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Review of night vision technology

INVITED PAPER

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Night vision based on technology of image intensifier tubes is the oldest electro-optical surveillance technology. However, it receives much less attention from international scientific community than thermal imagers or visible/NIR imagers due to series of reasons. This paper presents a review of a modern night vision technology and can help readers to understand sophisticated situation on the international night vision market.

Keywords: night vision technology, image intensifier tubes.

List of abbreviations

ANVIS	– aviator night vision imaging system (a term used commonly for binocular night vision goggles),
CCD	– charge couple device (a technology for constructing integrated circuits that use a movement of electrical charge by "shifting" signals between stages within the device one at a time),
CCTV	– close circuit television (type of visible/NIR cameras used for short range surveillance)
CMOS	– complementary metal-oxide-semiconductor (a technology that uses pairs of *p*-type and *n*-type metal oxide semiconductor field effect transistors for constructing image sensors
CRT	– cathode ray tube (a vacuum tube containing an electron gun and a phosphor screen used to generate images)
EMCCD	– electron multiplying charge coupled device
fc	– foot candela
fL	– foot lambert
ENVG	– enhanced night vision goggles
EBAPS	– electron bombarded active pixel sensor
FOM	– figure of merit
FOV	– field of view
HUD	– head-up display
ICCD	– intensified CCD (a technology that uses imaging modules achieved by combing image intensifier tube with CCD sensor)
IIT	– image intensifier tube
lp/mm	– line pair per millimeter
lp/mrad	– line per miliradian
MCP	– micro channel plate
MIL standard	– a United States defence standard, often called a military standard
NIR	– near infrared
NVD	– night vision device
NVG	– night vision goggles
RMS	– root mean square
SNR	– signal to noise ratio
SWIR	– short wave infrared
TFT LCD	– thin film transistor liquid crystal display.

1. Introduction

Humans achieve ability to see at night conditions by using several different imaging systems: night vision devices (image intensifier systems), thermal imagers, SWIR imagers, and some more sensitive visible/NIR (CCD/CMOS/ICCD/EMCCD) cameras. However, due to historical reasons, night vision technology is usually understood as night vision devices.

Night vision devices (NVDs) are apparently simple systems built from three main blocks: optical objective, image intensifier tube, and optical ocular (Fig. 1).

The task of the optical objective is to create low intensity, invisible image of the observed scenery at input plane of the image intensifier tube. The latter tube consisting of a photocathode, an anode in form of a phosphor screen, and other components, intensifies an input low-luminance image into a brighter image created on the anode (screen). The latter image is seen by human observer using the optical ocular.

Design of NVDs is apparently easy because crucial modules like image intensifier tube, optical objectives, optical oculars (eyepieces) are available on the market from dozen or more sources. However, in spite of this apparent design simplicity, the process of creating output image by these imaging systems is quite sophisticated. Many design rules must be well understood by manufacturers to deliver

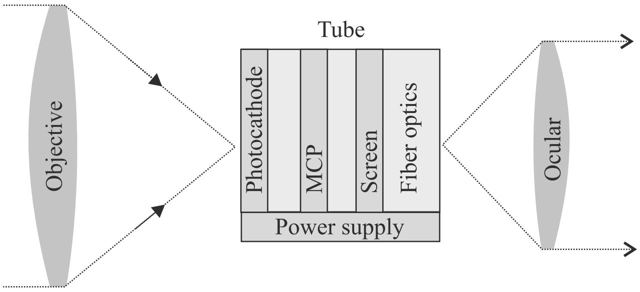

Fig. 1. Block diagram of night vision monocular.

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high performance NVDs. Every manufacturer of NVDs must carry out some kind of performance/cost optimization that requires deep knowledge of process of influence of different modules on quality of final image and functionality of final night vision device.

Night vision devices have a relatively long history in comparison to thermal imagers or visible/NIR cameras. First NVDs have been developed before the end of the Second World War [1] in situation when the first thermal imagers have been developed at the beginning of 1970s; and the first visible/NIR cameras based on modern solid state technology appeared on market in 1980s. However, NVDs have received much less attention from international scientific community than thermal imagers or visible/NIR cameras due to two reasons. First, technology of image intensifier tubes (crucial module of NVDs) has been developed mostly by big manufacturers, not by scientific institutes. The manufacturers have a natural unwillingness to free access publications in contrast to scientific institutes. Second, it was predicted many times that night vision technology will demise in near future due to competition from more modern surveillance imagers like thermal imagers, low light visible/NIR cameras (ICCD/EMCCD cameras), or more recently – SWIR imagers. Therefore, night vision technology has been treated by most scientists as rather old, unfashionable technology in the last several decades.

This low interest of scientific community in night vision technology resulted in a small number of specialist literature, a certain chaos in available literature, conflicting claims of superiority of different types of image intensifier tubes, marketing arguments promoted by different manufacturers and repeated by some scientists. Even specialists in night vision technology can have real problems with objective evaluation of modern night vision devices on the basis of available literature data.

This paper presents a review of modern night vision technology with aim to present a logical, consistent vision of this technology divided using a series of criteria. NVDs are classified in dependence on design configuration of NVD, type of image intensifier tube, type of night vision optics, targeted market, type of aviator NVD, and compatibility to aviation regulations. Short review of parameters and development trends of night vision technology are presented, as well.

2. Design configuration

There is no internationally accepted division of NVDs. The same types of NVDs can have different names in different literature sources. Here we will follow a division and a terminology used at websites of two big manufacturers of NVDs and divide modern night vision devices into four basic types [2,3]:

1. Night vision goggles;
2. Night vision monoculars;
3. Night vision sights;
4. Night vision binoculars.

Over 99% of NVDs offered on world market can be treated as equivalents of the models listed above and shown in Figs. 2–5.

(a)

(b)

Fig. 2. Night vision goggles: (a) binocular night vision goggles type AN/AVS–9 (ITT Night Vision [4]), and (b) monocular night vision goggles type BIG 25 (Vectronix AG [5]).

