Integrated Night Vision in Helmet-mounted Displays

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The primary function of the aircrew helmet is to protect the pilot. The advent of night vision devices and helmet mounted displays places additional constraints on the helmet, which is now an important element of the cockpit displays system, providing weapon aiming, and other information – such as aircraft attitude and status – to the pilot. The development of helmet-mounted displays (HMDs) for the military cockpit environment is therefore a demanding task if the operational benefits are to be realized without affecting pilot safety.

Night vision goggles (NVGs) are a primary means of providing enhanced vision at night for many rotary wing and fixed wing aircraft. The drive to introduce integrated helmet-mounted displays into service has resulted in the desire to combine the function of the NVG with that of the HMD.

In many applications this is achieved by adapting current in-service NVGs with the addition of a display device, such as a miniature cathode ray tube (CRT), to provide a display of symbology superimposed upon the night scene seen through the goggle.

Several integrated day/night helmet-mounted displays have been developed that provide additional capabilities, and also overcome some of the limitations inherent in the NVG-based solution. Many of these designs use the helmet visor as the display surface, whilst some utilize combiner eyepieces in front of the pilot's eyes. These systems provide wide field-of-view (FOV) displays that can be used in both day and night applications and include night vision sensors to provide the user with an enhanced view of the night scene.

Night Vision Goggles

Principle of Operation

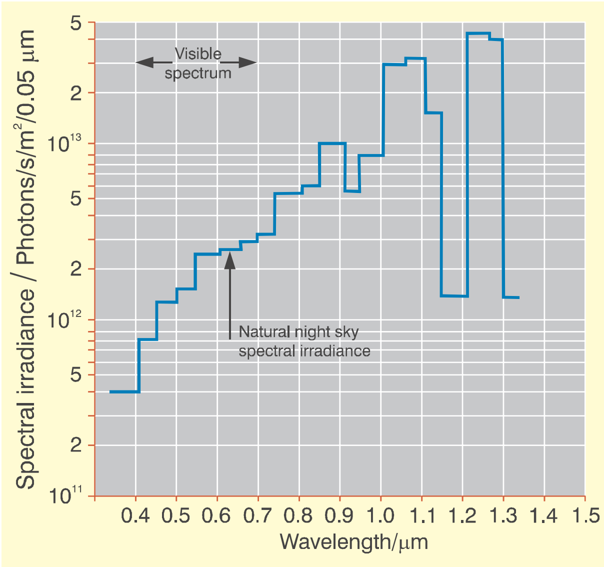
Night vision goggles use available red and infra-red (IR) light from sources such as the stars, moon and the night sky, intensified sufficiently to be presented to the eye as a visible image. All night vision goggles operate on the same basic principle and use image intensifier tubes (IIT) to produce a bright monochromatic (typically green) electro-optical image of the outside world in light conditions where the unaided eye can see little or nothing.

Glossary

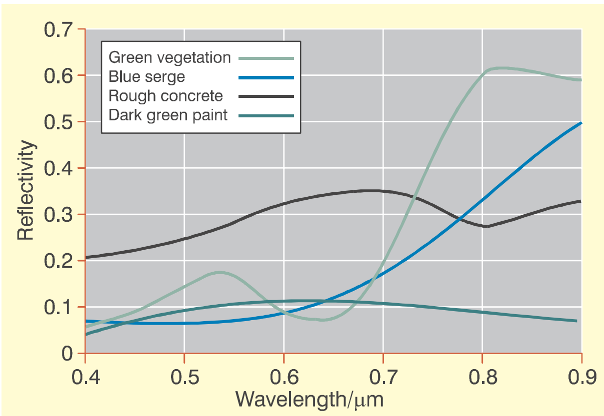
ANVIS	aviation night vision
CRT	cathode ray tube
FLIR	forward-looking infra-red
FOV	field of view
HMD	helmet-mounted device
HMDS	helmet-mounted display system
HUD	head-up display
IIT	image intensifier tube
NVG	night vision goggle
TI	thermal imager

The human visual perception system is optimized to operate in daytime illumination conditions. The visual spectrum extends from about 420nm to 700nm and the region of greatest sensitivity is near the peak wavelength of sunlight at around 550nm.

However, at night, far fewer visible light photons are available and only large, high-contrast objects are normally visible. Fine-detail and low-contrast objects are not resolvable by the human eye; its photoreceptors (rods and cones) must receive large numbers of visible light photons to register an image. Fig. 1 is a plot of the night sky spectral irradiance and this shows that the photon rate in the region from 800 - 900nm is five to seven times greater than in the visible region around 500nm. Fig. 2 plots reflectivity of various materials against wavelength. Note that reflectivities rise in the near IR and that for green vegetation reflectivity is four times higher between 800nm and 900nm than at 500nm. Therefore, at night, more light is available



1 Night spectral irradiance

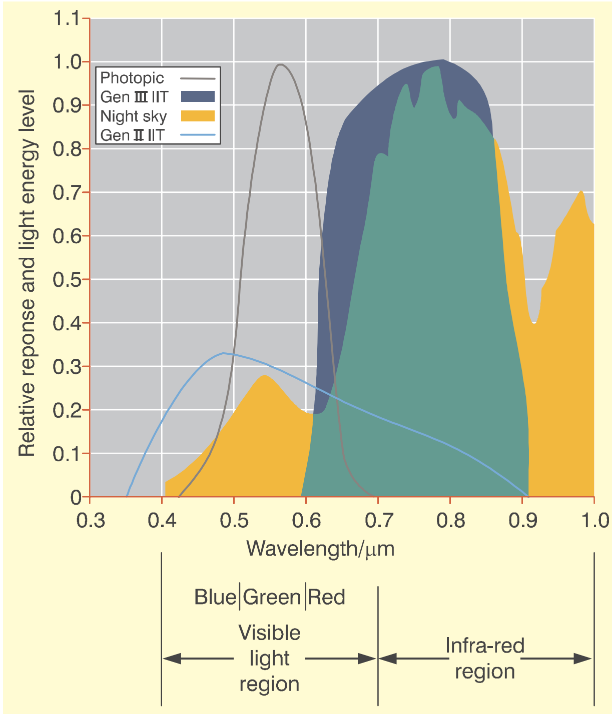


2 Reflectivity of various materials

in the near IR than in the visual band and that against certain backgrounds, notably green vegetation, more contrast is available.

