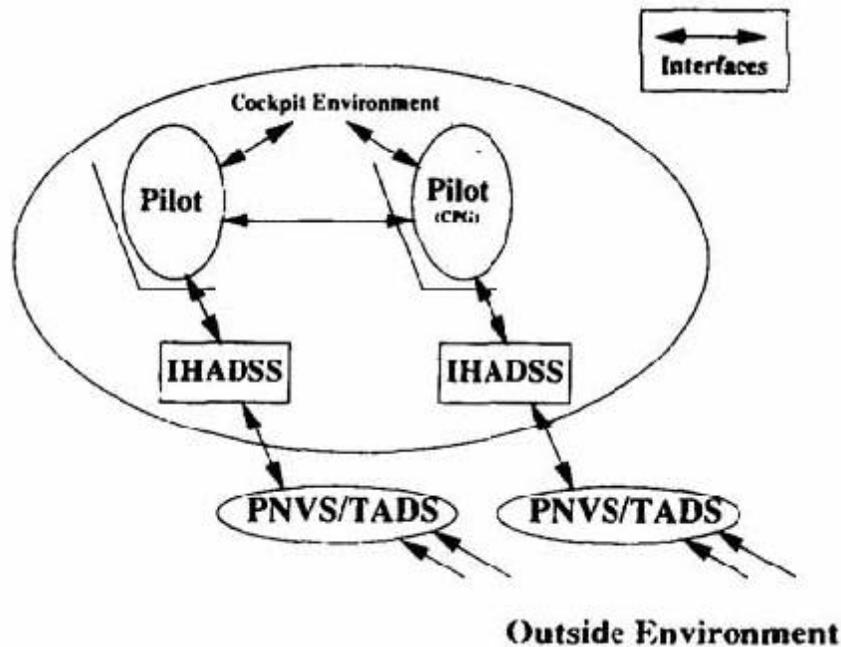


Figure 21. A simple Sensor-Display-Human interaction model for the AH-64 pilotage system.

However, this mode of sensor location does provide the advantage of unobstructed visual fields. The aviator's field-of-view is no longer affected by the physical obstructions of the aircraft frame. The PNVS sensor provides the aviator with the capability to look through the floor of the aircraft, a definite advantage when landing in an uncleared area, where the sensor can be used over the full field of regard. However, this field of regard is affected by the attitude of the aircraft. The design for the next generation U.S. Army helicopter calls for the integration of FLIR and I² sensors. Due to the weight and size characteristics of FLIR technology, the FLIR's position will remain exocentric. However, the I² sensor has two location options. It may be collocated with the FLIR sensor on the nose of the aircraft, or it may be helmet mounted. If both sensors are exocentric located, only the basic concerns of this mode of location, as listed above, require consideration. However, if the I² sensor is helmet mounted, there may be problems associated with the mixed location modes and the resultant switching of visual reference points.

14. AH-64 ACCIDENT EXPERIENCE

This paper has focused on the characteristics and limitations of helmet-mounted thermal night imaging systems, such as the PNVS/IHADSS used on the AH-64. Many of the factors discussed have potential safety implications; therefore, it would be useful to review the actual AH-64 accident experience, to document any contributory role of these advanced sensor/display systems. Since all Army accident investigation records are maintained at the U.S. Army Safety Center at Fort Rucker, Alabama, such a review is possible. Accordingly, the past five years of AH-64 accident investigation reports were reviewed by the authors.

During the period 1985-1989, there were 37 Class A, B, or C accidents involving the AH-64 aircraft (damage costs exceeded \$10,000 or injuries resulting in at least one lost workday). In these 37 accidents, there were 28 "occurrences" which were judged to be in some way related to the sensor/display systems used in the AH-64. These occurrences were grouped using a simple sensor-display-human interaction model, which was created to depict the critical sensory interfaces involved in AH-64 pilotage (Figure 21). Components of the model include the two aviators, the display system (IHADSS), the cockpit, the sensor (PNVS), and the outside environment. The model does not account for material factors (e.g., engine or tail rotor problems) or other accident causes, so this discussion does not reflect the total AH-64 accident experience.

In the AH-64 accidents reviewed, the IHADSS pilot interface was most frequently implicated (Figure 22). The most frequent accident event in this interface, "undetected aircraft drift" (cited five times), frequently is reported by aviators flying with night imaging systems.^{3, 6, 19, 40} Hovering a helicopter is an endeavor dependent almost entirely on visual cues, since the human vestibular system is unreliable in detecting the low amplitude accelerations characteristic of hovering flight. However, current night vision systems present the aviator with limited visual information (compared to daylight conditions). Static visual cues (e.g., shading, texture gradients, color, interposition, and contours) are reduced primarily by degraded acuity, dynamic visual cues (e.g., motion parallax, optic field flow, and size change) are limited by degraded acuity as well as reduced FOV.²⁹ It should be pointed out symbology providing aircraft position and drift information is available to the AH-64 aviator via the HDU. These reduced visual cues also affect depth perception and distance estimation. Two accidents occurred in which the aviator "misjudged aircraft clearance." These judgments are impaired by reduced visual acuity (important to monocular depth perception) as well as by the complete lack of stereopsis inherent in a monocular display.

