7

Night Vision Goggles

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7.1 Introduction

7.1.1 NVG as Part of the Avionics Suite

Visual reference to the aviator's outside world is essential for safe and effective flight. During the daylight hours and in visual meteorological conditions (VMC), the pilot relies heavily on the out-the-windshield view of the airspace and terrain for situational awareness. In addition, the pilot's visual system is augmented by the avionics which provide communication, navigation, flight control, mission, and aircraft systems information. During nighttime VMC, the pilot can improve the out-the-windshield view with the use of night vision goggles (NVG). **NVG lets the pilot see in the dark during VMC conditions!**

This chapter deals with NVG for aviation applications. There are many various nonaviation applications of NVG that are not addressed herein: NVG for personnel on the ground or underwater, and for ground vehicles and sea vehicles.

7.1.2 What Are NVG?

NVG are light image intensification (I^2) devices that amplify the night-ambient-illuminated scenes by a factor of 10^4. For this application "light" includes visual light and near infrared. The development of the microchannel plate (MCP) allowed miniature packaging of image intensifiers into a small, lightweight, helmet-mounted pair of goggles. With the NVG, the pilot views the outside scene as a green phosphor image displayed in the eyepieces.

Various terms are associated with NVG type equipment:

NVG — general term of any I^2 device, usually head-worn and binocular
I^2 — Image Intensifier type of sensor device used in NVG
ANVIS — Aviator's Night Vision Imaging System; a type of NVG designed for aviators
NVIS — Night Vision Imaging System; a general class of NVG including ANVIS
Gen II—Second-generation intensifier technology utilizing MCP and multi-alkali photocathode which enabled construction of AN/PVS-5 NVG
Gen III—Third-generation intensifier technology utilizing improved MCP and galium arsenide photocathode which enabled construction of AN/AVS-6 ANVIS
NVG HUD — Night Vision Goggle with a Head-Up Display attached
HMD — Helmet-Mounted Display; in this chapter it includes NVG HUD
PNVG — Panoramic Night Vision Goggle; usually about 100° FOV
LPNVG — Low-Profile Night Vision Goggle; usually conforms to face
AGC — Automatic gain control

7.1.3 History of NVG in Aviation

7.1.3.1 1950s

In the 1950s there was considerable and diverse research on night image intensification as reported at the Image Intensifier Symposium.[4] The applications included devices for military sensing and for astronomy and scientific research, but were not directed specifically to head-mounted pilotage devices. The U.S. Army first experimented with T-6A infrared driving binocular in helicopters in the late 1950s, according to Jenkins and Efkeman.[2] The binocular device was a near infrared (IR) converter which required an IR filtered landing light for the radiant energy, and was not satisfactory for aviation. In the late 1950s, the first continuous-channel electron multiplier research was being conducted at the Bendix Research Laboratories by George Goodrich, James Ignatowski, and William Wiley. The invention of the continuous-channel multiplier was the key step in the development of the microchannel plate (Lampton[1]).

7.1.3.2 1960s

In the early 1960s first-generation I^2 tubes were developed. The tubes allowed operation as a passive system, but the size of the three-stage I^2 tubes was too large for head-mounted applications. Passive refers to needing no active projected illumination; the system can operate using the ambient starlight illumination, thus the name "starlight scope" from the Vietnam era foot soldier's sniper scope. In the late 1960s, the production of the microchannel plates, used in the second-generation wafer technology I^2 tubes, allowed night vision devices to be packaged small enough and light enough for head-mounted applications. Thus, in the late 1960s and early 1970s the U.S. Army Night Vision and Electro-Optics Laboratory (NV&EOL) used Gen II I^2 tubes to develop NVGs for foot soldiers, and some of these NVGs were tried by aviators for night flight operations.

7.1.3.3 1970s

In 1971 the USAF began limited use of the SU-50 Electronic Binoculars. In 1973 the Army adopted the Gen II AN/PVS-5 as an "interim" NVG solution for aviators, although there were known deficiencies in low-light-level performance, weight, visual facemask obstruction, and refocusing (due to incompatibility with cockpit lighting systems). The *aviator's* night vision imaging system (ANVIS) was the first NVG developed specifically to meet the visual needs of the aviator. The NV&EOL started ANVIS development in 1976 utilizing third-generation image intensifier technology and requiring high-performance, lightweight, and improved reliability and maintainability.

7.1.3.4 1980s

Two versions of the ANVIS were introduced into military aviation:

- AN/AVS-6(V)1 for most helicopters; fits onto the helmet with a centerline mount.
- AN/AVS-6(V)2 for AH-1 Cobra only; fits onto the helmet with an offset mount.

ANVIS operation would not have been feasible or safe in the aircraft if the cockpit lighting had remained the traditional red-lighted or white-lighted incandescent illumination. In 1981 the U.S. Army released an Aeronautical Design Standard, ADS-23,[5] to establish baseline requirements for development of cockpit lighting to be compatible with ANVIS. In 1986 the Joint Aeronautical Commanders Group (JACG) released a Tri-Service specification, MIL-L-85762,[7] which defined standards for designing and measuring ANVIS-compatible lighting. GEC-Marconi introduced a Gen III projected view NVG, called the "Cat's Eye" for use in the AV-8 Harrier.

An updated MIL-L-85762A[8] was released in 1988 in which it defined NVIS as a general term (replacing the specific ANVIS term) and expanded the lighting requirements to accommodate various type NVIS. The controversial utilization of the AN/PVS-5 continued in aviation pending full fielding of ANVIS. Based upon a series of nighttime accidents often involving NVGs, a Congressional Hearing was convened (1989) to review the safety and appropriateness of NVGs in military helicopters. ANVIS was deemed necessary.

7.1.3.5 1990s

Head-up flight information symbology was desired, along with the out-the-window view, within the NVG. Integrating the symbology and imagery resulted in a new type of helmet-mounted display (HMD) referred to as the "NVG HUD". Two types of NVG HUDs were placed in service:

- AN/AVS-7 NVG HUD was installed on CH-47D and HH-60 aircraft.
- Optical Display Assembly (ODA) NVG HUD was installed on OH-58D.

NVG-compatible cockpit lighting was incorporated in high-speed fixed-wing aircraft, but an additional requirement evolved for NVG to be safe during pilot ejection. The AN/AVS-9 (model F4949) was developed for the USAF for ejection capability. In an effort to provide a greater field of view (FOV) than the normal 40° for NVG, the USAF developed a Panoramic Night Vision Goggle (PNVG) to provide about 100° FOV. Several other development programs attempted to reduce the size of the large protrusive goggle optics. Versions of the Low Profile Night Vision Goggle (LPNVG) folded the optics to fit conformally around face. Several integrated helmet development programs incorporated integral I^2 devices and electronic projected display systems. In the early 1990s, several civilian helicopter operators expressed interest in utilizing NVG. Ongoing investigations into the use of NVG in civil aviation delved into applications, safety, and FAA certification.