Image intensifiers provide a means of taking advantage of this situation by effectively amplifying the available near IR light and presenting the user with an image that is sufficiently bright to be clearly visible without their being dark adapted (that is, scotopic).

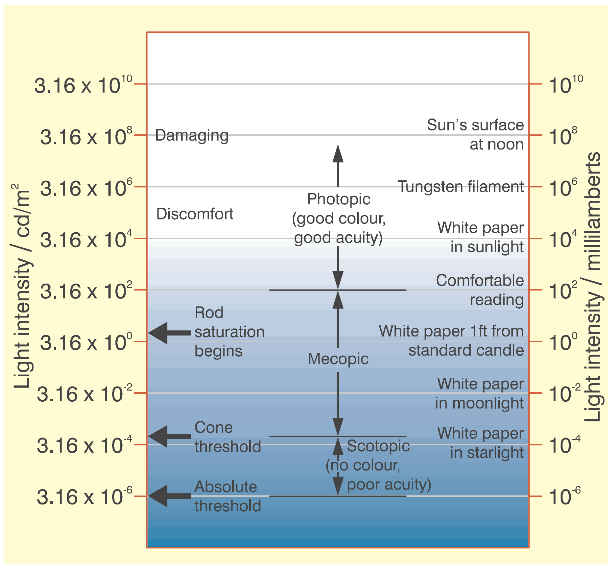
Third-generation (GEN 3) IITs are fitted with a gallium arsenide photo-cathode; this is most sensitive in the near IR and so makes maximum use of the available light and contrast information in the night scene. Fig. 3 shows the response of a typical GEN 3 image intensifier superimposed on night sky radiation spectrum. The output from the IIT is a phosphor screen that emits in the centre of the visual band, where the eye is most sensitive. The light intensity output of the IIT is mainly in the low photopic/mesopic area, that is, the user is not dark-adapted. Fig. 4 illustrates the scotopic, mesopic



3 Image intensifier tube (IIT) spectral response curves

and photopic intensity bands. Fig. 3 also shows the CIE photopic curve, which illustrates the spectral response of the human visual perception system. Also shown is the GEN 2 (second generation) IIT response.

Both second-generation and third-generation IITs are used in airborne applications. Third-generation devices have better sensitivity and resolution than second-generation devices and operate over a slightly different spectral range but are significantly more expensive than GEN 2 devices.



4 Light intensity bands

Night Vision Goggles Configuration

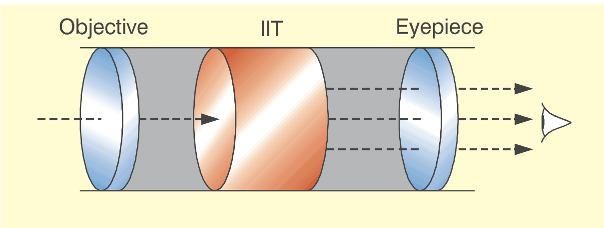
Night vision goggles were originally developed for ground-based applications and early airborne devices were derivatives of these systems. Many of these devices used a single second-generation image intensifier viewing the scene through a single objective lens. The output image is optically split and presented to each eye through two eyepieces. This bi-ocular approach was found to be unsuitable for the demanding airborne environment so airborne NVGs use two IITs to provide the pilot with a binocular view of the night scene.

These devices, for the most part, have a common configuration and their ancestry in ground-based systems is apparent. Typically, an airborne NVG comprises two monocular assemblies mounted on a bracket that is attached to the front of the pilot's flying helmet. The bracket provides the various adjustments required to align the monoculars correctly with the pilot's eyes, and also provides the interface that allows goggles simply to be clipped onto the pilot's flying helmet.

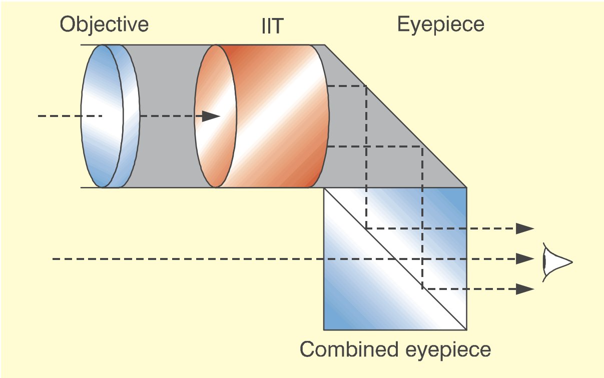
An important feature is that the power for the goggle is normally provided by batteries located either within the bracket or mounted remotely on the rear of the helmet. This means that NVG operation is completely independent of aircraft power.