Fig. 3. Night vision monocular type Tarsius (Vectronix AG [5]).

Fig. 4. Night vision sight type Trident (ATN Corp. [2]).

(a)

(b)

Fig. 5. Night vision binoculars: (a) two-channel ATN Night Raven-2 binoculars (ATN Corp. [2]), and (b) single-channel Diana 3x binoculars (Optix Corp. [6]).

The first two groups of NVDs (goggles, monoculars) are basically devices of a wide field of view (FOV) similar to human vision (FOV about 40°, magnification equal to one). These NVDs can be treated as human eyes of improved sensitivity.

Binocular night vision goggles enable observation using two eyes to achieve stereo vision (three-dimensional (3D) vision). In other words, human using binocular night vision goggles can achieve perception of depth from two slightly different projections of the world onto the retinas of the two eyes. Binocular night vision goggles are typically used by pilots, drivers or other people who need a 3D-vision of surrounding scenery at night conditions.

Monocular night vision goggles can be treated as a cheaper version of the earlier discussed binocular night vision goggles. Two costly image intensifier tubes are replaced by one tube. A comfortable two-eye observation is still possible. Some depth perception is still achieved even during a single-channel observation.

In case of night vision monoculars the simplification process goes even further. The monoculars are practically one-channel binocular night vision goggles. Price is reduced by factor at least two in comparison to binocular night vision goggles. Additional advantage is small size and mass of these devices.

The last two groups of NVDs (sights, binoculars) are basically devices of narrow field of view (FOV from about 4° to about 13°, magnification from about 3 to about 10). These devices can be treated as human eyes of improved sensitivity equipped with magnifying optical scope.

Night vision sights (called also often night vision scopes) are generally monoculars of a narrow FOV that provide magnification of an image perceived by a human operator by a factor from 3 to 10. These devices are typically attachable to weapons.

Night vision binoculars are night vision goggles built by using bigger optical objectives of a longer focal length. The binoculars enable magnification of an image perceived by a human operator by a factor from 3 to 10 like typical day level binoculars. If built using two separate optical channels then the binoculars offer also stereoscopic vision.

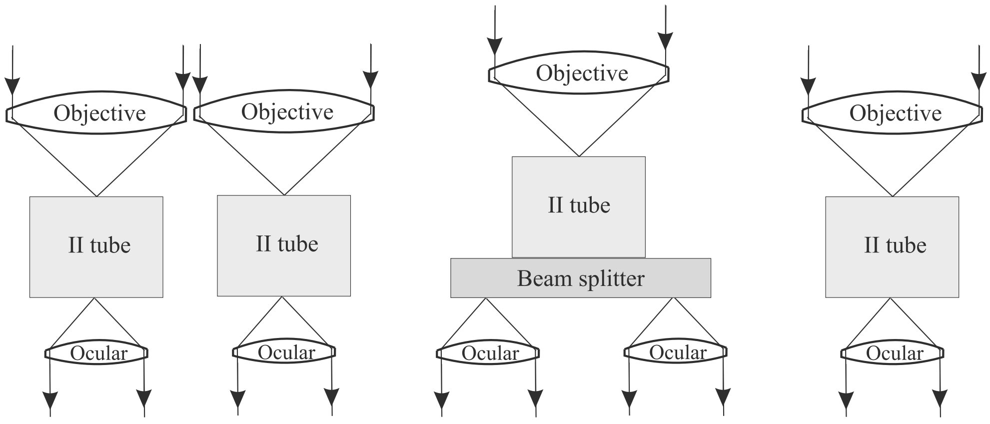
So far, we listed four different basic types of NVDs that look and work differently from final user point of view. However, night vision devices can be divided in different way taking into account their design. From the latter point of view differences between goggles and binoculars, and between monoculars and sights are small. The differences are caused only by one module; optical objective. Because of this minor technical difference, the borders between earlier discussed groups of NVDs are fluid. Night vision goggles can be easily converted to night vision binoculars if optical objectives are exchanged for bigger objectives of a longer focal length or some afocal adapters are added. Then, night vision monoculars can be converted into night vision sights by exchanging objective and by adding some mechanics that make possible to attach the monocular to weapons. There are many such NVDs on the market.

Therefore, from designer point of view, NVDs are divided into three basic types (Fig. 6):

1. Bino-channel NVDs;
2. Mixed channel NVD;
3. Mono-channel NVD.

Technical differences are significant between them and it is not possible to convert easily one type of NVDs to another types of NVDs. The latter division is based on more logical ground and presents deeper differences than the earlier discussed commercial division. However, the first division is more popular and should be remembered if someone wants to understand terminology used by manufacturers of NVDs.

So far NVDs have been divided using easily visually noticeable differences (number of objectives, number of oculars, size of objective, field of view). Now, let us discus more subtle, but also more important differences between different NVDs.



(a) (b) (c)

Fig. 6. Block diagrams of three types of night vision devices: (a) bino channel NVDs, (b) mixed-channel NVDs, and (c) mono channel NVDs.

3. Image intensifier tubes

Image intensifier tubes (IITs) are vacuum tubes that amplify a low light-level image to observable levels. The incoming light is converted into photoelectrons through a photocathode of the tube. Next, highly intensified photoelectrons strike the phosphor screen (anode) and a bright image is created that human can easily see.

Image intensifier tubes are the most important component of night vision devices and typical classification of night vision devices is based on a tube classification.

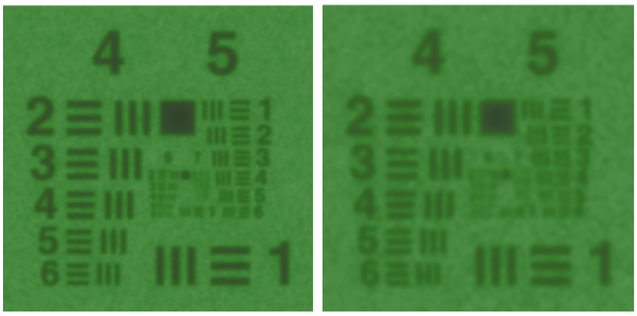
IITs are typically divided into several generations in dependence of the method to amplify incoming light (photocathode material, tube design structure) as the basic criterion. IITs can be also classified by using other criteria like type of input optics, type of output optics, phosphor screen, photocathode size, or tube performance.