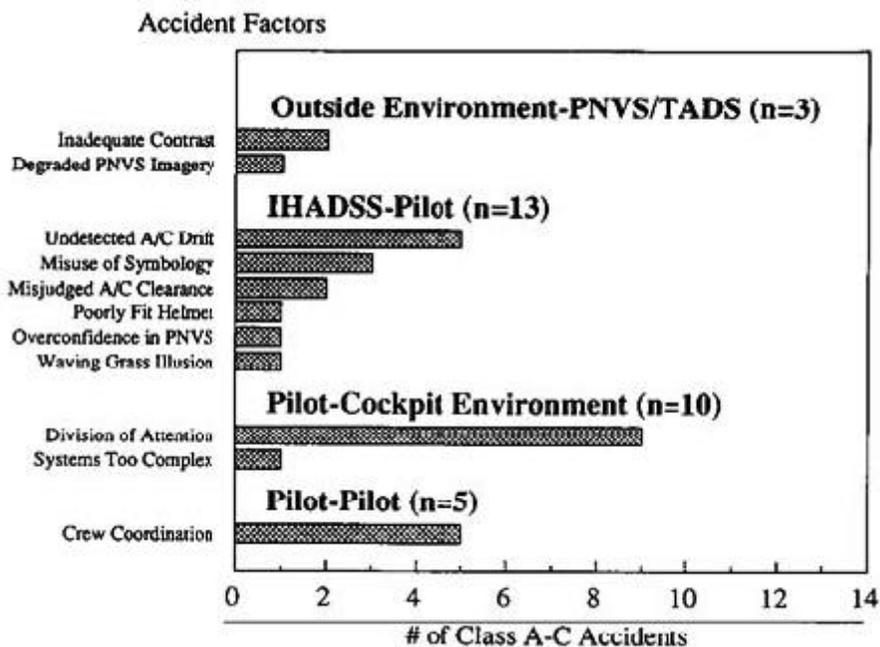


Figure 22. The number of Class A-C AH-64 accidents, occurring from 1985-89, involving PNVS-IHADSS.

Aviators involved in three AH-64 accidents had problems using the display symbology. In one accident, the tail rotor contacted trees during landing. The aviator did not correctly interpret head tracker symbology indicating the orientation of the aircraft center line, and allowed the aircraft to descend sideways along the flight path. In another accident, the crew experienced PNVIS image deterioration due to poor weather conditions. While removing the HDU in order to transition to conventional head-down instrument flight, the aircraft impacted the ground. The aviator was not sufficiently comfortable with the symbology to rely exclusively on the HDU for flight, although the displayed information is adequate to initiate a safe instrument recovery. Helmet-mounted displays allow the aviator to view flight information while remaining "head-up, eyes-out," but correct interpretation of the displayed symbology still requires significant cognitive work and attention, just as in traditional "head-down" instrument flight. In the third accident, the aircraft drifted rearward into a tree, while the crew was distracted by "perceived anomalies in the aircraft's visual symbology."

Although the IHADSS-Pilot interface contained the greatest number of occurrences (13), the pilot-cockpit environment interface contained the single most frequent factor, "division of attention" (cited 9 times). Generally, this means the aviators were distracted within the cockpit, and consequently failed to maintain adequate obstacle clearance. Closely related are the "crew coordination" factors (pilot-pilot interface), since proper delegation of cockpit labor would have prevented many accidents in which division of attention was cited. These breakdowns in human-machine interaction, while not specifically related to the IHADSS, could be considered as a measure of the overall complexity and workload inherent in the AH-64. Helmet-mounted displays, multifunctional CRT panel displays, and other harbingers of the totally "glass cockpit," may reduce some aspects of cockpit workload, but create new problems (*e.g.*, confusing symbology, complex system messages, and time-consuming pages of computer menus). Crew coordination is particularly important in a tandem seating arrangement (*i.e.*, the AH-64), since the two crewmembers cannot see each other. Visual monitoring of the outside environment by at least one crewmember is essential in the obstacle-rich tactical helicopter environment.

Although the number of AH-64 accidents in this brief analysis is small, already it is evident the accident experience parallels concerns expressed by aviators in the published user surveys, cited throughout this paper. These reports should provide direction to future human factors and safety research.

15. SUMMARY

Thermal imaging systems provide the aviator with the ability to operate effectively at night and in adverse weather. However, these systems do not provide imagery comparable to that achieved by the unaided eyes during daylight. The quality of the image presented to the aviator is impacted by the operating characteristics of the system's optics, detector, and display. In addition, among the most significant factors influencing image quality, and hence aviator performance, are the energy levels of the scene targets and background, and environmental effects on these levels.

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