HELICOPTER NIGHT PILOTAGE

In 1971, the United States Army determined that, in order to survive on the modern battlefield, tactical helicopters had to fly very near the ground and hide behind terrain contour or trees. Flying at very low altitude, masked by hills and trees, was required in order to overcome the threat of enemy ground to air weapons.

Flight to and from the battle area is at high speed and constant altitude above the ground, generally less than thirty feet above the terrain or local obstacles. This is called contour flight. Flight in the battle area is nap-of-the-earth (NOE). During NOE flight, at least part of the aircraft is below treetop level, and the aircraft flies around obstacles rather than over them in order to remain hidden. NOE and contour flight requires night imaging sensors with field of view (FOV) and resolution sufficient to allow the pilot to fly the aircraft near trees and other ground obstacles.

The night pilotage task is very demanding on both the aviator and the helicopter night sensors. A helicopter night pilotage sensor should allow the pilot to fly "heads up and eyes out"; the system should provide the same type of contextual information at night which allows the pilot to orient and fly the aircraft during the day with unaided vision. The sensor should provide an image that permits the pilot to perform precision aircraft movements in a confident and aggressive manner. The sensor should permit the pilot to discern terrain features for navigation, select low-level flight paths, and detect possible threats. A good pilotage sensor will also maximize the fraction of time that at least minimal performance can be gained from the sensor in order to execute a mission.

NIGHT PILOTAGE SENSORS CURRENTLY IN USE

Image Intensifiers

The first fielded imaging aid used for low-level night pilotage was the AN/PVS-5 Night Vision Goggle which was adopted from ground use. The AN/PVS-5 goggle is shown in Fig. 1. This sensor uses image intensifier (I^2) tubes which amplify moonlight and starlight. The goggle amplifies visible light and provides a considerably brighter image to the pilot than would be available without the goggle.

The goggle provides a binocular image (an image to both eyes) with 40° circular FOV. To illustrate this field of view, a 19-inch television set viewed from 21 inches would provide about the same field of view to the eye as the goggles. The goggle image, however, is optically projected as a virtual image that appears to be outside the aircraft; this relieves eye strain and makes the image appear more natural. The image is unity magnification, meaning that objects appear life-sized.

Under optimal light conditions, the AN/PVS-5 goggles have a limiting resolution of 0.7 cycles per milliradian (cy/

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

Figure 1. The AN/PVS-5 goggle provides a good image with moonlight illumination. In use, it covers the entire upper portion of the face.

Figure 2. The ANVIS goggle provides a good image with moonlight or starlight illumination. The pilot can view instruments by looking under the goggle.

mrad) which is equivalent to a visual acuity of about 20/50. (When an optometrist says that you have "20/50 vision," he means that you can read the same size letters at 20 feet as are legible to most people at 50 feet. The human eye resolution at the 20/20 level corresponds to the ability to resolve roughly one minute of arc.)

Experience with the ground goggle showed it to be a significant aid for night flight. Two significant problems were encountered, however. In use, the ground goggle covers the entire upper portion of the face, so that the pilot viewed both the outside world and aircraft instruments through the goggle. The goggle optics could not be focused to simultaneously show both the nearby instruments and the outside world. The second problem with the ground goggle was that it provides a good image only when the moon is up; flying with these goggles was difficult under starlight illumination conditions.

The development of an I^2 goggle specifically designed for aviation use was initiated in the late 1970s. The new goggle was designated the AN/AVS-6 Aviator's Night Vision System (ANVIS). ANVIS mounts to the pilot's helmet as shown in Fig. 2 and allows the pilot to view his instruments by looking under the goggle. ANVIS can also be rotated up to a stow position on top of the helmet, leaving the pilot's vision completely unobstructed.

ANVIS provides a good image under starlight illumination conditions. In addition to being more sensitive than the AN/PVS-5 in responding to visible light, the ANVIS spectral band encompasses more of the ambient light available at night. ANVIS responds to near infrared light as well as to visible light. ANVIS provides a 40°, binocular, unity magnification image with better resolution than the original ground goggle. Under optimal illumination conditions, ANVIS limiting resolution is about 0.9 cy/mrad corresponding to a limiting acuity of 20/40.

The AN/AVS-7 Heads Up Display (HUD) was added to ANVIS in the early 1990s; it is a small apparatus which clamps onto one of the ANVIS oculars. The HUD superimposes instrument symbology on goggle imagery, allowing the pilot to see important information like altitude, heading, and gyro horizon without looking inside at the cockpit instruments. Figure 3 illustrates symbology superimposed on ANVIS imagery. The HUD allows the pilot to keep "heads up and eyes out," because the pilot need not focus his eyes and attention inside the cockpit to view important instrument information.

The primary problem with using ANVIS on helicopters is lack of compatibility with the cockpit instrument lighting. Modern image intensifiers amplify ambient light 2000 to 3000 times; cockpit lights can blind the goggles due to reflected glare off the canopy or off other objects in the cockpit. The problem is corrected by adding a spectral filter to ANVIS which rejects blue-green light, and only blue-green instru-