Five parameters of IITs must be defined to enable precision discussion about division of these tubes:

1. Radiant sensitivity is a ratio of current induced into a photocathode (in mA units) of tested tubes by incoming light (in Watt units) for a specified wavelength.
2. Luminous sensitivity is a ratio of current induced into a photocathode (in μA units) of the tested tube by flux (in lumen units) of incoming polychromatic light of colour temperature equal to 2856 K.
3. Luminance gain is a ratio of luminance of output image (tube screen) to luminance of input image (tube photocathode). Measurement is done using light source of colour temperature equal to 2856 K. Luminance gain can be presented in several ways: in cd/lx¨·m^2 units (candela per lux times square meter), in lm/lm units (lumen per lumen), or in fL/fc (foot-lambert per foot candela). Image generated by a tube of low luminance gain looks darker than image generated by a tube of high luminance gain at the same input illuminance conditions.
4. Resolution is defined as a spatial frequency of a minimal 3-bar pattern of USAF 1951 target that can be resolved by an observer. Resolution is presented in lp/mm (line pairs per millimeter) units. Simulated images of USAF 1951 target of two tubes of different resolution at input illumination about 3 mlx generated using a Nightmet computer simulator program are shown in Fig. 7 [7]. Nowadays, resolution of typical IITs available on market is about 50–57 lp/mm; resolution of the best tubes can reach level of 81 lp/mm.
5. Signal to noise ratio (SNR) is a ratio of two components of a light signal emitted by a small part of a tube screen: average signal to root mean square signal (noise). The output signal is generated by illuminating a small part of photocathode (diameter 0.2 mm) at typical level of 108 μlx. Simulated images of USAF 1951 target of two tubes of different SNR at input illumination about 0.3 mlx obtained using Nightmet computer simulator program [7] are shown in Fig. 8. Nowadays, SNR of typical IITs available on market is about 18–22; SNR of the best tubes can reach level of 30.

3.1. Generations of image intensifier tubes

First night vision devices were developed during the Second World War [1]. The technology of image intensifier tubes has progressed very significantly since that time. This progress can be described using different divisions but the most



(a) (b)

Fig. 7. Magnified image of USAF 1951 resolution target generated by two tubes of different resolution: (a) tube of resolution 64 lp/mm and (b) tube of resolution 40.3 lp/mm (case of high input illumination).

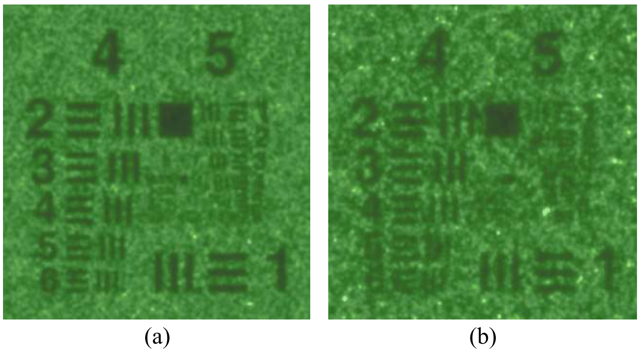

(a) (b)

Fig. 8. Magnified image of USAF 195,1 resolution target generated by two tubes of different SNR: (a) tube of SNR equal to 28 and (b) tube of SNR equal to 18 (case of low input illumination).

popular is division onto generations. US military has dictated the name of the generation of IITs over the last five decades. It should be however remembered that the division on generations is assumed in USA and presents US point of view on the night vision technology.

There are so far four enerations of image intensifier tubes: Gen 0, Gen 1, Gen 2, Gen 3 – at least according to the official US terminology. In general, generation numbering is related to significant changes in design of IITs that improve (with some exceptions) performance of these tubes.

As we see in Fig. 9, different generations of IITs use different photocathodes. There is a big positive difference between S–1 photocathode used by Gen 0 tubes and S–10 photocathode used by Gen 1 tubes. The positive difference between S–25 photocathode used by Gen 2 tubes and S–10 photocathode used by Gen 1 tubes is not so obvious. However, we must take into account that critical parameter of photocathodes of IITs – luminous sensitivity – is measured using light sources of 2856K colour temperature. This measurement method (simulating to some degree real applications) strongly favours photocathodes more sensitive in near infrared range – in this case S–25 photocathode. Finally, GaAs photocathodes used in Gen 3 tubes are again clearly more sensitive than S–25 photocathodes used in tubes of previous generation.

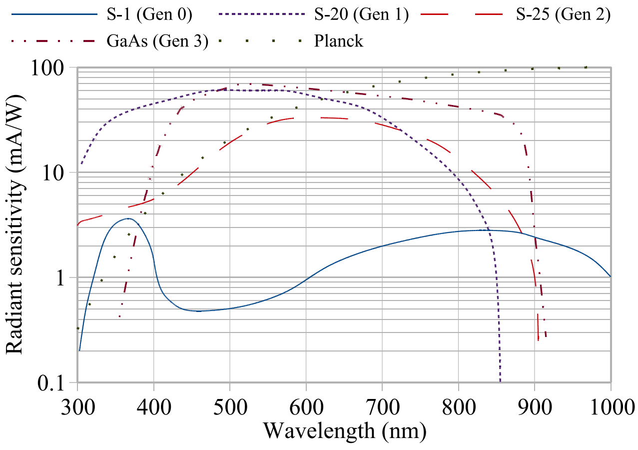


Fig. 9. Spectral sensitivity of typical photocathodes: S1(Gen 0), S–20 (Gen 1), S–25 (Gen 2), GaAs (Gen 3) and relative Planck curve.