7.2 Fundamentals

7.2.1 Theory of Operation

An **image intensifier** is an electronic device that amplifies light energy. Light energy, photons, enter into the I^2 device through the objective lens and are focused onto a photocathode detector that is receptive to both visible and near-infrared radiation. Generation III devices use gallium arsenide as the detector. Due to the photoelectric effect, the photons striking the photocathode emit a current of electrons. Because

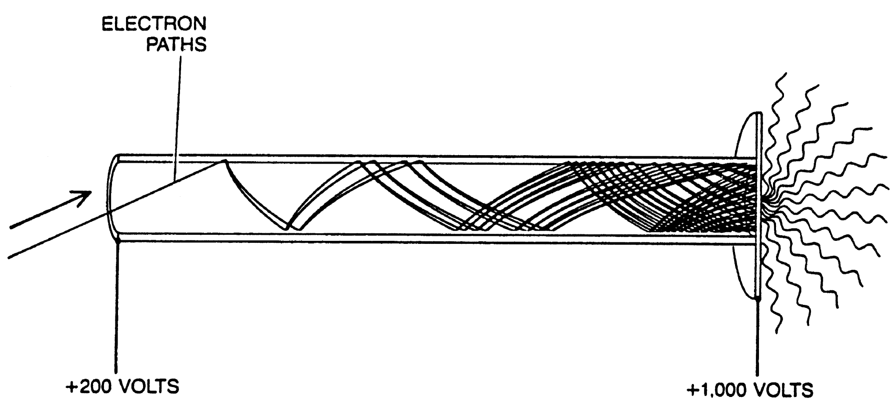

FIGURE 7.1 Electron amplification in a microchannel.[1]

the emitted electrons scatter in random directions, a myriad of parallel tubes (channels) is required to provide separation and direction of the electron current to assure that the final image will have sharp resolution. Each channel amplifier is microscopic — about 15 μm in diameter. A million or so micro-channels are bundled in a wafer-shaped array about the diameter of a quarter. The wafer is called a microchannel plate (MCP). The thickness of the MCP, which is the length of the channels, is about 0.25 in. Each channel is an electric amplifier. A bias potential of about 1000 V is established along the tube,

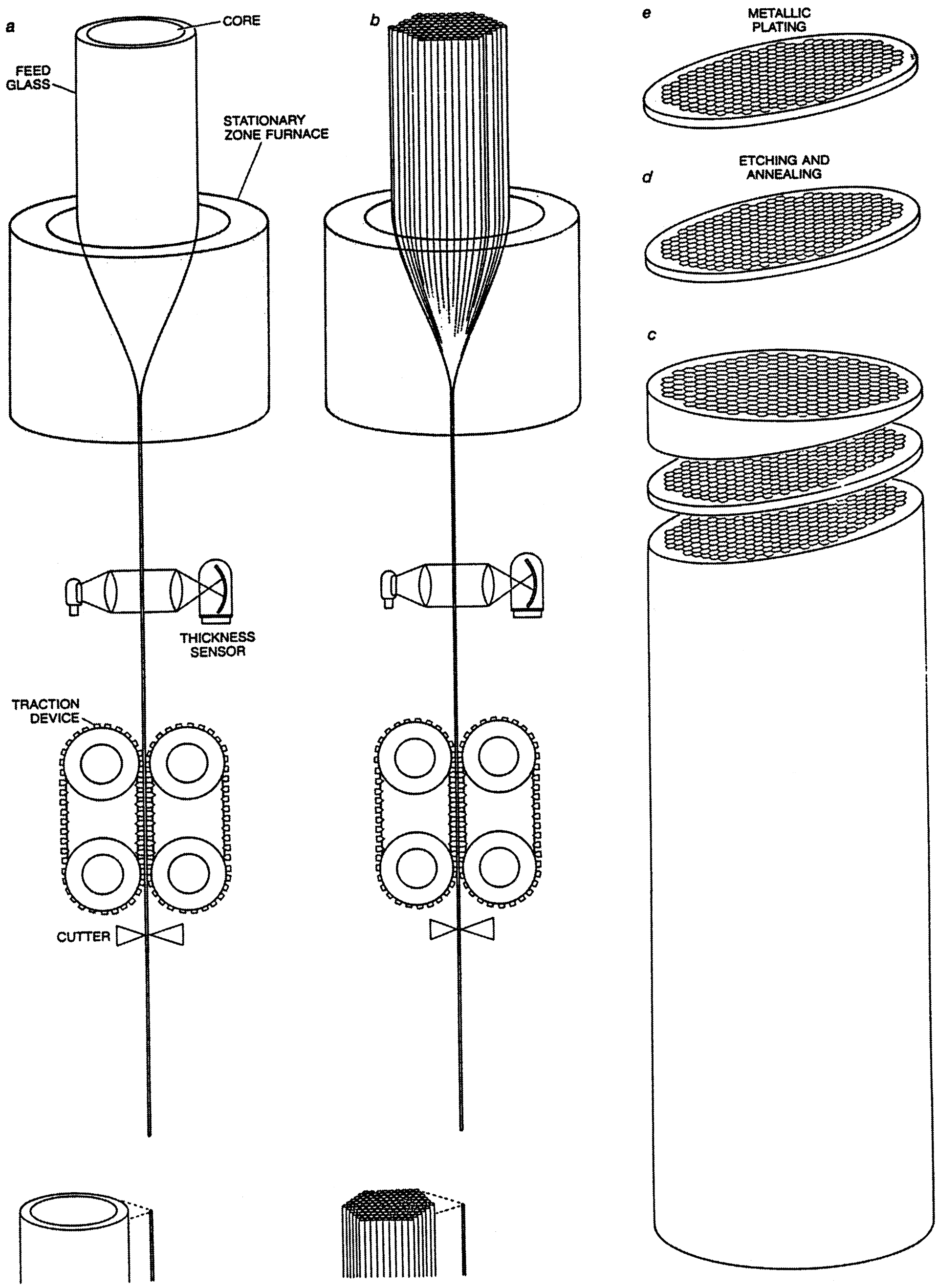

FIGURE 7.2 Double glass draw for MCP manufacture[1].

and each electron produced by the photoelectric effect accelerates through the tube toward the anode. When an electron strikes other electrons in the coated channel, they are knocked free and continue down the tube hitting other electrons in a cascade effect. The result of this multiplication of electrons is a greatly amplified signal. The amplified stream of electrons finally hits a phosphor-type fluorescent screen which, in turn, emits a large number of photons creating an image.

The microchannel plate is a solid-state light amplifier. The intensity of the image is a product of the original signal strength (i.e., the number of photons in the night scene) and the amplification gain within the channel. The fine resolution of the total image is a product of the pixel size from the MCP array and the focusing optics.

The manufacture of MCPs requires complex processes which are dependent on a two-draw glass reduction technique. A concentric tube of an outer feed glass and an inner core glass is drawn into a fine fiber about 1 mm in diameter. Then a bundle of thousands of the fibers is draw to form a multiple fiber about 50 mm in diameter. The core glass is etched out leaving a matrix of hollow glass tubes. Wafer sections are sliced, and the wafers are plated with the metallic coatings necessary for the signal amplification.

The finished product is an NVG which contains an MCP packaged inside an optical housing. The housing will contain objective lens and eyepieces appropriate for the NVG's utilization. For aviators using the NVG for pilotage, a one-to-one magnification is required. The pilot's perceived NVG image of the outside world must be equal to the actual size of the unaided-eye image of the outside real world to provide natural motion and depth perception. The image is displayed to the observer on an energized viewing screen at about 1 footLambert (fL). Screens may be the P20 or P25 phosphors. The light amplification may be 2000 or more, and to prevent phosphor damage, an automatic gain control (AGC) circuit limits the gain in high ambient conditions.

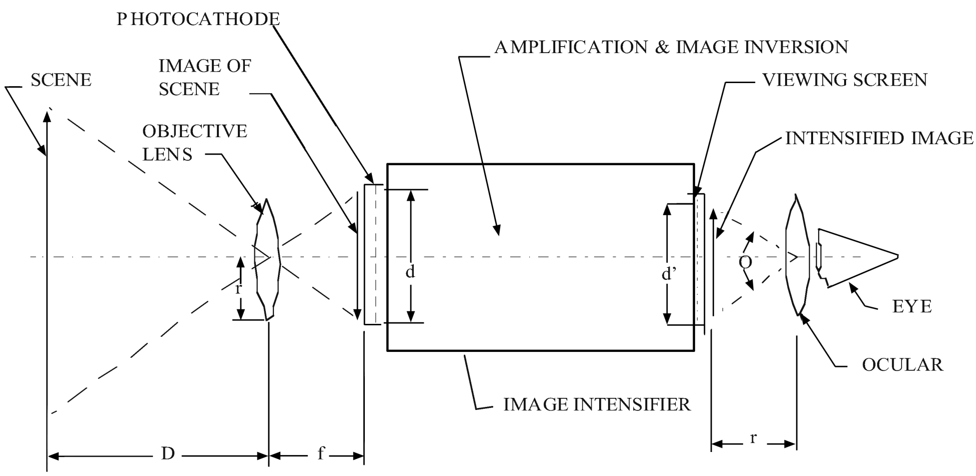

FIGURE 7.3 Typical NVIS image intensifier tube and optics.