Each monocular assembly has an objective lens that collects the available IR light from the outside world and focuses it onto the IIT input window (fig. 5). The objective lens also normally contains a 'minus blue' filter for compatibility with blue/green cockpit lighting. The electro-optical image is then relayed to the pilot's eye by an eyepiece assembly. Conventionally, these components are mounted directly in line with the pilot's line-of-sight (fig. 6), but can normally also be flipped up out of the way if necessary. Marconi Avionics 'Cat's Eyes' NVG provides a see-through eyepiece that combines IIT imagery with the real-world scene, providing improved view of cockpit instruments and the HUD.

NVGs are now in widespread use in a multitude of applications, including rotary wing, fast jet, transport aircraft, and ground-based applications. Fig. 7 illustrates Marconi Avionics' conventional



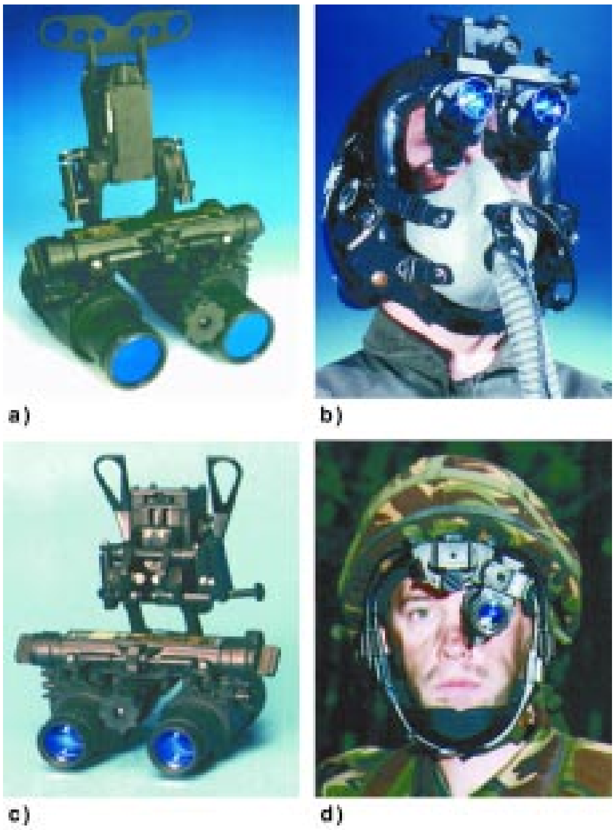
5 *NVG monocular configuration*



6 *Combiner eyepiece NVG*

NVG products that have been produced in large quantities and are all still in production.

Of key importance is the continual evolutionary increase in performance and capabilities in NVGs, resulting mostly from improvements in the performance of image intensifier tubes. Better resolution, enhanced performance at low light levels and improved signal-to-noise ratio make the capabilities provided by NVGs an essential element of airborne night vision systems. New NVG configurations are also being developed, such as the 'Night Viper', visor-projected ejection-



7 Marconi Avionics NVGs

8 *'Night Viper' ejection-safe visor-projected NVG*

safe integrated night vision helmet (fig. 8), which is in development, offering improved performance with better helmet integration. NVGs are now a mature technology and provide very major benefits in night operations.

Why Integrated HMDs?

Ever since aircrews began flying with night vision goggles in the early 1980s, the value of display-capable helmets has been recognized, leading to the development of helmet-mounted display systems (HMDS) offering a range of capabilities for both fixed-wing and rotary-wing aircraft.

Information Display

Combat experience has shown the need to provide the aircrew with information on aircraft attitude and status that is integrated with the night scene. This is normally displayed as a non-conformal (head-stabilized) symbology overlaid on the NVG image.

Weapon Aiming

Targeting and weapon-aiming applications require the appropriate symbology and also knowledge of where the user is looking both to position symbology on the display and also to steer missile seeker, gun or sensor. Symbology in this case can be as simple as an aiming reticle but a dynamic display of conformal (or real-world stabilized) symbology provides a more flexible solution.

Navigation and Target Acquisition

This application requires a conformal display of navigation data and aircraft status information combined with a display of target (or multiple targets) symbology. This application requires a dynamic display that is normally provided by miniature cathode ray tubes (CRT), but other technologies are now becoming available.

Multi-Sensor Night Vision

Image intensifier tubes rely on ambient light to function. NVG performance is therefore degraded in conditions where ambient illumination is very low, or where there is poor contrast from the outside world scene in the near IR part of the spectrum. Hence there is a need to provide imagery from another sensor operating in a different part of the spectrum – a thermal imager (TI), for example. Conversely, in adverse thermal conditions the image quality from a TI is degraded, hence the need for multiple sensors.

Pilot Safety & Comfort

A further concern is the nature of NVGs as a clip-on accessory to existing flying helmets. In general, most current helmets were not initially designed for such applications and have been adapted to facilitate the fitting of NVGs. In many cases this combination induces pilot fatigue resulting from increased head-supported mass and poor centre of gravity. Pilot safety can also be compromised, particularly during ejection from fast jets or in crash situations in rotary-wing applications.

Cost-Effective Increase in Capability to Satisfy Operational Need.

Helmet displays broadly offer a capability in either day-only, or in 24-hour mission scenarios. The 24-hour capable systems display imagery from an associated night sensor such as forward-looking infra-red (FLIR) or image intensifier devices. Such systems naturally offer greater advantages over day-only HMDs or night vision goggles alone.

A helmet display is a most cost-effective method of upgrading an existing cockpit design, requiring little modification to the aircraft or cockpit structure in return for a significant improvement in mission effectiveness, failure survival capability and adaptability.