It should be noted that radiant sensitivity of photocathodes type S1, S20, S25 and GaAs can vary significantly. The graphs presented in Fig. 9 refer to tubes considered as typical based on practical experience of author.

Differences between different generations of IITs are much deeper that the simple scheme shown in Fig. 9. Several more parameters should be considered in order to show important differences between tubes of different generations. Photocathode material is only one of these parameters. Next, the differences between different generations are not always clear. Further on, some of generations can be further divided into sub-generations. All these subtle details shall be now discussed.

Generation 0 refers to the technology developed during World War II, employing fragile, vacuum-enveloped image converters with poor sensitivity and little gain. These were single stage tubes that achieved image intensification due to acceleration by high voltage of electrons emitted by the photocathode and striking the phosphor screen. S–1 (silver-oxygen-caesium) photocathode, electrostatic inversion and electron acceleration were typically used to increase brightness of input image.

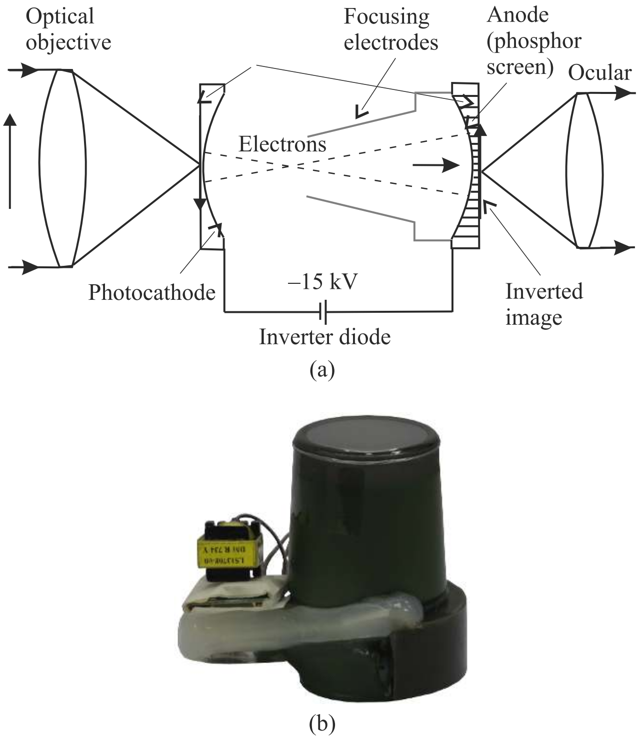
S–1 photocathode has two small peaks of its sensitivity: the first in ultraviolet (UV) and the second in near infrared (NIR) about 800 nm, but is characterized by low sensitivity at visible band (Fig. 9). This situation fits badly for a task to amplify brightness of input image created by nocturnal light characterized by negligible amount of UV light and high amount of visible light. Therefore, luminous sensitivity of S–1 photocathodes was not higher than about 60 μA/lm (microampere per lumen). Further on, luminance gain was no more than about 150 lm/lm. Such a low luminance gain is not sufficient to create a bright image of scene of interest at typical night conditions. Therefore, Gen 0 tubes were in the past used in active night vision systems cooperating with an IR illuminator. High power tungsten bulbs covered with an IR filter suppressing visible radiation were used as illuminators. Active character of use of these first night vision devices was their significant disadvantage.

Generation 1. First Gen 1 tubes were in general improved Gen 0 tubes. Initial experiments with new photocathode materials showed that S–11 photocathode (cesium-antimony) is characterized by an extremely high quantum efficiency up to 20%) but only in a visible range. Therefore, only slight improvement of luminous sensitivity to the level of 80 μA/lm was achieved using this new type of photocathodes because the value of luminous sensitivity depends more on tube sensitivity in near infrared band than on sensitivity in visible band.

The breakthrough came about 1956 with a discovery of S–20 photocathode (multialkali photocathode: sodium-potassium-antimony-cesium) that is sensitive in both visible and near infrared (Fig. 9). Significantly improved photocathode sensitivity (luminous sensitivity up to 200 μA/lm), and improved technique of electrostatic inversion and electron acceleration enabled to achieve luminance gain from about 400 lm/lm to about 800 lm/lm. Because of this quite high luminance gain some of Gen 1 NVDs were used as passive night vision systems, but majority of Gen 1 tubes was still used in active systems. The reason for using support of artificial infrared illuminators is the fact that much higher luminance gain in the order over 30 000 times is necessary to achieve ability to see even at medium illuminated (overcast quoter moon) night conditions.

First generation IITs are characterized by good image resolution (25–30 lp/mm), a wide dynamic range (the ability to reproduce the ratio between bright and dark parts of an image), low noise, and clear image with few blemishes. Due to earlier mentioned advantages and low production costs, Gen 1 tubes are still manufactured and NVDs built using Gen 1 tubes still dominate in commercial market. However, Gen 1 tubes are only very rarely used for military applications due to low luminance gain and significant distortion present in images generated by these tubes.

From technical point of view Gen 1 tubes are apparently simple devices. Focusing is achieved by using an electron lens to focus electrons, originating from the photocathode, onto the screen (Fig. 10). In the inverter diode tube presented in Fig. 10 an electrostatic field directs the photoelectrons and focuses an inverted image on the phosphor screen. Electron lens can be achieved by combining an electrostatical field with an axial magnetic field provided by either a solenoid or permanent magnet. A uniform magnetic field enables to achieve a good resolution over the entire screen and at the same time keeps distortion low. Fibre optics windows are used in Gen 1+ tubes to minimize degradation of the image resolution towards the edge of the tube. The fibre optics can potentially enable also efficient coupling to another image tube, to an imaging detector, or to photographic film.



(a)

(b)

Fig. 10. Gen 1 tube: (a) diagram of a NVD built using a Gen1 tube, and (b) photo of Gen 1 tube with external electronic power supply.