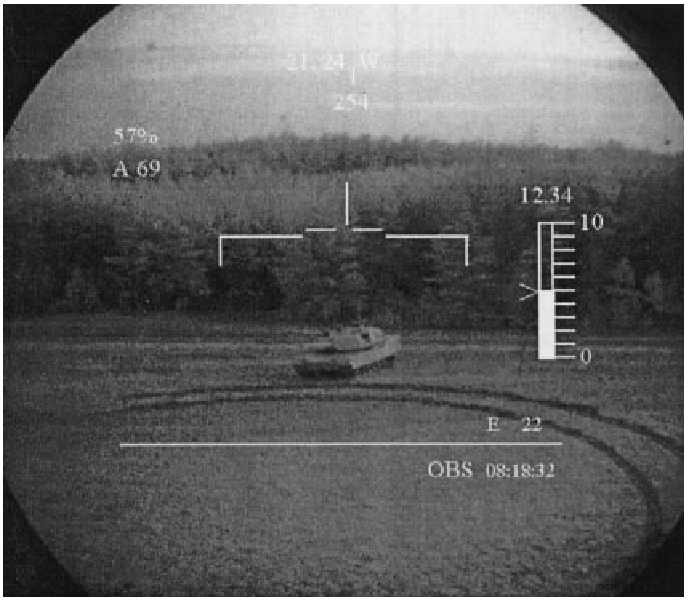

Figure 3. Flight symbology is superimposed on the ANVIS imagery; the pilot does not need to look inside the cockpit to see important aircraft status information.

ment lighting is used on the newer Army helicopters. Red light is avoided because ANVIS is quite sensitive to red light. Lighting requirements for ANVIS compatibility are discussed in ref. 1.

Thermal Imagers

In 1973, development was initiated on the first thermal imager for pilotage use. The AN/AAQ-11 Pilot's Night Vision System (PNVS) was developed for the AH-64 Apache Advanced Attack helicopter. PNVS is a gimbaled thermal imager mounted on the nose of the helicopter. The position of the PNVS on the helicopter is shown in Fig. 4. The PNVS images 8 μm to 12 μm thermal energy (that is, heat) and provides a 40° horizontal by 30° vertical FOV.

The pilot is in the cockpit, while the PNVS thermal imager is on the nose of the aircraft. The system hardware must provide some means of pointing the sensor where the pilot wants to look and some means to remote the thermal image back to the pilot in the cockpit. Figure 5 illustrates how this is accomplished on Apache.

A helmet tracker slaves the sensor line of sight to the pilot's head. The pilot wears a helmet-mounted display through which he views the thermal image. The helmet display projects a virtual image which appears to be outside the aircraft. The helmet-mounted display is monocular, viewed with the right eye only, and provides the same 30° vertical by 40° horizontal field of view as the sensor. The system therefore provides a unity magnification, thermal image of the world which the pilot can orient by moving his head.

A second thermal imager is available on the Apache helicopter. The second thermal imager is one of several sensors in the AN/ASQ-7 Target Acquisition and Designation System (TADS); the TADS is the large, barrel shaped object located below the PNVS shown in Fig. 4. This imager is normally used by the copilot/gunner to locate and engage targets. However, the TADS thermal imager has three fields of view with the wide field of view identical to the PNVS field of view. The copilot/gunner can use the TADS image in a pilotage mode in exactly the same way that the pilot uses the PNVS. A helmet tracker senses the copilot's head motion and moves the TADS to align the line of sight of the thermal imager. The copilot views the image via a helmet-mounted display.

Figure 4. The PNVS thermal imager mounted on the front of the Apache Helicopter. The TADS system is the barrel-shaped object with two windows mounted beneath the PNVS.

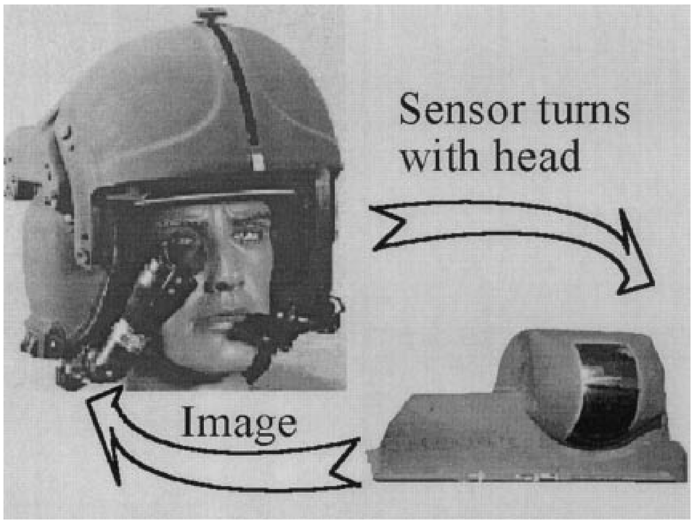

Figure 5. Pilot wears a helmet mounted display in front of right eye; he uses this to view the PNVS thermal imagery. A helmet tracker turns the PNVS sensor to match the pilots head movement.

Heads-up instrument symbology is an integral part of the PNVS and TADS systems on the Apache helicopter. Both pilot and copilot can view important flight and status information superimposed on the thermal imagery. With symbology superimposed on his night vision imagery, the pilot does not have to focus his eyes inside the cockpit to determine critical information such as altitude, heading, or caution status.

Combinations of Thermal Imagers and Image Intensifiers

In 1987, an adapter was designed to permit the ANVIS to be mounted on the Apache copilot's helmet. The adapter allows the ANVIS to be mounted simultaneously with the Apache helmet display, although ANVIS and the helmet display cannot be viewed simultaneously. When the copilot is using ANVIS, the TADS thermal imagery and symbology can be viewed on a panel display by looking under the ANVIS. The copilot can use the ANVIS imagery and periodically cross reference the thermal imagery as a safety check. If the copilot is using the helmet-mounted display and TADS thermal sensor, the ANVIS is placed in the stow position on top of the helmet.