Integrating Helmet-mounted Displays with Night Vision Devices

The two main approaches to combining the NVG function and head mounted display are:

- optical image combination of IIT and CRT images, and
- electronic image combination using electrical output image intensifier or night vision devices

The former is currently the most widely-used technique for combining imagery from IITs and displays in head-mounted applications. This technique is used in products that simply add a display function to existing NVGs (such as the Tracor AN/AVS-7 NVG HUD) and also in more advanced integrated designs such as Marconi Avionics' 'Knighthelm' HMD.

Electronic image combination, although not new, is now becoming a practical solution for many applications and significant development activity is now focused on developing high-performance night vision cameras for use with HMDs.

Optical Image Combination

This technique involves optically combining the output of a helmet-mounted CRT or other display device with the output of the image intensifier tube at a single intermediate image plane. There are several design trades to be made in selecting the characteristics of the image combination optics, but these are dictated by the nature of the application. IITs have a low output luminance whilst CRTs are capable of a very wide luminance range. Therefore, a key characteristic is the transmission ratio of the display channel luminance and IIT channel luminance.

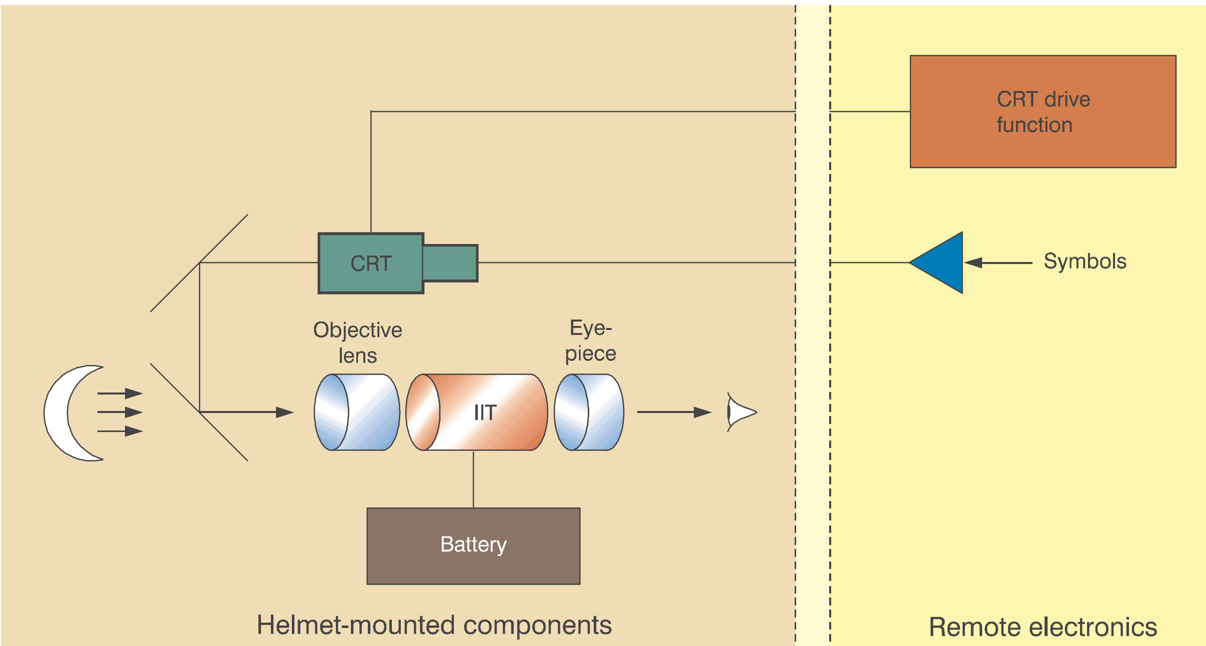
The following paragraphs describe three example systems that each use optical image combination:

AN/AVS-7 NVG HUD

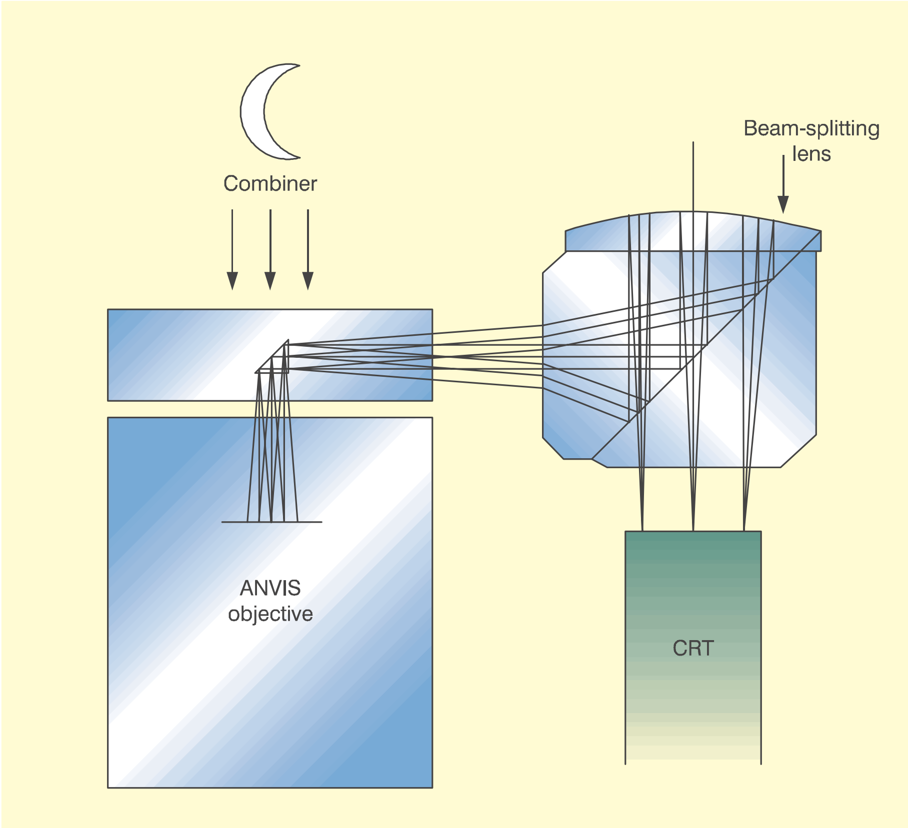
Several mishaps have been recorded when operating with NVGs in helicopters. In some types of terrain, such as undulating desert, the number of visual cues available to the pilot is reduced, or non-existent, in conditions where workload is such that there is little time to look down at cockpit instruments. This has resulted in pilots misjudging altitude and closure rates, leading to several accidents. The addition of symbology providing flight information, whilst still allowing the pilot to remain head-up, greatly improves this situation.