As it was earlier said, luminance gain of a single Gen 1 tube was still too low to enable design a truly passive NVDs. A simple solution to overcome this drawback was proposed in a form of a cascade tube built by combining two or three single tubes. The experiment carried out in 1950s showed that it is possible to design a cascade tube of luminance gain even over the level of 30 000 lm/lm capable to produce a usable image of scenery of interest even at starlight conditions. The first cascade tubes coupled using optical systems were too bulky (length up to about 40 cm) to be used in NVDs for military applications. However, introduction of fibre optics for coupling of image intensifier tubes enabled designing of much shorter cascade tubes that were used in big numbers in devices manufactured during Vietnam war in 1960s and partially also during 1970s.

Two other big drawbacks of the cascade tubes were low SNR and high cost of manufacturing. The first drawback means that output images were very noisy because the next stage of the tube amplified noise present in the image generated by the previous stage. The second drawback was caused by the necessity to use typically three single stage tubes to design a single cascade tube. Because of these three earlier discussed drawbacks the cascade tubes were quickly eliminated with advent of Gen 2 tubes in 1970s. Nowadays the cascade tubes are only rarely used in scientific applications.

Generation 2 image intensifier tubes represent a significant breakthrough in night vision technology. These are small, compact IITs that offered luminance gain at the level of about 30 000 lm/lm and the later even more. Such a significant increase of tube luminance gain, while making tube also smaller, was achieved due to four basic reasons.

First, Gen 2 tubes use microchannel plate (MCP) to amplify electrons emitted from photocathode (Fig. 11). The MCP is a very thin plate of conductive glass containing millions of small holes. An electron entering a channel strikes the wall and creates additional electrons, which in turn create more electrons (secondary electrons), again and again (Fig. 11). The microchannel plate is an array of miniature electron multipliers oriented parallel to one another and have length to diameter ratios between 40 and 100. Channel axes are typically normal to, or biased at a small angle (≈ 8°) to the MCP input surface. The channel matrix is usually fab-

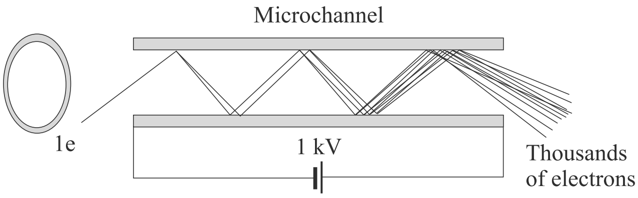


Fig. 11. Principle of work of a microchannel plate.

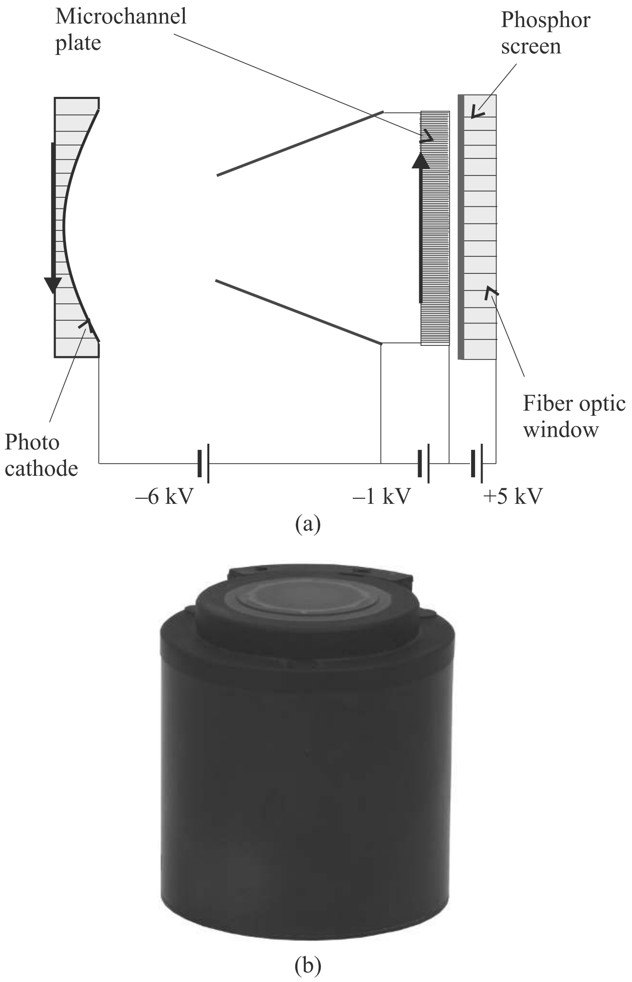
ricated from a lead glass, treated in such a way as to optimize the secondary emission characteristic of each microchannel and to render the channel walls semiconducting, so as to allow charge replenishment from an external voltage source. Parallel electrical contact to each channel is provided by the deposition of a metallic coating on the front and rear surfaces of the MCP, which then serve as input and output electrodes, respectively. The total resistance between electrodes is in the order of $10^9\ \Omega$. Such microchannel plates allow electron multiplication factors of 10^3–10^5 depending on channel length and number of layers. Spatial resolution is limited by channel dimensions and spacing; 12 μm diameter channels with 15 mm center-to-center spacings was typical for first and second generation tubes. Nowadays both dimensions and spacing can be about two times smaller.

Second, Gen 2 tubes use new S–25 photocathode. This is actually the same multialkali photocathode as S–20 photocathode used in Gen 1 tubes but S–25 photocathode is built using thicker layers of the same materials. In this way extended red response and reduced blue response was achieved making sensitivity spectrum of S–25 photocathode well matched to spectrum of nocturnal light. Luminous sensitivity of the first S–25 photocathodes was about 250 μA/lm. It is a noticeable improvement in comparison to S–20 photocathode used in Gen 1 tubes but almost negligible in comparison to revolution in luminance gain achieved by introduction of MCP plate.