In the late 1980s, the Helicopter Night Vision System (HNVS), AN/AAQ-16, was fielded on some UH-60 Blackhawk Utility helicopters and on some CH-47 Chinook Cargo helicopters. The HNVS is a thermal imager which operates on similar principles to the PNVS and the TADS. The HNVS is mounted on the nose of the aircraft and is viewed via a panel-mounted display in the cockpit. The HNVS is not head tracked, but can be pointed by a hand controller. The sensor has two fields of view. The wide FOV is 30° vertical by 40° horizontal; the narrow FOV is 5° vertical by 7° horizontal.

Both pilot and copilot use ANVIS to fly. The panel displayed HNVS imagery is used to cross reference and verify the information provided by the ANVIS. The aviators use HNVS as a backup, and as a cross reference for terrain avoidance, target location, check point verification, and during low illumination or poor visibility conditions where ANVIS vision is degraded.

The newest Army helicopter, currently in development, is the RAH-66 Comanche; Comanche is a reconnaissance and light attack helicopter. The Comanche Night Vision Pilotage System will integrate an advanced, high -resolution thermal imager, an I^2 camera, and flight symbology into a single package. The pilotage sensors will be mounted on the nose of the aircraft in a manner similar to Apache; however, the nose turret will include both thermal and I^2 sensors. The pilot will wear a binocular helmet display rather than the monocular display worn by Apache aviators. The field of view of the NVPS with the new helmet-mounted display will be 30° vertical by 52° horizontal.

SENSOR THEORY OF OPERATION

Image Intensifiers

The image intensifiers used in ANVIS amplify ambient light, moonlight, and starlight, at spectral wavelengths between 0.5 and 0.9 μm. A schematic of a goggle ocular is shown in Fig. 6; binocular goggles use two oculars to provide an image to both eyes. An inverted image of the scene is formed on the cathode by the objective lens. The cathode emits photo electrons; the shot noise associated with cathode photoelectrons dominates the performance of image intensifiers. Photoelectrons from the cathode are accelerated to the microchannel plate (MCP) by a voltage difference applied between the cathode and MCP.

The MCP acts as an electron multiplier and provides most of the gain of the I^2 tube. A detail of the MCP is shown at the bottom of the Fig. 6. The MCP is a thin, glass plate made up of fiberoptic bundles with the core etched away. The plate has millions of channels (holes) with photoemissive material on the inside of the channels. Each face of the MCP is metalized, and a high voltage is applied across the plate. As electrons strike the inside of the MCP channels, secondary electrons are emitted. Multiple secondary electrons are emitted for each cathode electron. The secondary electrons are accelerated by the voltage along the channel, the secondary electrons strike the channel wall and cause more electrons to be emitted, and the electron multiplication process is repeated.

The amplified electrons from the MCP are accelerated to the phosphor, where a brighter version of the cathode image is formed. The fiberoptic twist erects this image. The eyepiece magnifies the image for presentation to the eye. ANVIS provides a scene to eye light gain of about 3000. In the absence of fog or obscurants, ANVIS performs well under clear starlight illumination. Generally, ANVIS provides good imagery with naked-eye visibility exceeding 200 m to 300 m and minimum light levels of 7E-5 footcandles (2).

Thermal Imagers

Thermal imagers like the Apache helicopter PNVS detect radiation in the 8 μm to 12 μm spectral band. This band is chosen because the atmosphere has a "window" where the transmission of thermal energy is good. Everything near room temperature radiates at these wavelengths. The emissivity of natural objects is generally above 70%; most human-made objects are also highly emissive. It should be noted, however, that thermal sensors derive their images from small variations in temperature and emissivity within the scene. Typically, the thermal scene is very low contrast even under good thermal viewing conditions. Scene thermal contrast is affected by the amount of solar heating during the day. Thermal contrast is decreased by the presence of clouds. Thermal contrast can be poor at night, particularly after extended periods of clouds or precipitation.

In current thermal imagers like the PNVS, a linear array of infrared detectors is used. Figure 7 illustrates the theory

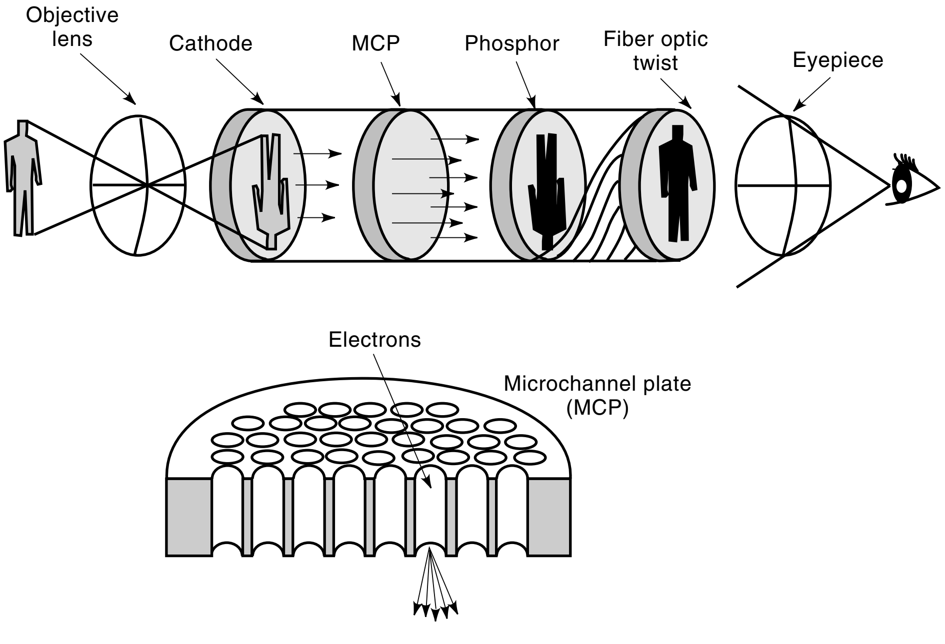

Figure 6. Theory of operation for an image intensifier. The microchannel plate is illustrated at the bottom.