7.2.2 I^2 Amplification of the Night Scene

Second-generation image intensifiers utilize multi-alkali photocathodes that are sensitive in the visible and near-IR bandwidth of 400–900 nm. Gen II utilization is generally limited to a minimum of quarter-moon or clear sky illumination (10^{-3} to 10^{-4} fc).

Third-generation image intensifiers utilize galium arsenide (GaAs) photocathodes which are more sensitive than Gen II and have a bandwidth of 600–900 nm. Gen III NVIS can be used in starlight and overcast conditions (10^{-4} to 10^{-5} fc).

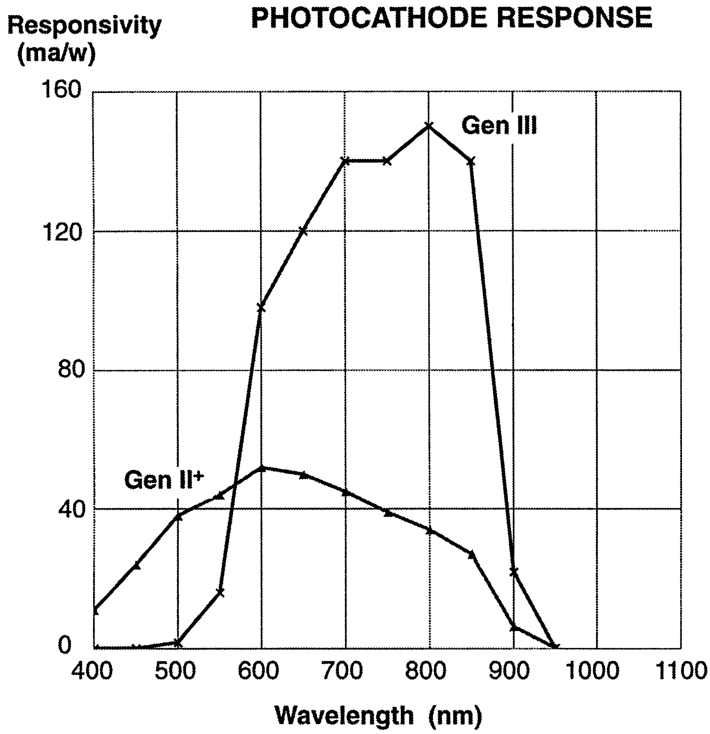

FIGURE 7.4 Photocathode sensitivity.

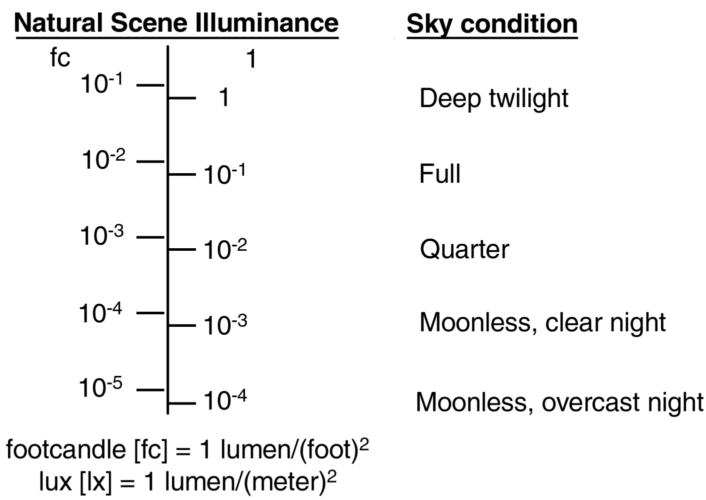

FIGURE 7.5 Illumination from the night sky.

7.2.3 NVG Does Not Work without Compatible Lighting!

NVG lighting compatibility is required for effective NVG use by pilots. If the cockpit lighting is not compatible and it emits energy with spectral wavelengths within the sensitivity range of the night vision goggles, the lighting will be amplified by the NVG and will overpower the amplification of the lower illumination in the outside visual scene.

Compatibility can be defined as a lighting system that does not render the NVG useless or hamper the crew's visual tasks (with or without NVG).

NVIS compatibility permits a crew member to observe outside scenes through vision goggles while maintaining necessary lighted information in the crew station. The Gen III NVIS are insensitive to blue/green light, so the cockpit lighting can be modified with blue cutoff filtering to reduce emitted energy in the red and near-IR regions to achieve compatibility. The complementary minus-blue coatings on the NVIS objective lens provide a sharp cutoff filter to block any red or near-IR light. Blue-green lighting allows external viewing through the ANVIS and internal viewing of the instruments by using the "look-around" technique. The ANVIS look-around design allows the pilot visual access (with unaided eyes) into the blue-green lighted cockpit without head movement. NVIS compatibility requirements are defined by MIL-L-85762.

MIL-L-85762 lighting requirements, and by default the various NVIS, have been categorized into Types and Classes to match the appropriate cockpit lighting system depending on the type of NVIS being used in the aircraft. The original issue of MIL-L-85762 was based on recommendations for ANVIS compatibility (Schmickley[7]) and addressed lighting only for ANVIS (Type I, Class A). MIL-L-86762A added Type II and Class B NVIS. The USAF is in the process of defining a Class C NVIS. A rationale was published to aid manufacturers and evaluators on interpreting the requirements (Reetz[9]).

Type I: Type I lighting components are those lighting components that are compatible with Direct View Image NVIS. Direct View Image NVIS is defined as any NVIS using Generation III image intensifier tubes which displays the intensified image on a phosphor screen in the user's direct line of sight — such as the ANVIS.

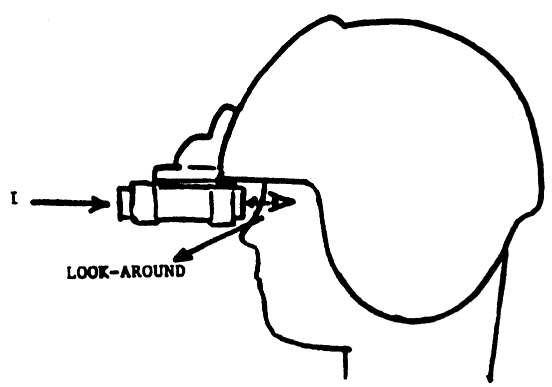

FIGURE 7.6 Type I (direct view). ANVIS with "look-around" vision into the cockpit.

Type II: Type II lighting components are those lighting components that are compatible with Projected Image NVIS. Projected Image NVIS is defined as any NVIS using Generation III image intensifier tubes which projects the intensified image on a see-through medium that reflects the image into the user's direct line of sight — such as the Cat's Eyes.

Class A: Class A lighting components are those lighting components that are compatible with NVIS using a 625-nm minus-blue objective lens filter which results in an NVIS sensitivity lens as shown in the figure below. (The standard AN/AVS-6 ANVIS are equipped with 625-nm minus-blue filters.)

Class B: Class B lighting components are those lighting components that are compatible with NVIS using a 665-nm minus-blue objective lens as shown in the figure below. Class B lighting allows red and yellow colors in cockpit displays, but the consequence is a reduced Gen III NVIS sensitivity to the outside visual scene. The 665-nm minus-blue filter reduces the NVIS sensitivity by 8 to 10% of the Class A NVIS in moonless conditions.