The Tracor [Marconi North America] NVG HUD injects a display into the standard ANVIS NVG that is seen by the user as part of the outside world scene viewed by the image intensifier. Symbology is overlaid on the NVG view of the outside world, providing the information necessary to fly the aircraft, plus additional symbology selected by the user. A block diagram illustrating the basic configuration of the NVG HUD is shown in fig. 9.

The NVG HUD uses a high-resolution 0.5 inch diameter (12.5mm) CRT to provide the symbology display. The CRT output is collimated and injected



9 *NVG HUD block diagram*



10 ***AN/AVS-7 NVG HUD optical image combination***

into the objective lens of the NVG (fig. 10). Both the symbology and the scene energy are focused onto the photocathode of the IIT by the NVG objective lens. The CRT brightness is controlled to be suitable for direct combination with the outside world scene on the photo-cathode of the IIT. The image viewed by the user is therefore a single collimated image of the symbology and the intensified night scene.

The CRT drive electronics, symbology generation and aircraft data interfaces are all housed remotely from the helmet (see fig. 11). An important feature of this approach is that the NVG operation is independent of the display function. The battery-powered goggle will therefore continue to function normally, should the display system fail.

The clip-on nature of the standard ANVIS-6 NVG is retained, albeit with the additional weight and attendant centre of gravity shift associated with the addition of the CRT and image combination optic. A key point to note is that the symbology display in this type of system is not conformal with the outside world scene, as viewed through the NVG. This could be achieved, however, by the addition of a helmet-tracking function providing helmet line-of-sight information to the graphics generator.

ANVIS E-HUD

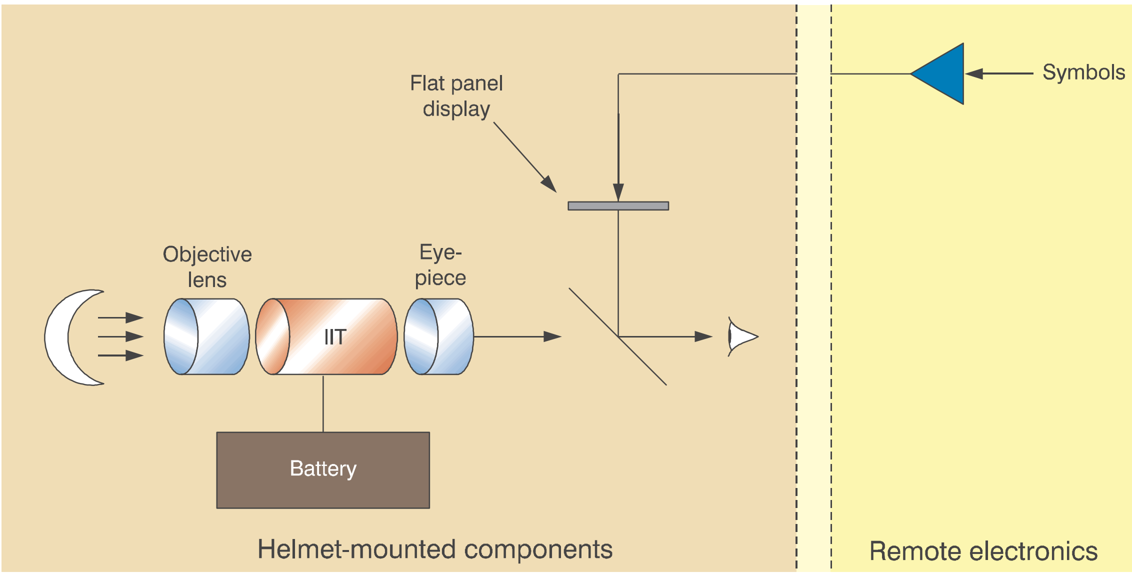
The Tracor [Marconi North America] ANVIS E-HUD also injects a display into a standard NVG but, in this case, the optical image combination takes place within the eyepiece of the NVG – that is, after the IIT has amplified the night scene. This approach provides advantages over the front injection system described above:

- The E-HUD is capable of displaying colour (amber) symbology over the green NVG scene for improved contrast against the background.
- E-HUD symbology can be displayed when the NVGs are off, or in very low light conditions.
- Reduced symbology washout when ambient light levels are increasing.

The E-HUD was initially designed with a CRT display but this has now been replaced by a miniature flat-panel device, an Active Matrix Electro-Luminescent display (AMEL). A simplified block diagram of the E-HUD is given in fig. 12.