Third, first Gen 2 tubes were inverter tubes that used an electrostatic inversion, in the same way as the Gen 1 tubes did, but with an added MCP (Fig. 12). The size of Gen 2 inverter tubes was only slightly lower than size of Gen 1 tubes. However, introduction of proximity focused tubes that could also carry out an image inversion using a fibre bundle with a 180 degree twist in it enabled the design of much smaller tubes (Fig. 13). Nowadays, almost all tubes used for night vision applications are proximity focused tubes.

Fourth, Gen 2 tubes were integrated with small electronic modules capable not only to power tubes using high voltage but also to carry out automatic gain control and bright spot protection. This new feature is a sharp contrast to a bulky external high voltage power supplies used by Gen 1 tubes (Fig. 10).

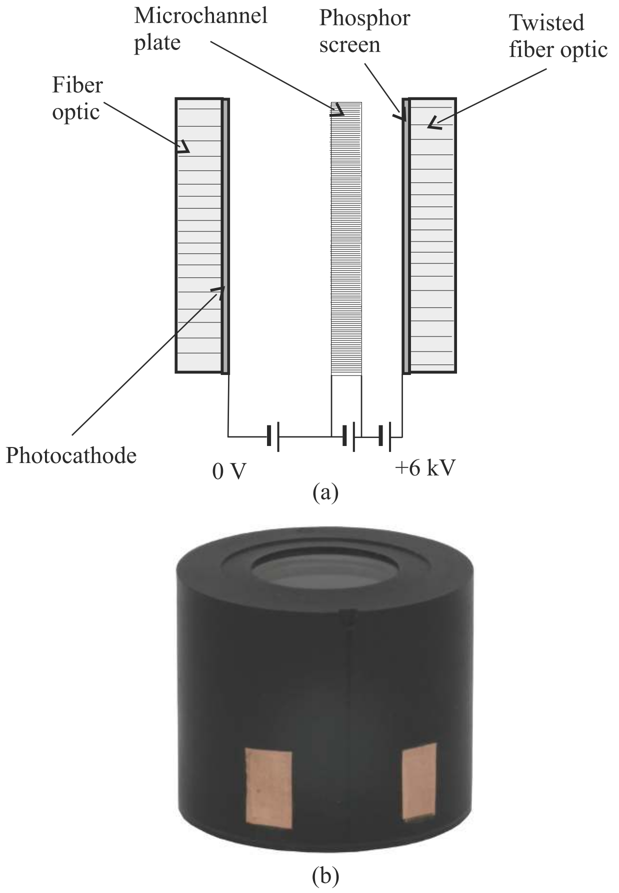
To summarize, Gen 2 tubes should be treated as a real revolution in image intensification technology. There is a big difference between Gen 2 tubes and Gen 1 tubes in situation when border between Gen 3 tubes and Gen 2 tubes is much more blurred, especially between Gen2+ tubes and Gen 3 tubes.



(a)

(b)

Fig. 12. Inverter Gen 2 tube: (a) diagram and (b) photo (tube dimensions Φ52.8×55.5 mm).



(a)

(b)

Fig. 13. Proximity focused Gen 2 tube: (a) tube diagram and (b) photo (tube size Φ35.5×31 mm).

Two plus generation (Gen 2+) is not formally recognized by U.S. authorities. This term refers to technologies used to improve sensitivity of the tri-alkali S–25 photocathodes and manufacturing new generation microchannel plates. In detail, photocathode sensitivity was improved more than two times, microchannel plates of highly increased open-area ration up to about 70%, and reduced internal noise were developed. These new technologies enabled to manufacture Gen 2+ tubes of expanded spectral sensitivity up to about 950 nm and of luminous sensitivity up to about 700 μA/lm. First Gen 2+ tubes were developed by Photonis company (France) in 1989. Further development of Gen 2+ tubes has been continued by several non-U.S. manufacturers in France, Netherlands, Russia, China, and India. Nowadays Gen 2+ tubes (marketed using different names like Gen II Plus, SuperGen, HyperGen, XD4, XR5) represent majority of hi-end image intensifier tubes manufactured by non-U.S. manufacturers.

Gen 3 tubes are very similar to the Gen 2 tubes from design point of view. The primary difference is the material used for the photocathodes. The second generation image intensifiers use photocathodes with a multialkali coating whereas the third generation image intensifiers uses photocatodes with a GaAs/GaAsP coating. The latter photocathodes are characterized by higher sensitivity and additionally the spectral sensitivity band is extended more in near infrared (Fig. 9).

Manufacturing of Gen 3 tubes was started in 1980s but some development works were done earlier in 1970s. Literature sources state that the photocathodes used in Gen 3 tubes are characterized by radiant sensitivity in the near infrared about three times better in comparison to photocathodes with a multialkali coating used by Gen 2 tubes (Fig. 14) [8].

Higher radiant sensitivity of Gen 3 tubes means higher luminous sensitivity. SNR is theoretically proportional to square root from luminous sensitivity. Therefore, the situation shown in Fig. 14 should theoretically guarantee SNR of Gen 3 tubes to be about two times better than for Gen 2 tubes. However, such a conclusion is typically not true due to two main reasons. First, radiant sensitivity of modern Gen 2+ tubes is much better than data shown in Fig. 14. Second, Gen 3 photocathodes have a significant drawback. These photocathodes can be quickly seriously degraded by positive ion poising that can reduce photocathode sensitivity up to about two times within a period about 100 hours. In order to protect the photocathode from positive ions and gases produced by the MCP, manufacturers of Gen 3 tubes have added a thin film of sintered aluminium oxide attached to entrance of the microchannel plate. This technique protects effectively photocathode but the protecting film traps about half of electrons emitted by the photocathode. These trapped electrons will not be amplified. Therefore, the effective luminous sensitivity of Gen 3 tube can be almost two times lower than photocathode luminous sensitivity of such a tube. The final result is that SNR of typical Gen 3 tubes is often comparable to good Gen 2+ tubes. The diagram presented in Fig. 15 explains graphically the earlier mentioned effect of reduction of effective sensitivity of Gen 3 tubes.