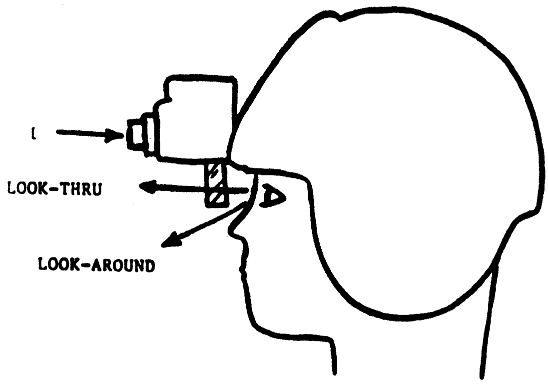

FIGURE 7.7 Type II (projected image). Cat's Eye with "look-through" outside viewing and "look-around" vision into the cockpit.

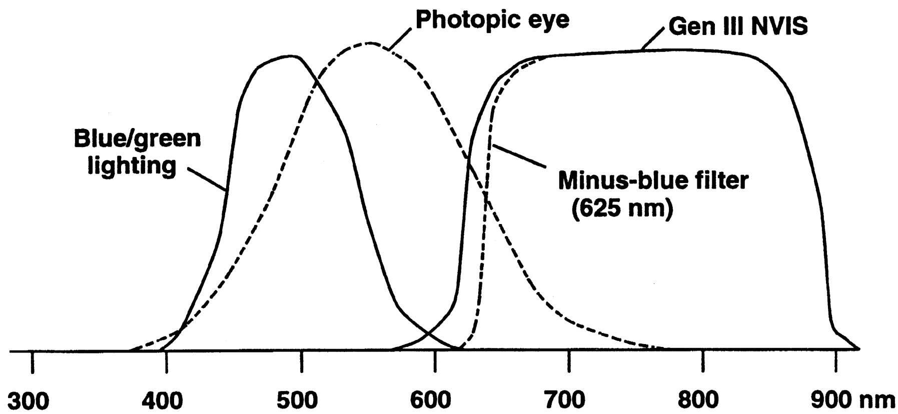

FIGURE 7.8 Typical Class A blue-green lighting and 625-nm minus-blue coating on NVIS.

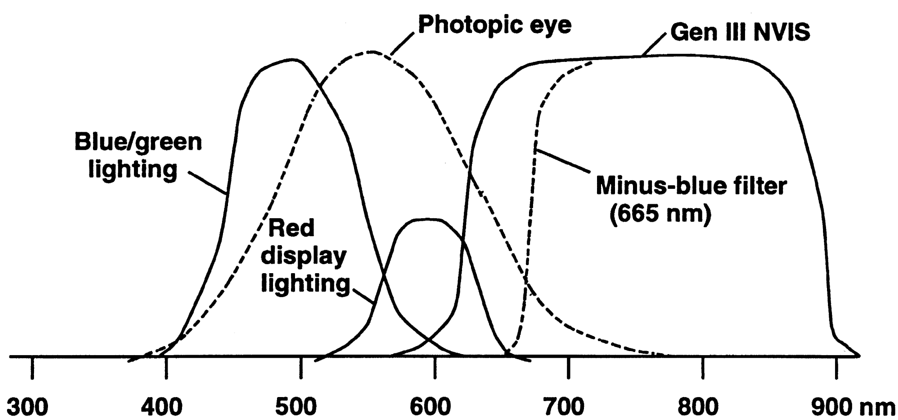

FIGURE 7.9 Typical Class B lighting allows blue-green, yellow, and red with 665-nm minus-blue coating on NVIS.

7.2.4 I^2 Integration into Aircraft

The integration of NVIS into an aircraft crew station usually requires very little modification with respect to the crew compartment space (volume). The primary aircraft requirements are

1. Adequate helmet and NVIS motion envelope;
2. Acceptable visual fields of view (FOV) and windshield transparency in the NVIS range;
3. Compatible cockpit lighting and displays;
4. Compatible interior (cabin) and exterior lighting.

The alerting quality of warning/caution/advisory color coding can be diminished with NVIS compatible (Class A) cockpit lighting. Audio or voice warning messages may be considered to augment the alerting characteristics.

The NVIS is normally a self-contained standalone sensor that is powered by small batteries. The cost of a typical NVIS unit is $10,000, whereas the cost of an aircraft-mounted IR sensor system is 10 to 20 times that amount. The integration of an NVG HUD requires more modification to the aircraft than the NVIS.

Incorporation of NVIS produces some advantages and some disadvantages for the aircraft and missions. **NVIS advantages usually outweigh disadvantages**. The advantages are

- NVIS allows 24-hour VFR operations (pilots say: "I'd rather fly with them.")
- Enhanced situation awareness; pilots can see the terrain.

The disadvantages are

- Limited instantaneous FOV which requires deliberate head movement;
- Neck strain and fatigue (due to increased helmet weight & increased head movement);
- Cost of equipment (NVIS + compatible lighting);
- Pilot training; currency; proficiency;
- Not useful in IMC weather or fog;
- Safety — if there is inadequate training or overexpectations of system capability.

There are known limitations of the NVIS imposed by the limited FOV. Training is required to emphasize the required head motion scanning to compensate for the FOV. Depth perception is sometimes reported as a major deficiency, although it is most likely that inadequate motion perception cues due to limited peripheral vision are a contributor to this perception.

Military training programs have been implemented to exploit the capabilities of the NVIS sensor for various types of covert missions, and to improve safety and situation awareness. Curricula have been developed "*…to assure that there is an appropriate balance of training realism and flight safety*." Training programs include visual aids, laboratory, and simulation to cover:

- Theory of I^2 operation;
- FOV, FOR, adjustment;
- Moon, weather, ambient conditions;
- Different visual scans, head motion.

7.3 Applications and Examples

7.3.1 Gen III and AN/AVS-6 ANVIS

To aid night flying, in the 1980s the Army developed the Aviator's Night Vision Imaging System (ANVIS) which is a third-generation (Gen III) NVG. The ANVIS is designated as AN/AVS-6. ANVIS is lightweight (a little over 1 lb) and mounts on the pilot's helmet. The 25-mm eye relief allows the pilot to see around the eyepieces for viewing the instruments in the cockpit. The Gen III response characteristics are more sensitive than Gen II and the spectral range covers 600 to 900 nm. This spectral range takes advantage of the night sky illumination in the red and IR. Luminance gain is 2000 or greater. The FOV is 40° circular and the resolution is about 1 cy/mr. The total weight is 1.2 to 1.3 lb.

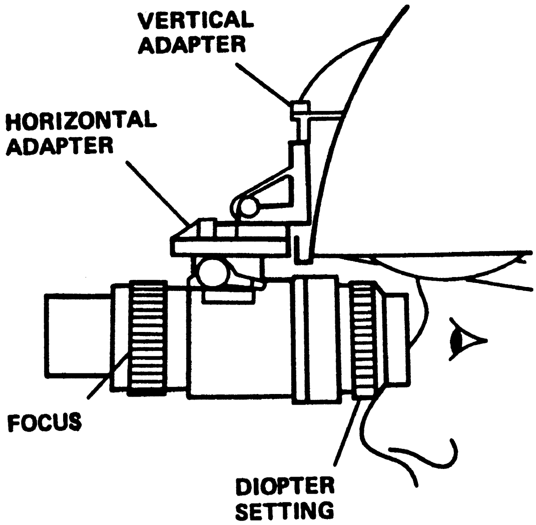

FIGURE 7.10 ANVIS adjustments.[17]

There are several adjustment features on the ANVIS to accommodate each pilot's needs:

- Inter-ocular adjustment
- Tilt adjustment
- Vertical adjustment
- Eye relief (horizontal) adjustment
- Focus adjustment
- Diopter adjustment

The pilot can also flip up the ANVIS to a "helmet stow" position. The mount has a break-away feature in case of a high *g* load or crash.