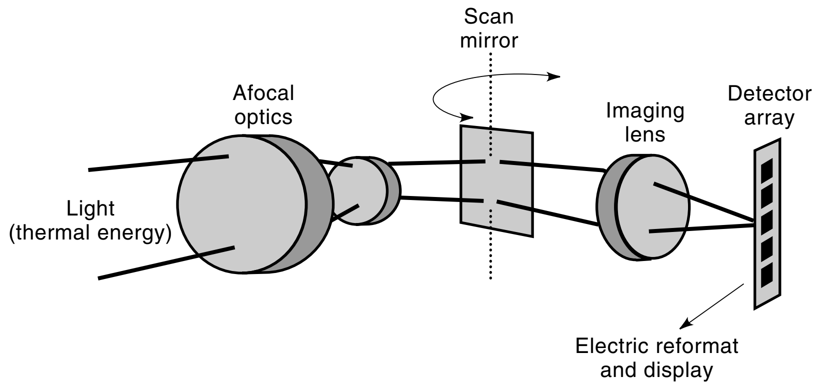

Figure 7. Theory of operation for a thermal imager.

of operation. The afocal optics provide a magnified image of the scene at the scan mirror. The linear array of detectors is scanned over the image by the oscillating mirror. The image is formed by rapidly sampling each element of the detector array as it is scanned over the whole image area. A video image is formed electronically from the detector samples; the video image is viewed via the helmet-mounted display.

The linear array in PNVS has 180 detectors; interlace is used to generate 360 active lines in the image. Interlace is achieved by nodding the scan mirror alternately up and down a small amount after each sweep of the field of view.

Detector noise dominates the performance of these imagers. PNVS provides usable imagery with tree to ground equivalent blackbody temperature differences greater than 0.3 K; performance with less than 0.1 K temperature difference is poor (2).

PILOTAGE SENSOR PERFORMANCE

The performance of a pilotage aid depends on the image delivered to the pilot during flight. Depending on the weather and other factors, the image can fade, become very noisy, and even disappear completely. The image quality of image intensifiers and thermal imagers is affected by ambient atmospheric conditions and the nature of the local environment. The I^2 image quality depends on available illumination from the moon and stars, on atmospheric visibility conditions, and on the diversity and contrast of ground objects in the local area. Thermal image quality depends on thermal contrast within the scene and on atmospheric transmission in the thermal spectral band. Thermal contrast is increased by solar heating during the day and is reduced by heavy or prolonged cloud cover or precipitation.

User surveys were conducted in 1987, 1990, and after Desert Storm in 1992 (3–6). Structured flight evaluations have also been performed (2,3,4,7). These surveys and evaluations provide insight into the environmental conditions under which the pilotage systems perform well.

While it is straightforward to define good and poor weather and environment conditions for ANVIS and PNVS usage, it is very difficult to define the conditions which are safe. An aviator will change the aircraft airspeed, altitude, and flight profile as needed to adapt to the conditions encountered. As night sensor imagery degrades, the pilot will also depend more on the instruments and the HUD symbology. The engineering trades for a night vision sensor relate to the ability of the sensor to deliver the desired visual information; these trades do not relate to the ability of the entire weapon system to accomplish a mission.

When there is good thermal contrast in the scene, and in the absence of fog, heavy rain, or snow squalls, the PNVS thermal imager supports terrain (NOE and contour) flight. Good thermal contrast occurs when there has been clear weather with sunshine for at least a few hours during the day, heating up objects in the background scene. If there has been no sunshine during the day, or if there has been only a little sunshine followed by heavy rain or hours of drizzle, the thermal contrast will be poor, leading to poor visual flying conditions.

Further, the thermal radiation which PNVS images is attenuated by heavy fog and by the atmospheric water vapor content found with heavy rain and persistent drizzle. Image contrast might be poor even when the scene is providing a usable thermal signature. Thus, poor local weather, such as patches of fog or squalls, may make terrain flight difficult at the midpoint of a flight, even though conditions are good at the starting point and destination.

ANVIS performs well under clear starlight conditions but becomes marginal to unusable under overcast starlight conditions. Heavy fog will shut down ANVIS. Even a moderate fog can severely degrade imagery if flight is toward the moon; scattered light from the fog can severely degrade contrast and mask the view of the terrain. Also, ANVIS tends to “bleach out” or shut down when bright lights are in the field of view; this occurs around city lights, when flying toward the moon if it is low on the horizon, and under dawn and dusk conditions.

Flying over land that has no features, such as the sand dunes of Saudi Arabia, presents a challenge; judging distance and closure to the ground requires scene detail. Areas devoid of distinguishable features, such as snow fields, lakes, and dry lake beds, will provide poor imagery for terrain flight. Under these circumstances, the availability of flight symbology is critical.

Pilots express strong feelings that thermal sensors and image intensifiers are complimentary and that both are needed for night contour and NOE flight. The combination supports flight under a wider range of conditions than either alone, although environments certainly exist where even the combination will not support terrain flight.

Also, each sensor brings a unique capability to the aircraft. The two sensors operate in different spectral bands and depend on different physical principles for performance. The ability of the aircrew to detect wires and other obstacles is significantly enhanced. Even on poor thermal nights, the PNVS and HNVS provide a good capability to perceive and react to close in targets. Even on nights with poor illumination, ANVIS gives the ability to see town lights and therefore provides navigational aid; because ANVIS can see aircraft running lights, it also provides a better ability to fly formation as well as safety from collision with other aircraft.