The protecting film generates also significant blurring that occurs when it is bombarded by a high intensity concentrated electron beam. Therefore, halo effect in Gen 3 tubes is typically significantly bigger than in Gen 2+ tubes (Fig. 16).

In 1998 the U.S. company Litton informed general public about the development of the filmless image intensifier tube built using the GaAs/GaAsP photocathodes [10]. Development of such tubes meant elimination of main drawback of Gen 3 tubes – the ion protecting film trapping electrons emitted by photocathode (Fig. 17). This new technological solution could potentially increase SNR of IITs at least over 25%. Therefore, the new tubes caused significant

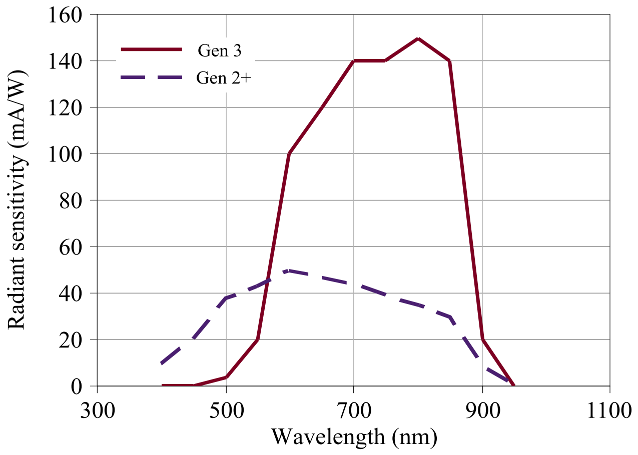


Fig. 14. Radiant sensitivity curves of Gen 2 tube photocathode (S–25 extended red multialcali) and Gen 3 tube (GaAs) photocathode (after Ref. 8).

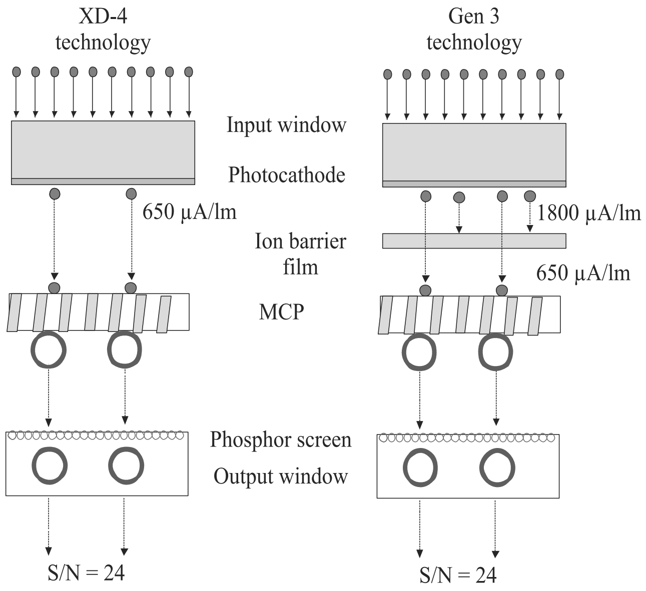


Fig. 15. Two tubes (Gen 2+ tube – XD–4 class and Gen 3 tube) of much different luminous sensitivity generating output image of the same signal to noise ratio (after Ref. 13).


(a) (b)

Fig. 16. Image generated by two night vision devices built using image intensifier tubes of different halo: (a) big halo, and (b) small halo (after Ref. 9).

interest of U.S. military authorities and Night Vision and Electronic Sensors Directorate (NVESD) assigned these new tubes as Gen 4 tubes. However, it was soon found that the new Gen 4 tubes are too fragile for real military conditions (sensitivity to mechanical shock) and additionally cannot pass typical reliability tests when the tubes are exposed to sudden uniform/concentrated flashes of light. Therefore, in 2002 NVESD revoked its previous decision designating filmless tubes as Gen 4 tubes. Since that time these new tubes are called as Gen 3 Filmless tubes and there is officially no Gen 4 tubes.

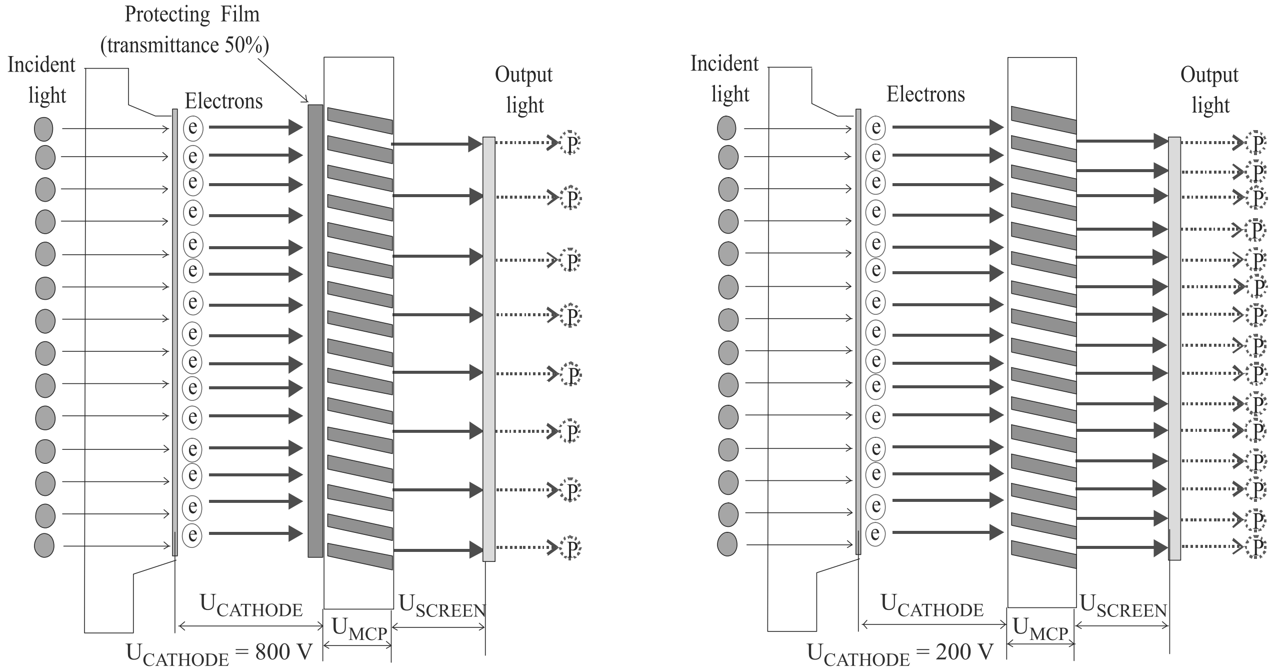
Despite of setback with reliability problems development of Gen 3 filmless tubes have been continued and brought significant technology improvements. Two techniques have been found to overcome the problem of photocathode poisoning. First, using of improved scrubbing techniques during manufacture of the microchannel plate that is the primary source of positive ions in a wafer tube. Second, using of autogating technique to power photocathode because a sufficient period of autogating causes positive ions to be ejected from the photocathode before they could cause poisoning of the photocathode [10].