Early production models of ANVIS units produced system luminance gains of 2000 fL/fL. With improvements in manufacturing techniques and yields, and with increased photocathode sensitivities, newer units have system gains of over 5000. The Army procured large lot quantities of AN/AVS-6 through "omnibus" purchase orders. Omni IV and Omni V AN/AVS-6 have system luminance gains of 5500. The luminance gains of the intensifiers may be 10,000 to 70,000, depending on the ambient illumination being amplified, but with optics and system throughput losses, the overall system gains are 5000+. Presently, the two major suppliers in the U.S. for AN/AVS-6 are ITT and Litton, and the Army splits the procurement of the Omni lots. Adaptations and improved versions of the AN/AVS-6 include the AN/AVS-8 with a 45° FOV, and the AN/AVS-9 which has a front-mounted battery to allow use in ejection seats. The AN/AVS-9 also has a "leaky green" sensitivity to allow viewing of the HUD symbology.

7.3.2 Gen II and AN/PVS-5 NVG

The generation II AN/PVS-5 is outdated and is not now recommended for aviators. The AN/PVS-5 is discussed here because it was the most common device allowing night flying with NVG aided vision. The AN/PVS-5A provided Army ground forces with enhanced night vision capability. Later, pilots used the NVG to fly helicopters. Tests indicated that pilots using NVG could fly lower and faster than pilots without NVG, and concluded that NVG provided considerable improvement over unaided, night-adapted vision.

The AN/PVS-5A weighs 2 lbs and has a full face mask. Wearing these NVG requires the pilot to make all visual observations via the NVG, including cockpit instrument scanning. The pilot must move his head and refocus the lens to read the instruments. Annoyance, discomfort, and fatigue result from these restrictions.

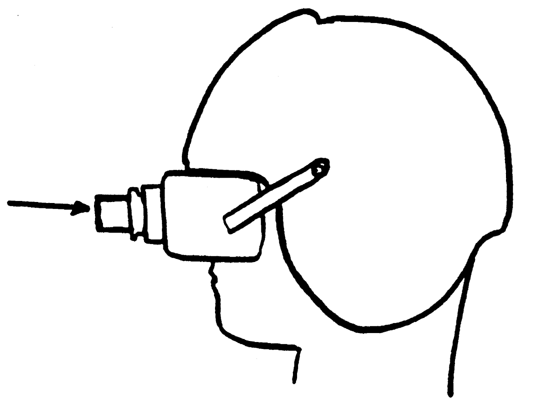

FIGURE 7.11 AN/PVS-5A NVG with full face mask.

The spectral range of the Gen II NVG is from 350 to 900 nm which includes the entire visual spectrum (380–760) plus some near-IR coverage. Most 1970s cockpits had red incandescent lamp lighting which had large red and IR emissions. The NVG's automatic gain control (AGC) shuts down the NVG in the presence of large amounts of radiant energy in the goggles' range. Therefore, the use of Gen II NVG requires that all visible lighting must be reduced below the pilot's visual threshold in order that the lighting does not degrade the NVG operation. Commonly, this is accomplished by extinguishing the lights or using a "superdim" setting. Under these conditions, crew members without NVG cannot read the cockpit instruments. Crew members with NVG must refocus from outside viewing to read the instruments. Research in the U.S. and U.K. on shared-aperatures and shared-lens attempted to provide viewing of the cockpit instruments with the NVG. Modifications to the face mask to provide peripheral and in-cockpit vision produced the "cut-away" mask.

The utilization of AN/PVS-5 NVG in aviation was controversial. The incorporation of NVG into aviation somewhat repeated the development of aviation itself, with a period of trial and error incorporation, sometimes with inadequate or inappropriate equipment, producing some pioneering breakthroughs and some accidents. In the 1980s there were nighttime accidents often involving NVGs. The *Orange County Register* published a lengthy investigative article because several of the helicopter crashes took place within the county.[14] A congressional hearing was convened to review the safety and appropriateness of NVGs in military helicopters.[15] The necessity of NVGs for night flight operations was confirmed along with an emphasis on better equipment and training. A review of AN/PVS-5 and AN/AVS-6 testing concluded both were acceptable.[16] Since that time, AN/AVS-6 ANVIS has become the preferred device for aviators.

7.3.3 Cat's Eyes

The "Cat's Eye" is a Type II (projected image) Gen III NVIS made by GEC-Marconi, and is standard in the AV-8 series of Harrier aircraft. The weight is slightly over 1 lb. The two optical combiner lenses have the I^2 image displayed for out-of-the-cockpit viewing. The combiner has see-through capability to view the aircraft's HUD. When the pilot is looking at the HUD, the I^2 imagery is automatically turned off to allow visibility of the HUD symbology. The combiner glass see-through transmission is $<30\%$. The Cat's Eye has a 25-mm eye relief to allow look-under for cockpit instrument viewing.

7.3.4 NVG HUD

Systems termed "NVG HUD" have been produced that add head-up display (HUD) symbology onto the displayed night vision imagery provided by the NVG. Usually the HUD portion is a CRT image projected onto a combiner glass mounted in front of one of the NVG objective lens. The symbology displayed is aircraft information (attitude, altitude, airspeed, navigation data, etc.) that is generated in a processor box integrated to the aircraft systems.

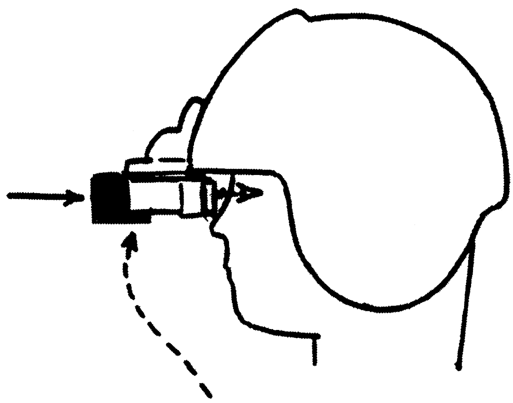

FIGURE 7.12 Aircraft symbologgy.

7.3.5 ANVIS HUD

Honeywell produces the Optical Display Assembly (ODA). The OH-58D that integrates the ODAS also is one of the few aircraft that provides aircraft power for the NVG (instead of self-contained battery power). Elbit produces the AN/AVS-7 NVG HUD. *Note*: The AN/AVS-7 (NVG HUD) should not be confused with AN/PVS-7 single-tube NVG for ground troops.

	Weight on NVG	I^2 FOV	Application
AN/AVS-7	0.25 lb	33° H × 24° V	CH-47, HH-60
ODA	? lb	40°	OH-58D

7.3.6 Panoramic NVG

Panoramic NVG (PNVG) have been developed for the USAF to provide an increased instantaneous FOV of the image. Night Vision Corporation developed the PNVG using four AN/PVS-7 image tubes. The four tubes produce a combined overlapping FOV of 100°.

	Weight	I^2 FOV	Type
PNVG	1.25 lb	100° H × 40° V	Direct view optics

7.3.7 Low Profile NVG

Low Profile NVG (LPNVG) have been developed for several reasons: to improve the head-borne c.g., to allow visors, and to reduce possible injury caused by the protrusion of the longer I^2 tubes. The depth is 2 to 3 in. compared to 5 to 6 in. for other NVIS. ITT developed the Modular, Ejection-Rated, Low profile, Imaging for Night (MERLIN) Aviator Goggle for use by pilots in high-performance fixed-wing aircraft. Litton produces the AN/AVS-502 LPNVG for multi-role missions (parachute operations, weapons firing). Canadian Air Forces approved the AN/AVS-502 for flight engineers in the cabin where head clearance and winds are issues. Systems Research Laboratories (SRL) developed the Eagle Eye™ for fixed-wing and multi-role.

	Weight	I^2 FOV	Type
MERLIN	1.8 lb	35°	See-through optics
AN/AVS-502	1.5 lb	40°	See-through optics
Eagle Eye™	1.2 lb	40°	See-through optics

7.3.8 Integrated I^2 Systems

I^2 sensors can be incorporated in avionics suites in several ways besides standalone NVG on a crew member's helmet. One method is to incorporate an I^2 sensor on-board an IR sensor pod to provide video imagery of either I^2 or IR to the crew.