The AMEL output is combined with the IIT output image at the beam combiner and is presented to the user as a single collimated image of symbology

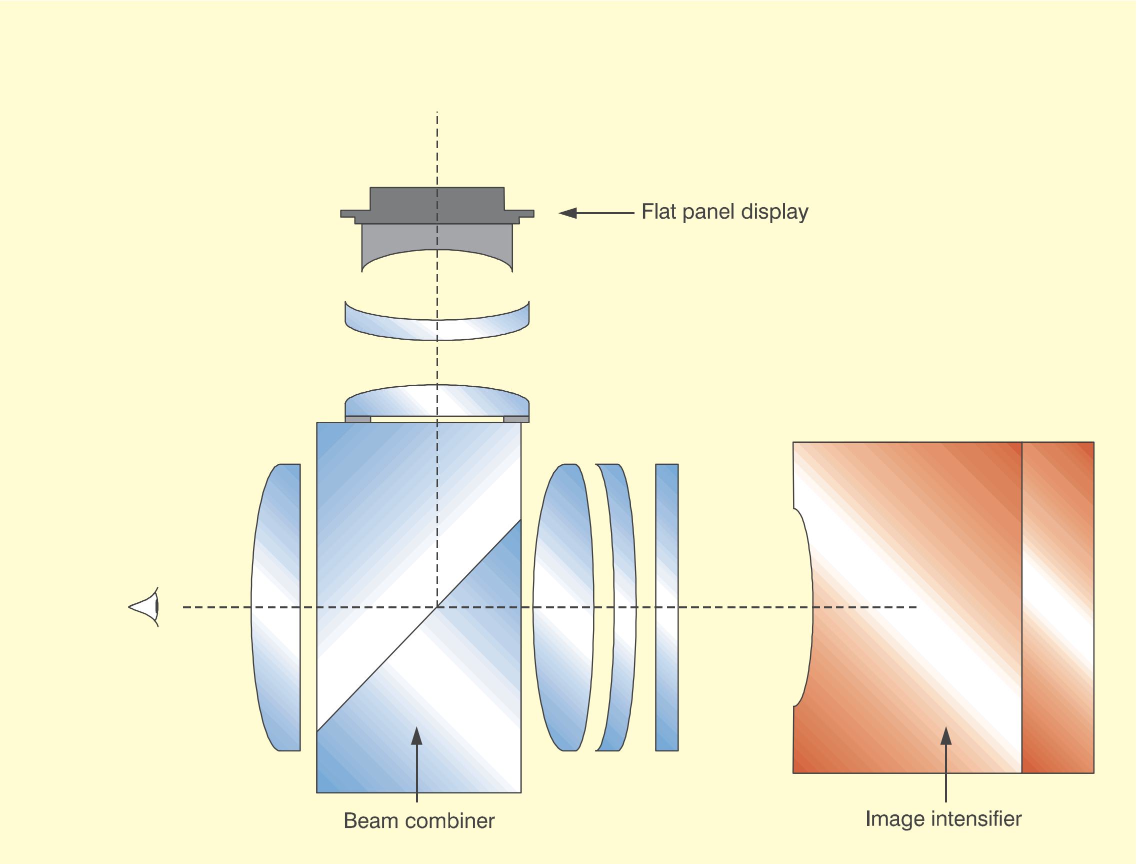
11 ***AN/AVS-7 NVG HUD fitted to a flying helmet***



12 ***E- HUD block diagram***

and night scene (see fig. 13). The display brightness is controlled to be suitable for combination with the intensified outside world scene on the output window of the IIT. The image viewed by the user is therefore a single collimated image of the symbology and the intensified night scene.

The clip-on nature of the standard NVG is also retained and the additional weight and attendant centre of gravity shift associated with the addition of the display is greatly reduced, compared with the CRT variant. Also, the compact nature of the display injection into the eyepiece allows a 25mm eye relief to be maintained and allows the modified eyepiece to be easily interchanged with a standard eyepiece. Fig. 14 is a photograph of the E-HUD fitted to a standard NVG.



13 ***E- HUD optical image combination***

14 ***E- HUD fitted to standard NVG***

Knighthelm Integrated Helmet-mounted Display

The NVG HUD exploits and enhances the utility and availability of existing NVGs but is currently limited to providing an information display. Also the weight and centre of gravity of the head-mounted components can be fatiguing and compromises safety in some applications. A more integrated approach is required to combine advantages of NVGs with a display function to provide a true 24-hour operational capability. This is essential where a second sensor – such as FLIR – is to be displayed and when the system is required to operate in day (symbology only) and night (multi-sensor night vision and symbology).

The 'Knighthelm' HMD has been developed to provide the user with a display that can be used in both day and night conditions during a single mission without the need to reconfigure the HMD. Key features of the design are:

- binocular display integrated with a lightweight purpose-designed flying helmet;
- dual sensor display capability: image intensifier tube or thermal imager with ability to switch instantly between image sources as required;
- symbology display overlaid on real-world scene or sensor image; and
- operation in both day and night flying conditions.

The principle of the Knighthelm HMD optical system is illustrated in fig. 15. In this approach the image intensifier output is optically combined with the CRT imagery in such a way that IIT imagery transmission is maximized whilst retaining a daylight compatible CRT display of symbology and FLIR imagery. A relay lens then routes the combined image to the combiner eyepiece where it is viewed by the user as a collimated image superimposed on the normal line of sight. This approach exploits all of the performance available from current GEN 3 IITs to provide excellent night vision with symbology overlay. The display has a 1:1 correspondence with the real-world scene.