DATA RELATING TO DESIGN IMPROVEMENTS

On the basis of feedback from pilot interviews, current night vision sensors like the ANVIS, PNVS, TADS, and HNVS provide a significant improvement in mission effectiveness over previous techniques of flying and fighting at night. Apache aviators stated that the thermal pilotage and targeting sensors on Apache (the PNVS and TADS systems) completely changed their capability to fight at night so that comparisons to previous aircraft were not meaningful. It is also clear from the pilot surveys, however, that further enhancement of night effectiveness can be gained from further hardware development.

In recent years, the quality of both image intensified and thermal imagery has improved substantially. Even with advanced technology, however, optimizing the design of electrooptical pilotage sensors involves trade-off of resolution, field of view, and sensitivity. At any given level of technology, for example, an increase in the sensor field of view requires a decrease in sensor resolution or a decrease in sensitivity or both.

Further, the optimum performance trade-off of imaging sensor parameters depends on specifying the visual task. Night helicopter pilotage involves many visual tasks. Flying a helicopter near the ground involves judging distance, judging closure to terrain or terrain objects, maintaining orientation of the aircraft, looking for a suitable flight path, searching for obstacles and threats, and other visual tasks.

Over the years since the mid-1970s, responsible Army organizations have undertaken field surveys of operational users, flight evaluations, and flight experiments in order to develop design criteria for helicopter night pilotage systems. These efforts have focused on determining the fraction of time that existing pilotage sensors support mission accomplishment and on finding sensor design parameters which optimize flight handling. These efforts are summarized.

User Feedback on FOV and Resolution

In each of the three surveys taken between 1987 and 1992, the aviators were asked to answer questions, based on their total flight experience, about needed design improvements in field of view and resolution for ANVIS and PNVS. In an operational context, sensor resolution refers to image quality and therefore depends on the sensor sensitivity as well as the optical resolving power of the sensor.

The results of all the surveys are consistent and can be summarized as follows. Based on total flight experience, pilots rate both the FOV and the resolution of ANVIS as acceptable. Pilots would choose to expand ANVIS FOV but not at the expense of current image quality. On the basis of total flight experience, pilots rated the PNVS FOV as adequate but the resolution as inadequate; they would improve image quality before expanding FOV. The pilots are interested in increased PNVS FOV but only in combination with improved image quality.

Table 1. 1987 Survey: Pilot Rating of PNVS and ANVIS FOV and Resolution

Sensor/Feature	Good	Adequate	Inadequate
PNVS FOV	5	35	9
PNVS Resol.	1	18	30
ANVIS FOV	9	17	3
ANVIS Resol.	13	13	3

A summary of the responses to each survey is given below.

The 1987 survey queried 49 Apache helicopter pilots, all with PNVS thermal imager experience; 29 of these aviators had ANVIS experience (3,4). When given an open choice of which sensor they preferred, 42 of 49 wanted both PNVS and ANVIS.

The Apache crews were asked to give an overall rating for PNVS and ANVIS as to adequacy of FOV and resolution (image quality); they were to answer based on their total flight experience. Table 1 summarizes how many pilots rated FOV and resolution as good, adequate, and inadequate. In general, the pilots rated the PNVS FOV as adequate but the resolution as inadequate. They rated both the FOV and resolution of ANVIS as adequate.

The large majority of Apache aviators, 45 out of 49, would improve PNVS resolution before expanding FOV. The opinion on ANVIS was about evenly split between improving resolution and FOV. However, two cautions were emphasized by the respondees. First, these numbers do not reflect a lack of interest in increased FOV if it accompanies improved image quality. Second, the user will not accept a smaller FOV than currently provided.

The 1990 survey involved 52 ANVIS aviators from three units flying a variety of missions (5). Twenty of the ANVIS aviators regularly used the HNVS thermal imager in addition to ANVIS. Twenty-one PNVS aviators were also surveyed; eighteen of the PNVS aviators also used ANVIS. Again, when given an open choice of sensor, the overwhelming majority chose a pilotage system with both thermal and image-intensified imagery.

The aviators were asked to give an overall rating for PNVS and ANVIS as to adequacy of FOV and resolution (image quality); they were to answer based on their total flight experience. Table 2 below summarizes their answers.

Seventeen of the twenty-one Apache aviators would improve PNVS resolution rather than expanding FOV with the current resolution. Fifty of the ANVIS aviators would expand ANVIS FOV if the current ANVIS resolution could be maintained.

Table 2. 1990 Survey: Pilot Rating of PNVS and ANVIS FOV and Resolution

Sensor/Feature	Good	Adequate	Inadequate
ANVIS FOV	16	45	8
ANVIS Resol.	32	36	1
PNVS FOV	2	18	1
PNVS Resol.	0	9	10

The 1992 survey was conducted after Desert Storm (6). No area is as devoid of distinguishable terrain features on such a scale as Saudi Arabia. The sand dunes lacked almost any vegetation and had rises and falls varying as much as 75 feet. The lack of features made the terrain relief imperceptible through the night vision sensors. This was a difficult area in which to use night vision sensors.

Of 66 aviators surveyed, 70% judged ANVIS performance in Saudi Arabia to be good or adequate. What should be noted is that the 30% inadequate rating was never experienced elsewhere. Of the 34 Apache aviators surveyed, 70% rated the PNVS performance in Saudi Arabia as good or adequate. Thermal conditions were better at the beginning of the war, and image intensifier conditions were better at the end of the war. Aviators with a choice used both systems about half the time.