Several integrated helmet designs and future helmet concepts are integrating I^2 devices along with CRT, LCD, and LED helmet-mounted displays.

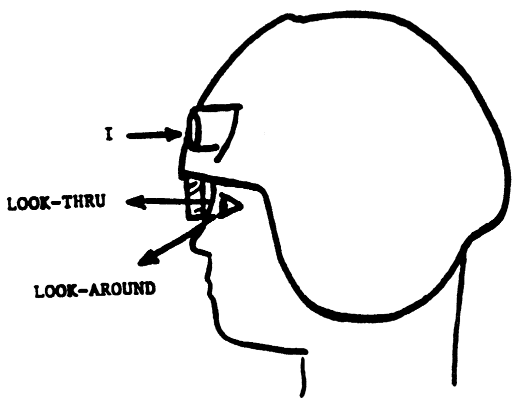

FIGURE 7.13 Integrated helmet.

7.3.9 Testing and Maintaining the NVG

NVIS manufacturers also supply testing and servicing equipment. Examples are the ANV-126 NVG Test Set, TS-6 Night Vision Device Test Set Kit, TS-4348/UV Night Vision Device Assessor, and the TS-10 Night Vision Leak Test and Purge Kit.

7.3.10 Lighting Design Considerations

NVIS-compatible aircraft interior lighting is essential to allow night flying with NVIS. Interior lighting consists of primary lighting (instrument and control panels), secondary lighting (task lights, area lights, floodlights), signals (warning, caution, advisory), and electronic displays.

The key specification that defines NVIS-compatible lighting is MIL-L-85762A. This specification is unique in that it specifies two independent characteristics for the lighting system:

1. **Luminance and chromaticity requirements** for visual (unaided eye) viewing in a dark cockpit, and
2. **Radiance requirements** for limiting any NVIS interference.

The luminance levels remain approximately the same as traditional red and white lighting systems in all previous aircraft. The chromaticity requirements generally produce a blue-green lighted cockpit. Four lighting colors for aviation have been defined in MIL-L-85762A (where u' and v' are 1976 UCS chromaticity coordinates of the defined color):

NVIS Green A — The color for primary, secondary, and advisory lighting. The chromaticity limits are within a circle of radius .037 with the center at $u' = .131, v' = .623$.

NVIS Green B — The color for special lighting components needing saturated color (monochromatic) for contrast. The chromaticity limits are within a circle of radius .057 with the center at $u' = .131$, $v' = .623$.

NVIS Yellow — The color for master caution and warning signals in Class A cockpits. The chromaticity limits are within a circle of radius .083 with the center at $u' = .274$, $v' = .622$.

NVIS Red — The color for warning signals in Class B cockpits. The chromaticity limits are within a circle of radius .060 with the center at $u' = .450$, $v' = .550$.

Chromaticity and luminance requirements for various types of cockpit lighting and displays and cabin lighting are listed in Table VIII of MIL-L-85762A.

NVG compatibility is not assured with proper chromaticity coordinates alone. Lights with different spectral compositions can appear visually as the same color. Similar visual colors are called metamers. But all colored lights used in the NVG cockpit must have filtering to block almost all the energy in the 600- to 900-nm range. The "NVIS-visible" portion of the lighting emission is to be limited per the NVIS radiance definition: NVIS radiance (NR) is the integral of the curve generated by multiplying the spectral radiance of the light source by the relative spectral response of the NVIS.

"Formula 14a" of MIL-L-85762A is used to calculate the NVIS radiance of Class A lighting equipment, and "Formula 14b" is for the NVIS radiance of Class B equipment.

$$\text{NVIS radiance } (NR_A) = G(\lambda)_{max} \int_{450}^{930} G_A(\lambda) S N(\lambda) d\lambda \qquad \text{(Formula 14a)}$$

$$\text{NVIS radiance } (NR_B) = G(\lambda)_{max} \int_{450}^{930} G_B(\lambda) S N(\lambda) d\lambda \qquad \text{(Formula 14b)}$$

where:

$G_A(\lambda)$	= relative NVIS response of Class A equipment
$G_B(\lambda)$	= relative NVIS response of Class B equipment
$G(\lambda)_{max}$	= 1 ma/w
$N(\lambda)$	= spectral radiance of lighting component (w/cm^2 sr nm)
S	= scaling factor
dl	= 5 nm

For example, to be compatible, a Class A lighting system requirement is to have the blue-green primary lighting not exceed 1.7×10^{-10} NR_A when the lighting produces 0.1 fL luminance. If the lighting component is actually greater than 0.1 fL when it is measured, the scaling factor *S* scales the NR to 0.1 fL.

For cockpits where red or multicolor displays are desired, a similar equation for NR_B applies to assure Class B compatibility. Note that "Class B" NVIS must be utilized with a Class B cockpit.

NR requirements for various types of cockpit lighting and displays and cabin lighting are listed in Table IX of MIL-L-85762A.

All other aircraft lighting, not just the cockpit lighting, must be made compatible with NVG. This includes stray light from the aircraft's interior cabin, the aircraft's exterior lighting system, and any

Chromaticity Requirements (from Table VIII, MIL-L-85762A)

	TYPE 1										TYPE II									
	Class A					Class B					Class A					Class B				
Lighting Component(s)	u_1'	v_1'	r	Cd/m^2 (fL)	NVIS Color	u_1'	v_1'	r	Cd/m^2 (fL)	NVIS Color	u_1'	v_1'	r	Cd/m^2 (fL)	NVIS Color	u_1'	v_1'	r	Cd/m^2 (fL)	NVIS Color
Primary	.088	.543	.037	0.343 (0.1)	Green A						.088	.543	.037	0.343 (0.1)	Green A					
Secondary	.088	.543	.037	0.343 (0.1)	Green A						.088	.543	.037	0.343 (0.1)	Green A					
Illuminated Controls	.088	.543	.037	0.343 (0.1)	Green A						.088	.543	.037	0.343 (0.1)	Green A					
Compartment lighting	.088	.543	.037	0.343 (0.1)	Green A			Same			.088	.543	.037	0.343 (0.1)	Green A			Same		
Utility, work, and inspection	.088	.543	.037	0.343 (0.1)	Green A			as			.088	.543	.037	0.343 (0.1)	Green A			as		
Caution and advisory signals	.088	.543	.037	0.343 (0.1)	Green A			Class A			.088	.543	.037	0.343 (0.1)	Green A			Class A		
Jump lights	.088	.543	.037	17.2 (5.0)	Green A						.088	.543	.037	17.2 (5.0)	Green A					
	.274	.622	.083	51.5 (15.0)	Yellow						.274	.622	.083	51.5 (15.0)	Yellow					
Special lighting components where increased display emphasis by highly saturared (mono-chromatic) color is necessary, or adequate display light readability cannot be achieved with "GREEN A"	.131	.623	.057	0.343 (0.1)	Green B						.131	.623	.057	0.1	Green B					
Warning signal	.274	.622	.083	51.5 (15.0)	Yellow	.274	.622	.083	51.5 (15.0)	Yellow	.274	.622	.083	51.5 (15.0)	Yellow	.274	.622	.083	51.5 (15.0)	Yellow
						.450	.550	.060	51.5 (15.0)	Red						.450	.550	.060	51.5 (15.)	Red
Master Caution signal	.274	.622	.083	51.5 (15.0)	Yellow	Same as Class A					.274	.622	.083	51.5 (15.0)	Yellow	Same as Class A				

Note: u_1' and v_1' = 1976 UCS chromaticity coordinates of the center point of the specified color area; r = radius of the allowable circular area on the 1976 UCS chromaticity diagram for the specified color; fL = footLamberts; Cd/m^2 = candela/(meter)^2.