A significant benefit of this approach is that the IITs may be powered either from aircraft power or from a small helmet-mounted battery pack providing night vision independently of aircraft power. The CRT may also be used to display FLIR imagery from a head-steered FLIR, providing a true multi-sensor capability within one optical system.

In designing optics for HMDs, optical performance is only one of several design criteria. Lowest possible mass is achieved by minimizing the number of optical components, by using plastic elements where possible, and by the use of advanced lightweight materials. Durability is essential and has involved careful design of the mechanical structure to maintain the structural integrity of the optical system under mechanical and thermal stresses.

The resultant Knighthelm HMD (shown in fig. 16) has now completed an extensive flight-test programme that has demonstrated a high level of performance, both in day and night missions. The optical combination of symbology with the IIT imagery has greatly enhanced the mission effectiveness compared with existing in-service NVGs; and the ability to switch instantly between the head-steered FLIR and the intensifier image gives the system a very high level of operational availability in all conditions, day or night.

Electronic Image Combination

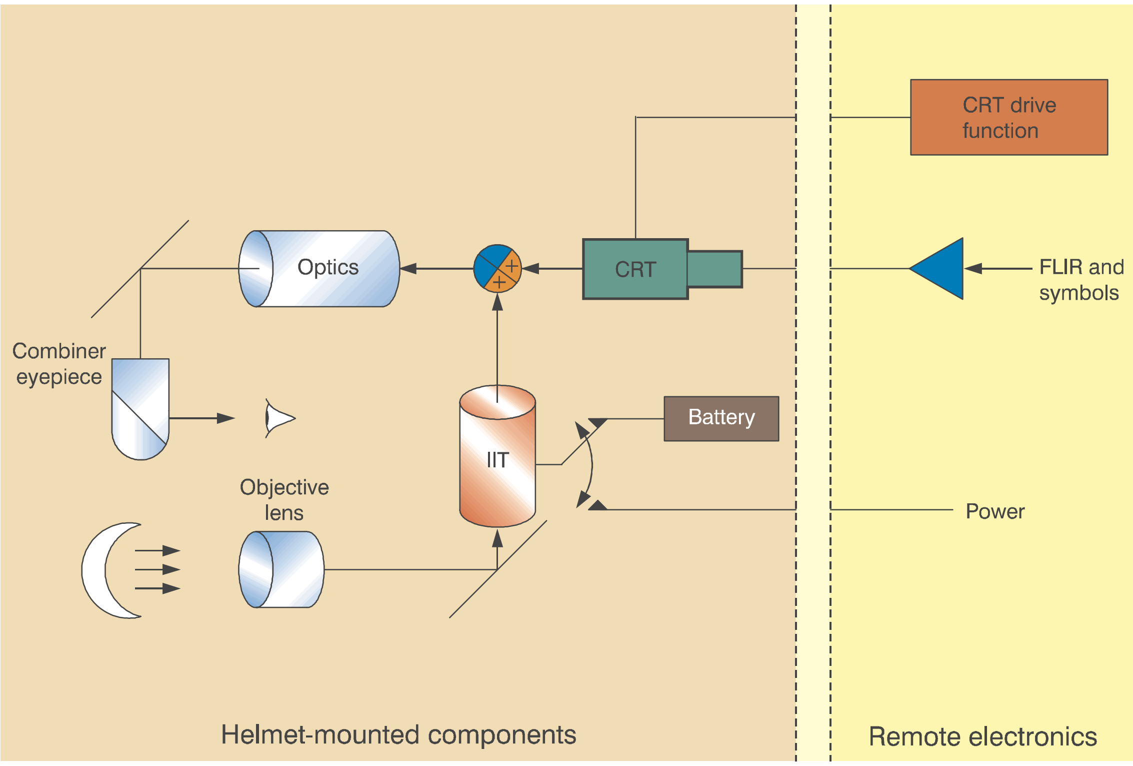
The principle of electronic image combination is illustrated in fig. 17. In this approach, enhanced night vision is provided by a miniature helmet-mounted night vision camera. This is typically an image-intensified CCD camera, although other techniques are in development.

The output of this is a video signal that is fed back to the remote display drive electronics where it is electronically combined with the symbology and displayed on the helmet-mounted CRTs in the normal way. The advantage of this approach is that it maximizes the performance of the CRT display by removing the need to mix IIT and CRT imagery optically. This also reduces head-supported mass and bulk, which are critical in fast jet applications and in small cockpits.

Although this approach still utilizes image intensifier technology the intensified imagery is now presented in a raster format, allowing the potential to enhance the night vision image, improving image contrast and reducing some of the unsatisfactory characteristics of directly-viewed IITs such as image blooming.

Using the example of the featureless desert terrain, the ability to enhance the image contrast electronically allows the user to see undulations in the terrain not visible using conventional NVGs. Similarly, a bright point source of light viewed by a conventional NVG results in a halo effect that blots out the surrounding scene. This effect can be eliminated, allowing the user to view clearly a scene containing bright sources of light, such as street lights.

However, the performance of current night vision cameras in terms of resolution is inherently



15 ***Optical mixing of IIT and CRT imagery***

16 ***The 'Knighthelm' 24-hour HMD***

lower than that provided by the best NVGs. This is largely a function of the conversion of the optical image into a video signal for presentation on the helmet-mounted CRT display. Night vision camera resolution performance, therefore, has to be considered in the context of complete system performance – that is, from camera through to CRT on the HMD – as there are many non-linear factors that affect performance.