The FOV of both systems was rated as adequate. Of the 34 Apache aviators, 55% rated the PNVS and TADS resolution as inadequate and 75% felt that improving resolution took precedence for a design improvement. Although image quality was a problem in Saudi Arabia, 60% of the 66 ANVIS aviators felt that improving FOV should take precedence based on their total flight experience; another 15% felt that improving FOV and resolution should take equal priority.

Flight Experiments

The flight experiment results can be summarized as follows.

With normal eyesight acuity, performance improves with FOV up to a plateau between 40° and 80° depending on flight maneuver. However, degraded visual acuity strongly affects these results. Once a minimum FOV of about 40° is achieved, performance is a strong function of image quality. Holding the sensor FOV to 40° and optimizing image quality is usually the best design tradeoff.

Increasing FOV by diverging ocular lines of sight (that is, both eyes see the center third of the total FOV, but the outer third on each side is seen by only one eye) does not improve performance and may hurt performance. Although the total FOV is increased, the data indicate that fixations and ocular tracking are limited to the central, overlapped region of the FOV. In some important respects, the sensor FOV becomes the small, overlapped region.

Based on pilot assessment of flight trials, a detector dwell time (exposure time) of 16 ms is unacceptable in a pilotage system; a dwell time of 4 ms is not noticeable. Also, image processing delays (the time delay between capture of the image by the sensor and display of the image to the pilot) should be 33 ms or less. Delays of 100 ms lead to serious flight control problems.

FOV and Resolution Trades. In 1975, the U.S. Army Aeromedical Research Laboratory performed a flight test comparing standard 40° FOV, AN/PVS-5 goggles to modified goggles with a 60° FOV (8). On the basis of the flight conditions, the limiting resolution of the 40° and 60° goggles was 0.6 and 0.4 cy/mrad, respectively. Participating aviators rated the 40°, higher resolution goggle as more suitable for terrain flight. Also, the 40° goggles were associated with smoother, more gradual control stick movements than the lower resolution, 60° goggles.

During 1985, a flight experiment was conducted by the NASA Ames Research Center to determine the visual cues essential for low speed and hover flight (9). This test was conducted in order to determine the importance of field of view and resolution on the fidelity of flight simulators. The variables in this flight test were field of view, the amount of macrotexture (large objects), and the amount of microtexture (fine detail) in the imagery. Field of view was varied by masking portions of the windscreen. Microtexture was varied with a set of liquid crystal goggles which selectively fogged the image. Macrotexture was varied by changing flight location and by laying objects like tires on the ground near the flight path. The test fields of view ranged from a 10 by 14° rectangular window to a multiwindowed case encompassing 9000 square degrees. Two resolutions were used: 20/15 visual acuity, which is normal for these pilots, and 20/40 degraded visual acuity.

Subject pilot ratings indicated that low speed and hover flight can be performed with reasonable workload using a 23 by 38 degree FOV with normal visual acuity. Also, when acuity was degraded, increasing field of view resulted in little improvement in pilot ratings.

The effects of FOV and limiting resolution on flight handling were explored in two flight experiments performed by the Army's Communications and Electronics Command in the late 1980s (10,11). Direct-view goggles were built to provide various combinations of FOV and resolution. These goggles are similar to ANVIS except they do not incorporate an image intensifier and are used during the day only.

Pilots using these goggles were asked to fly preplanned NOE and contour flight profiles. Hover and lateral flight tasks were also evaluated. In both tests, trail runs were flown without goggles to establish baseline performance levels. The aircraft used was an AH-1 COBRA Attack helicopter with the subject pilot in the front seat. The aircraft and flight profiles were selected after consultation with test and user pilots.

Six subject pilots participated, each flying three trials of each task. Measured data included altitude, airspeed, and head motion. After each trial of each task, pilots answered questions on workload, confidence, and aircraft handling qualities. Table 3 shows the combinations of resolution and FOV flown on a test range at Fort Rucker, Alabama in February, 1987.

The term "ocular overlap" in Table 3 is described as follows.

With 100% overlap, both eyes see the whole field of view. One technique to enlarge the display FOV while maintaining

Table 3. FOV and Resolution Combinations Flown in 1987 Experiment

FOV in Degrees	Limiting Resolution	Ocular Overlap (%)
Unrestricted	Normal eyesight	Normal
40	Normal eyesight	100
40	0.9 cy/mrad	100
40	0.6	100
40 × 60	0.9	50
60	0.6	100
60	0.5	100
60 × 75	0.6	75

high resolution is to partially overlap the two oculars of a binocular display. With partial overlap, both eyes see the central portion of the FOV, but only one eye sees each edge of the FOV. For example, 50% overlap of a 60° goggle means that both eyes see the central 30° of the field of view. The right eye sees the right 15° of the total field of view, and the left eye sees the left 15° of the total field of view. This technique lets the optical designer reduce weight and volume by covering a large total FOV with smaller individual oculars.

The test device with 40° FOV and with 0.6 cy/mrad resolution represents current thermal imager capabilities under very favorable thermal contrast conditions. This combination also represents the capabilities of ANVIS night vision goggles under quarter moon illumination. With the exception of the device with 40° FOV and normal eyesight resolution, the other combinations shown in Tab. 3 represent achievable performance in the 1990s time frame under good thermal contrast or high light level conditions.