NVIS Radiance Requirements (from Table IX, MIL-L-85762-A)

	TYPE 1						TYPE II					
	Class A			Class B			Class A			Class B		
Lighting Components	Not Less than: (NR_A)	Not Greater than: (NR_A)	fL	Not less than: (NR_B)	Not Greater than: (NR_B)	fL	Not Less than: (NR_A)	Not Greater than: (NR_A)	fL	Not Less than: (NR_B)	Not Greater than: (NR_B)	fL
Primary	—	1.7×10^{-10}	0.1		Same as Class A (see Note)		—	1.7×10^{-10}	0.1		Same as Class A (see Note)	
Secondary	—	1.7×10^{-10}	0.1				—	1.7×10^{-10}	0.1			
Illuminated Controls	—	1.7×10^{-10}	0.1				—	1.7×10^{-10}	0.1			
Compartment	—	1.7×10^{-10}	0.1				—	1.7×10^{-10}	0.1			
Utility, work and inspection lights	—	1.7×10^{-10}	0.1				—	$1.7 - 10^{-10}$	0.1			
Caution and advisory lights	—	1.7×10^{-10}	0.1				—	$1.7 - 10^{-10}$	0.1			
Jump lights	1.7×10^{-8}	5.0×10^{-8}	5.0	1.6×10^{-8}	4.7×10^{-8}	5.0	—	5.0×10^{-8}	5.0	—	4.7×10^{-8}	5.0
Warning signal	5.0×10^{-8}	1.5×10^{-7}	15.0	4.7×10^{-8}	1.4×10^{-7}	15.0	—	1.5×10^{-7}	15.0	—	1.4×10^{-7}	15.0
Master Caution Signal	5.0×10^{-8}	1.5×10^{-7}	15.0	4.7×10^{-8}	1.4×10^{-7}	15.0	—	1.5×10^{-7}	15.0	—	1.4×10^{-7}	15.0
Emergency Exit Lighting	5.0×10^{-8}	1.5×10^{-7}	15.0	4.7×10^{-8}	1.4×10^{-7}	15.0	—	1.5×10^{-7}	15.0	—	1.4×10^{-7}	15.0

Electronic and electro-optical displays (monochromatic)		—	1.7×10^{-10}	0.5	—	1.6×10^{-10}	0.5	—	1.7×10^{-10}	0.5	—	1.6×10^{-10}	0.5
Electronic and electro-optical displays multicolor	White	—	2.3×10^{-9}	0.5	—	2.2×10^{-9}	0.5	—	2.3×10^{-9}	0.5	—	2.2×10^{-9}	0.5
	MAX	—	1.2×10^{-8}	0.5	—	1.1×10^{-8}	0.5	—	1.2×10^{-8}	0.5	—	1.1×10^{-8}	0.5
HUD systems		1.7×10^{-9}	5.1×10^{-9}	5.0	1.6×10^{-9}	4.7×10^{-9}	0.5	—	1.7×10^{-9}	5.0	—	1.6×10^{-9}	5.0

NR_A = NVIS radiance requirements for Class A equipment.
NR_B = NVIS radiance requirements for Class B equipment.
fL = footLamberts.

Note: For these lighting components, Class B equipment shall meet all Class A requirements of this specification. The relative NVIS response data for Class A equipment, $G_A(\lambda)$, shall be substituted for $G_B(\lambda)$ to calculate NVIS radiance.

external lights such as runway or shipboard lights. Often, exterior lights on military aircraft are extinguished to provide covertness. If exterior lights are required during NVG operations, they usually are in one of two categories:

- **Visible and NVG compatible** — such as electroluminescent formation lights which are green visible strips and are not degrading to pilots who are using NVG.
- **Invisible and NVG usable** — covert IR lights that provide illumination for the pilot using NVG or allow signaling or alerting to the pilot operating with NVG.

The cabin and cargo compartment interior lighting must be made NVG compatible if the aft crew uses NVG or if the cabin lighting is seen from the crew station. The cabin compartment in the HH-60Q "Medevac" helicopter requires white lighting for the medical personnel to attend to patients. The cabin has blackout curtains to protect the NVG compatibility of the crew station and to block any visual signature to the outside world.

7.3.11 Types of Filters/Lighting Sources

Aircraft lighting systems use various types of illuminating sources and lamps: incandescent, electroluminescent, fluorescent, light-emitting diode (LED), liquid crystal display (LCD), and cathode ray tube (CRT). Cockpit lighting can usually be modified by adding blue or blue-green glass filters. Glass filter companies and suppliers such as Schott, Corning, Wamco, Hoffman Engineering, and Kopp have produced usable filters. Usually, plastic filtering has not worked with incandescent sources since IR is transmitted freely, but Korry has developed a moldable plastic composition for NVG-compatible products. Manufacturers of filters, measurement equipment, exterior lighting (Grimes, Oxley, Luminescent Systems Inc., et al.) and interior lighting (Control Products Corp., Korry, Oppenheimer, IDD, Eaton, et al.) can be found through organizations involved in aircraft lighting such as ALI and SAE.

7.3.12 Evaluating Aircraft Lighting

A qualitative method of evaluating the NVG compatibility of the overall cockpit is available. The method is a field evaluation that should be conducted on a clear, moonless night with the aircraft parked in a secluded area away from disturbing light sources. A standard tri-bar resolution target board (e.g., USAF 1951), with patterns consisting of three horizontal and three vertical bar pairs arranged in decreasing size, is mounted in front of the aircraft. The resolution pattern is illuminated by the ambient starlight environment. The pilot (or observer) wears the NVG and views the resolution pattern while looking through the windshield. With all the aircraft/cockpit lighting extinguished, the pilot first determines the smallest resolvable line pair that is observed. Then, as each lighting zone or display is turned on, the pilot continues to report the smallest resolvable line pair. Lighting zones and displays are activated individually and then simultaneously. If the lighting and displays have no effect on the minimum resolvable pattern observed, then the cockpit is considered to be compatible with the NVG because there is no impact on goggle performance. Visually observed reflections from the lighting in the canopy or windshield can also be evaluated for NVG compatibility. Compatibility usually is demonstrated if the reflections are not apparent when viewed through the NVG.

7.3.13 Measurement Equipment

Laboratory measurements of the aircraft lighting components are obtained to quantify the following photometric and radiometric characteristics of the light output:

Luminance
Chromaticity
NVIS Radiance

Laboratory measurements use the guidelines of MIL-L-85762A to provide quantitative data to verify that the lighting components are NVG compatible. Units of radiometric measures are consistent with

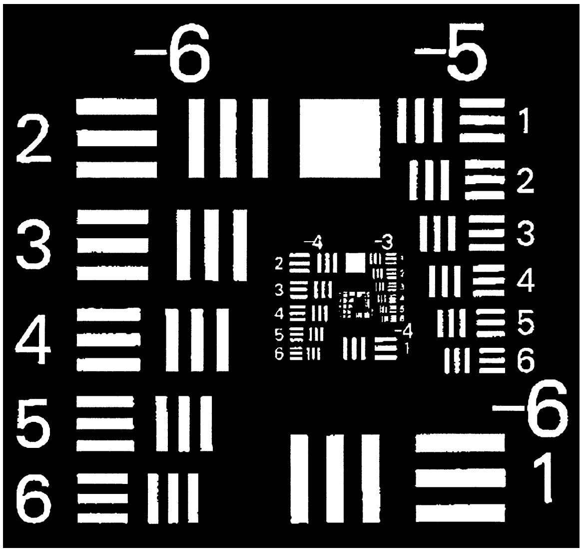

FIGURE 7.14 USAF 1951 Resolution Target.

terms in other electromagnetic radiant energy applications. The measurements based upon the visual eye response of the average human observer are termed photometric measurements. Luminance of lighted cockpit control panel and display presentation is frequently called "brightness." The color of the light is also necessary in defining the visual characteristic of the lighted presentations, and spectroradiometric measurements determine the chromaticity to quantitatively define the color. The typical chromaticity coordinates used are from the 1976 CIE UCS system.