In summary these are:

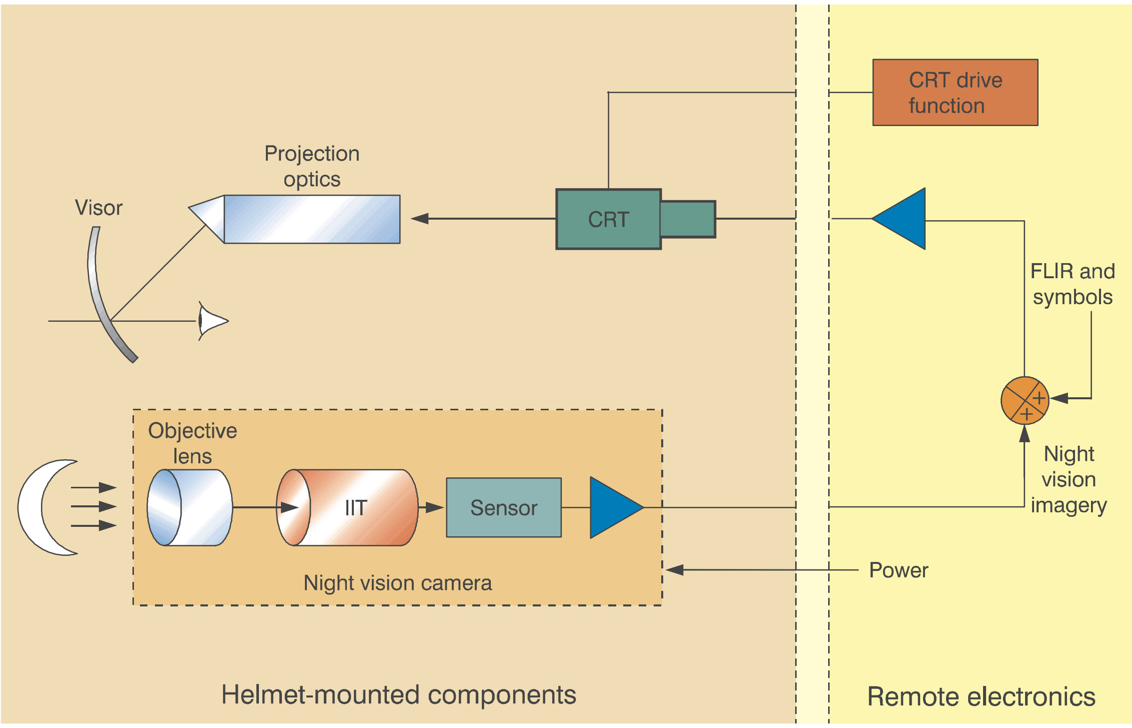
- image intensifier resolution vs. light levels,
- sensor (typically a CCD) resolution,
- display system video processing, and
- CRT resolution.

The following table is a summary that trades these factors against resolution performance:

TABLE 1

Factors Affecting Resolution Performance

Factor	Affected by	Effect
Intensifier resolution	Scene illumination	System resolution decreases as scene gets darker
Sensor resolution	Number of sensor pixels	Number of pixels limits maximum system resolution
Display system video processing	Display electronics bandwidth, cable losses, etc.	Inadequate electronics reduces system resolution
CRT resolution	CRT bandwidth	Inadequate CRT resolution reduces system resolution



17 *Electronic combination of IIT and CRT*

Scene illumination levels must also be taken into consideration when evaluating typical system operating performance. Peak resolution is achieved when intensifiers are illuminated with scenes brighter than many typical mission scenarios. As the scene illumination reduces to clouded moonlight, for example, system resolution will have significantly reduced because of the drop-off of resolution from the intensifier.

Developments now underway are solving these problems to provide very high performance night vision cameras. These, when combined with a high-performance HMD, provide the user with performance that matches existing in-service NVGs and has the potential to overcome some the limitations of the goggles.

Figs. 18,19 and 20 are illustrations of three HMDs that incorporate electronic image combination to provide night vision. These are all now under development within Marconi Avionics for both fast jet and rotary wing applications.

The 'Crusader' HMD is part of a technology development programme aimed at providing helmet solutions that can be applied into several fast jet and rotary wing applications. The variant illustrated provides a full day and night multi-sensor binocular display of symbology overlaid on sensor imagery from dual helmet-mounted night vision cameras, or from an external FLIR.

18 *'Crusader' binocular visor-projected helmet-mounted display*

The 'EF 2000' HMD is in full-scale development to meet requirements for day and night applications, combining the qualities of helmet cueing systems with the display of full flight symbology and multi-sensor imagery from FLIR and the on-helmet night vision cameras.

The 'Helicopter' HMD is in development for the AH-12 upgrade programme in the USA and will be used to provide very high quality night vision to the aircrew, combined with flight and weapon aiming symbology in both day and night missions.

19 ***'EF2000' binocular visor-projected helmet-mounted display***

20 ***'Helicopter' visor-projected helmet-mounted display***

Conclusion

Night vision goggles are now in widespread use in many airborne applications. They are a mature technology and offer significant operational benefits in night mission by providing the aircrew with greatly enhanced night vision. Their limitations are also well understood and this, combined with operational experience, has resulted in a drive to enhance NVGs by adding a display function. This paper has provided an overview of methods of achieving this using optical image combination techniques and has also discussed several practical implementations that are currently in service.

This paper has also discussed the extension of the basic concept into day and night integrated helmet displays combining the functions of the NVG with those of the HMD, using both optical and electronic image combination methods. Integrated helmet systems of this type offer a major increase in capability and mission effectiveness in all-weather 24-hour applications, which belies the relatively modest costs involved in installing HMD systems in aircraft. The technologies required to implement these products are either already available or are in an advanced stage of development.

Acknowledgements

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