The following observations were made based on the Fort Rucker test:

1. When FOV was held constant at 40°, decreasing resolution resulted in a substantial increase in altitude, a slight decrease in airspeed, and significantly poorer pilot ratings.
2. Decreasing FOV to 40° but retaining undegraded visual acuity had a very minor impact on altitude and airspeed. Pilot ratings for this combination were slightly below the unrestricted baseline but were better than all other combinations tested.
3. With the 40° FOV, 0.6 cy/mrad device as a baseline, increasing either FOV or resolution with fully overlapped oculars improved performance and significantly elevated pilot ratings. When comparing the 40° FOV with 0.9 cy/mrad goggles to the 60° FOV with 0.6 cy/mrad device, pilots had some preference for the wider FOV but exhibited no change in performance.
4. Increasing FOV by diverging ocular lines of sight (that is using less than 100% overlap of the images presented to the two eyes) did not improve performance when the 40° oculars were used and caused poorer performance with the 60° oculars. The 50% partial overlap of the 40° oculars resulted in increased head motion and fatigue. Distortion for the 40° oculars was less than 1%. However, distortion in the 60° oculars reached 6%; high distortion will undoubtedly cause image convergence problems between the two eyes and lead to degraded performance.

The FOV/resolution combinations tested at Fort Rucker represented performance projected to be attainable under favorable thermal contrast or high light level conditions. A second test was flown at Fort A.P. Hill, Virginia, to explore the resolution versus field of view trade-off when simulating less than ideal thermal contrast or light level conditions.

The FOV/resolution combinations which simulated less than ideal conditions were chosen to make the flight tasks difficult but possible. The potential benefit of trading lower resolution at the edge of a sensor field of view for higher resolution at the center was also evaluated. Table 4 gives the combinations evaluated in the second test which was flown during February and March, 1988. Four subject pilots participated; each subject flew four trails of each task.

Table 4. FOV and Resolution Combinations Flown in 1988 Experiment

FOV in Degrees	Limiting Resolution
40	0.9 cy/mrad
40	0.4
40	0.5 at edge/1.1 at center
60	0.6
60	0.3
60	0.2 at edge/0.9 at center

During this test, goggle configuration did not affect altitude and airspeed performance. Once the task was defined in the baseline flight, execution did not vary significantly in terms of the airspeed or altitude which was maintained. The highest workload and lowest confidence ratings were given to the 60°, 0.3 cy/mrad goggle simulators. In this test, the pilots consistently selected the higher resolution and smaller field of view devices over the larger field of view but lower resolution devices.

If resolution at the edge of a 60 degree device was substantially poorer than resolution at the center, two of the pilots consistently rated the 40 degree field of view goggles higher even when the 60 degree goggles had equivalent or better resolution in the central portion of the field of view. The other pilots rated these 40° and 60° devices as equal.

After test completion, the pilots were asked to explain this preference. The response was that, with the 60° goggles, they would see an object "and then lose it." This characteristic of the goggles was particularly bothersome during the 360° hover turn out of ground effect but also affected performance during lateral flight, NOE, and contour flight. It is likely that ocular tracking is important in the performance of all these tasks and that poor resolution at the edge of the field of view would therefore lead to adverse pilot reaction. However, ocular tracking was not measured during the test.

During 1994, a flight test was conducted to test the hypothesis that using an 18° ocular overlap in a 52° total FOV might result in abnormal eye and head movement patterns (12). A fully overlapped design was also flown for comparison. The flight test further determined if the difference would impact pilot performance of the prescribed flight tasks. Flight tasks included NOE, contour, out of ground effect hover, and lateral flight.

On the basis of the eye tracking data collected during the flight, the partial overlap does constrain the eye at the center of the FOV and significantly reduces the amount of time that the eye uses the outer portion of the total FOV. Averaged across all pilots and tasks, the percentage of eye fixations that occur outside the central 18° when using partial overlap was reduced by 60% ($p = 0.0170$) as compared to the full overlap (full = 24%, partial = 9%). There is no difference between tasks ($p = 0.2836$).

Looking at horizontal eye movement, the mean rms amplitude across the five subjects for the partial overlap was only 70% of the rms for the full overlap. This 30% reduction was significant ($p = 0.0136$). No statistically significant difference in rms amplitude was found between tasks ($p = 0.5022$) or for the interaction between overlap and task ($p = 0.7769$). The average head velocity for partial overlap increases by 12.5% and 6% for contour and NOE flights, respectively.

The pilots indicated higher workload and lower confidence when flying the partial overlap as opposed to the full overlap. Some subjects reported nausea and fatigue after use of the partial overlap; this occurred whether the partial overlap configuration was flown first or second. There was no noticeable visual problem reported on the full overlap configuration.

Overall, these results indicate a change in characteristic head and eye motion when the partial overlap is used. There is a 10% increase in average head velocity and a significant 45% increase in the fraction of time that the head is in motion. The data may suggest that the more frequent head dynamics may be substituting for the lack of the ocular tracking which is restricted (60% reduction) when the partial overlap design is in use. This appears to be consistent with the hypothesis that the eyes do not track across the overlap (binocular to monocular) boundary.

The subjective data suggest that the partial overlap effectively segregates the overall 52° FOV into an 18° brighter central and two dimmer outer regions. This perceived decrease in brightness and acuity apparently derives from the lack of binocular fusion in the outer regions. The subjects indicated that luning at the overlap boundary hid scene cues; they subjectively rated the partial overlap FOV as being smaller than the fully overlapped FOV.

It appears that the partially overlapped configuration limits ocular tracking, both because of the perceived loss in image quality at the overlap boundary and because of the loss of binocular fusion as the eye tracks over the boundary. The partially overlapped FOV configuration provides a functionally smaller FOV than the fully overlapped configuration.