Radiometric Term	Unit	Photometric Term	SI Unit	English Unit
Radiant flux	Watt	Luminous flux	Lumen	Lumen
Radiant	Watt/steradian	Luminous	Candela	Candela
Intensity	Watt/steradian/m^2	Intensity	Cd/m^2	FootLambert
Radiance	Watt/m^2	Luminance	Lux	Footcandle
Irradiance		Illuminance		

Radiant energy for the NVIS-weighted response is measured by a radiometer with very low energy sensitivity. The data is used to calculate the "NVIS Radiance" (as defined in MIL-L-85762) to determine the compatibility with the pilot's NVIS device. Some companies that manufacture photometric, radiometric, and spectroradiometric measurement equipment that can determine visual and NVIS characteristics are:

- Optronic Laboratories, Orlando, FL (http://www.olinet.com/)
- Photo Research, Chatsworth, CA (http://www.photoresearch.com/)
- Instrument Systems, Ottawa, Ontario (http://www.instrumentsystems.com/)
- Gamma Scientific, San Diego, CA (http://www.gamma-sci.com/)

7.3.14 Nighttime Illumination — Moon Phases

Flight planning requires knowledge of current weather conditions and the geography and topography along the route of the flight plan. For night flights when using NVG, night sky illumination, including the moon's phase and position at various times, is very important in planning the NVG flight. Astronomical data is available to determine times of sunrise, sunset, moonrise, moonset, and twilights. Data is also found for positions of the sun and moon, and on moon phase and illumination. The US Naval

Observatory offers a web version of the Multi-year Interactive Computer Almanac (MICA) on the Observatory's Astronomical Applications web site, *http://aa.usno.navy.mil/AA/*. A DOS or Mac version of the MICA Interactive Astronomical Almanac can also be ordered: NTIS Order No. PB93-500163, 5285 Port Royal Rd., Springfield, VA 22161.

7.3.15 NVG in Civil Aviation

NVG have application to civil aviation. The NVG enhances night VFR situation awareness and obstacle avoidance by allowing direct vision of the horizon, terrain, shadows, and other aircraft. The use of NVG does not require the operation to be covert. While NVG were primarily developed for military applications, NVG are being used in a variety of civilian situations requiring increased night viewing and safe night flying conditions. The forestry service uses NVG, not only to increase the safety in night fire-fighting operations, but also to find hot spots not readily seen by the unaided eye. Emergency Medical Services (EMS) helicopters utilize NVG for navigating into remote rescue sites. Civilian and commercial use of NVG in aircraft, land vehicles, and ships is growing.

The SAE G-10 Aerospace Behavioral Engineering Technology Committee, Vertical Flight Subcommittee, has been assessing human factors issues associated with NVG for application to civil aviation.

The SAE A-20 Aircraft Lighting Committee has prepared the following Aerospace Recommended Practices (ARP) documents to allow general aviation design guidance similar to military specifications and standards which defined NVG-compatible lighting:

ARP4168 — This SAE ARP recommends considerations for light sources for designing NVG-compatible lighting.

ARP4169 — This SAE ARP describes the functions and characteristics of NVG filters used in NVG compatible lighting.

ARP4967 — This SAE ARP covers design considerations for NVIS-compatible panels (also known as "integrally illuminated information panels" or "lightplates"). Panels may utilize incandescent, electroluminescent (EL), or light-emitting diode (LED) sources that are filtered to meet requirements specified in MIL-L-85762.

ARP4392 — This SAE ARP describes the recommended performance levels for NVIS-compatible aircraft exterior lighting equipment. Category I lights are compatible to be viewed by NVIS. Category II lights are illuminators to allow NVIS viewing of the surroundings. The "lights" may not be in the visible spectrum.

The FAA has conducted several studies and requested recommendations for civil application of NVG (Green[19–22]). The primary emerging philosophy for the incorporation of NVG into civil aviation is that "NVG do not enable flight". The use of NVG will not enable any mode of flight which cannot be flown visually within the framework of the existing regulatory authority.

Because civil aviation does not have the regimented control of pilots and aircraft as in the military, there is a danger to the public if untrained operators fly in ill-equipped, unregulated, and noncompatible aircraft. Therefore, minimum civil regulations and standards must be imposed. The future integration of NVG use in civil aviation will depend on the following key issues:

1. Limiting the I^2 device to Gen III;
2. Modification of cockpit lighting;
3. Modification of interior lighting;
4. Modification of exterior lighting;
5. Establishing training programs;
6. Updating FARs 61, 91, 135, et al.

Civil aviation should limit the Night Vision Device to Generation III ANVIS. The military experience has demonstrated that an NVG made for aviators is necessary. The third-generation sensor is preferred for starlight sensitivity. Gen II NVG with 625-nm minus-blue filters will work with MIL-L-85762A compatible lighting, but the filters reduce Gen II effectiveness. Without MIL-L-85762A lighting, the NVG Automatic Gain Control (AGC) can give a false sense of compatibility.

Cockpit lighting for civil aviation will have to be NVG compatible. All nighttime lighting requires NVG-compatible filtering. That normally includes control panel lightplates, numeric display read-outs, Warning/Caution/Advisory (W/C/A) legends, floodlights, flashlights, and electronic displays (CRTs, LCDs, LEDs). The MIL-L-85762A approach yields best compatibility results. An integral approach yields better lighting, although existing equipment can be modified with add-on bezels or filters. These add-ons can block viewing or reduce daylight readability.

Color coding of W/C/A legends (if red warning lights are utilized) and use of multicolor electronic displays (e.g., weather radar) must be limited to the use of Class B NVG with a 665-nm minus-blue filter.

Cabin and interior lighting for civil aviation will have to be NVG compatible. The cabin and cargo compartment interior lighting must be made NVG compatible, or else the compartment and lighting must be shielded from the cockpit. If the compartment is not isolated from the cockpit, then the passengers and crew must not operate carry-on lighting sources that are not NVG compatible. The carry-on equipment may include radios, television, computers, recorders, CD players, cellular phones, and flashlights. Also, smoking should be prohibited because smoking produces a noncompatible glow.

Exterior lighting for civil aviation will have to be NVG compatible. At present, NVG exterior lighting, including the ARP4392 exterior lighting, is not compliant with the Federal Aviation Regulations (FAR) for "see and be seen" navigation and anticollision lights necessary for civil aviation VFR flight. Invisible (covert) lighting will not be allowed as the only lighting for civil aviation. It will be necessary to develop and approve standards for exterior lighting which will be

- **Visible** (blue-green) to other aircraft VFR pilots not using NVG;
- **Visible and NVG compatible** (not degrading) to other aircraft VFR pilots who are using NVG; and
- **NVG compatible** (not degrading) to allow the pilot of the aircraft to operate with NVG.

New training systems will have to be established to support NVG use in civil aviation. Civilian pilots utilizing NVG will have to have minimum ground and flight training similar to that developed within the military. The basic ground training will include the theory of I^2 device, NVG limitations, NVG adjustments, nighttime moon and starlight illumination, FOV, and different visual scan and head motion techniques.

The FAA will have to establish certification and standards of NVG use in civil aviation. In order to allow NVG utilization in civil aviation, the FAA will have to modify regulations for pilot certification and ratings (FAR 61), equipment and flight rules (FAR 91), operating limitations (FAR 135), and airworthiness standards for various aircraft types (FAR 27, 29, etc.). Authority to operate with NVG may be documented through FAR, Special Federal Aviation Regulation (SFAR), Advisory Circular (AC), Type Certificate (TC), Supplemental Type Certificate (STC), Technical Standards Orders (TSO), Kinds of Operations List (KOL), and Proposed Master Minimum Equipment List (PMMEL).

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Further Information

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