An experiment conducted in 1996 evaluated the impact of field of view on precision flight maneuvers (13). Subjects flew with FOV restricted to 40° vertical and 20, 40, 60, 80, and 100° horizontal. Normal eyesight acuity was not degraded. Maneuvers included pirouette, hovering turn, bob-up and down, precision landing, acceleration and deceleration, and slalom. Performance measures included accurate aircraft position and heading, head movement, pilot rating of flight handling qualities, and pilot rating of visual cues.

Most of the measured data showed a general increase in performance with larger FOV. Flight data indicated that performance improves with FOV up to a plateau between 40 and 80° depending on the flight maneuver. Subjective ratings of flight handling and visual cues increased with FOV up to a limit of 60 to 80° depending on task. On the basis of all the collected data, it was the researcher's opinion that the greatest overall performance gain occurred prior to the 60 to 80° FOV range under the conditions tested.

Image Blur Due to Head and Sensor Motion. A flight test was conducted to determine suitable exposure time for a staring camera operating at the standard video frame rate (11). Cameras which use "staring" detector arrays are being considered for use in night pilotage aides. Most staring sensors use detector dwell times equal to the field or frame time of the imager, typically either the 60 Hz video field time or the 30-Hz video frame time. In a pilotage sensor, however, considerable image movement can occur in a video field time due to aircraft and head motion. The pilot will see a blurred image for the same reason that a photograph will be blurred if the exposure time is too long for the motion being captured.

Two pilots flew an AH-1 Cobra from the front seat using helmets and helmet-mounted displays from the Apache helicopter with a small video camera mounted on the helmet. The camera FOV was 30° vertical by 40° horizontal and provided unity magnification through the helmet display. The test camera had a limiting resolution of about 0.5 cy/mrad and electronic gating to control the dwell time for each video field. Selectable exposure times ranged from 1/60 s (one field) to under a millisecond. The pilot's visor was down and taped so that he flew solely by sensor imagery. The pilots performed hover, lateral flight, NOE, and contour tasks. The flight experiment was performed in January, 1989, at Fort A.P. Hill, Virginia.

Image blur at 1/60 s exposure time was unacceptable. Blur was present with either aircraft or head motion, and the blur interfered with task accomplishment. With an exposure time of 1/120 s, image blur was noticeable with head motion but no conclusion was reached regarding impact on performance. No image blurring was noted at 1/240 s exposure time.

Visual acuity is not degraded for ocular tracking rates up to about 30° per second, and ocular tracking is probably important during pilotage. The exposure time for each snapshot taken by a video camera should be short enough that images crossing the sensor FOV at up to 30° per second are not blurred. Note that acceptable exposure time depends on sensor resolution; exposure time should shorten as sensor limiting resolution improves.

Impact of Image Processing Delays. In advanced helicopter pilotage systems, digital processing will be used to enhance imagery and add symbology. Digital processing adds a delay between when the image is captured by the sensor and when it is seen by the observer. This kind of delay is not present in currently fielded systems; the impact of this delay on flight performance is unknown. A flight test was conducted to qualitatively assess the performance impact of delaying pilotage video (14).

Two aviators participated in the test and alternated as subject and safety pilot. The subject pilots wore Apache helmets and viewed a helmet-mounted camera through the Apache helmet-mounted display. The camera and display provided a 30° vertical by 40° horizontal, unity magnification image to the subject pilot. During the test, a cloth was draped over the subject's visor so that all visual cues came from the helmet display. A video digitizer provided a variable delay between camera and display. All flights were in daylight and good weather.

The project pilot established baselines for several, aggressive flight maneuvers using normal day, unaided vision. The maneuvers included rapid sidestep, pop-up, longitudinal acceleration and deceleration, rapid slalom, nap-of-the-earth, and contour flight. After practicing unaided and with the sensor hardware set for zero delay, the subject pilots repeated the maneuvers with the video delay increased after each iteration of the task set. Test results are based on subject and safety pilot assessments of flight performance.

On the basis of the qualitative assessment of these two pilots, there appears to be no performance impact from a 33 ms image processing delay.

Delays of 100 ms or more impaired the subject pilot's ability to make stable, aggressive maneuvers. All hover tasks were more difficult; sometimes a stable hover could not be achieved. Alternate strategies were developed for NOE and contour to compensate for the image processing delay. The subjects experienced the feeling that the aircraft motion was ahead of the visual scene.

On the basis of this limited flight test, processing delays of up to 33 ms cannot be sensed by the pilot and appear to have no impact on flight performance. However, with an image processing delay of 100 ms, the pilot senses that aircraft movement is ahead of the displayed image. During these flights, and without prior training with delayed imagery, the 100 ms delay led to significant flight control problems.

EVALUATION

Current night pilotage sensors like the ANVIS image-intensified goggle and the PNVS thermal imager provide a significant capability to fly helicopters at very low altitudes in order to hide behind hills, trees, and other terrain objects; this capability enhances the survivability of tactical helicopters on the modern battlefield. The availability of heads-up aircraft status symbology, that is, symbology superimposed on the night vision imagery, is a critical feature of these pilotage systems. Further, aviators report that their ability to perform night missions is greatly enhanced when both image-intensified and thermal imagers are available on the helicopter.

Flight experiments and the results of user surveys provide guidelines for design improvements. NOE and contour flight can be accomplished with reasonable workload using a pilotage system with 40° FOV and 0.6 cycles per milliradian limiting resolution; this resolution provides the pilot 20/60 visual acuity. Improving either FOV or resolution beyond these values will lessen pilot workload and lead to increased confidence. However, since the ability to resolve scene detail is important for terrain flight, night sensors should have sufficient sensitivity to provide 0.6 cycles per milliradian resolution under low thermal contrast or low scene illumination conditions. In advanced systems, this minimum level of image quality should not be traded for increased field of view.

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