Gen 3 Filmless tubes are characterized by excellent SNR (can be even over 30) and can produce clear image of scenery of interest even under very dark, moonless nights. Therefore, Gen 3 Filmless tubes are often used in night vision goggles for aviators or for special operation teams, but are avoided in night vision sights due to their vulnerability to mechanical shock.

Gen 3 Filmless tubes represent one group of significantly improved Gen 3 tubes. Gen 3 Thin Film tubes represent another group of improved Gen 3 tubes, and are often called Gen 3+ tubes.

Gen 3 Thin Film technology was developed by ITT Night Vision (the biggest U.S. manufacturer) as a response to competition from Gen 3 Filmless tubes offered by another U.S. manufacturer – Litton. ITT Night Vision found that by significantly thinning, rather than removing the protective film, it could achieve the army-mandated Gen 4 performance and end-of-life reliability requirements [12]. Maintaining the film also would protect all the important gallium arsenide photocathode structure. Therefore, Gen 3 Thin Film tubes use ion protecting ultrathin film of the thickness about 3 nm (typical situation) or sometimes as thin as 1 nm. Reduced voltage applied to photocathode is another but minor change in comparison to typical Gen 3 tubes.

Thin Film technology is not as effective as filmless technology in eliminating trapping of electrons emitted by photocathode. Up to 25% of electrons are still trapped by the



(a) (b)

Fig. 17. Graphical presentation of difference between Gen 3 tubes and Gen 4 tubes: (a) typical Gen 3 tubes, and (b) filmless Gen 4 tube (after Ref. 11).

thin protecting film. However, these losses are much lower than in case of typical Gen 3 tubes and Gen 3 Thin Film tubes offer very good SNR; almost as high as for Gen 3 Filmless tubes. At the same time Gen 3 Thin Film tubes are characterized by better reliability than Gen 3 Filmless tubes. Therefore, Gen 3 Thin Film tubes are nowadays the main group of hi-end image intensifier tubes used by U.S. military.

Short summary of basic features of different generations of IITs is shown in Table 1. It is clear that the generation number is a code that gives general description about technology that is used to manufacture the tubes. There are sub-classes within each of main generations depending on technology details.

The presented earlier division of image intensifier tubes into several generations is based on a manufacturing technology as the main criterion. As it was mentioned earlier there is no clear precision relationship between generation number and tube performance.

Gen 3 Filmless tubes and Gen 3 Thin Film tubes are two technologies that significantly improved performance of image intensifier tubes within last decade. Gating is the third less noticeable technology that improved performance of modern tubes.

Gating means a technique used to switch on and off image intensifier tube like an electronic gate. For several decades this technique has been used in gated image intensifiers used in high speed imaging systems to enable visualization of ultra fast temporal events (time intervals in nanoseconds or even picoseconds). More recently gated tubes have found application in active night vision systems that can potentially enable visualization of targets behind semi-transparent obstacles (including fog) and to measure distance to the target. However, both high speed gated night vision systems and active gated night vision systems are rather exotic types of night vision systems that are used rather rarely.

Auto-gating is a type of gating technique that has found mass application in modern image intensifier tubes. The experiments with this technique were carried out for a decade or more, but autogated tubes appeared on market about 2006 year. These tubes gate voltage applied to photocathode and MCP in order to keep constant current flowing through the MCP even when tube is strongly illuminated. The gating is done at very high frequency and is not noticeable on output image. Autogated tubes can be operated at much brighter conditions than typical tubes without damaging tubes or blurring output image. In other words, the autogated tubes are characterized by ultra extended dynamic that the tubes can generate clear image in both dark nights and twilight (or even day time) conditions.

In detail, resolution of typical tubes can drop several times when tube operates at day level illumination (from about 60 lp/mm to about 10–20 lp/mm). Resolution of autogated tubes drops at the same conditions no more than at about 20% (from about 60 lp/mm to about 50 lp/mm). Therefore, this new feature is of high value in military/security applications where illumination conditions can change very rapidly within several seconds and users of NVDs built using non-autogated tubes are blinded by sudden flashes of light or get blurred image at day conditions. At present, autogated tubes becomes increasingly popular in hi-end tubes for military applications. However, it should be noted that auto-gating technique can be used in both Gen 2+ tubes and Gen 3 tubes and the term "autogating" has no direct connection with a particular generation of image intensifier tubes.

3.2. Tube performance

There is a common view that higher generation number means a better tube. It is true if we compare Gen 0, Gen 1 or Gen 2 tubes but do not have to be true if we compare Gen 2 and Gen 3.

Main EU manufacturer of image intensifier tubes, Photonis, claims that generation numbering based on manufacturing technology introduced by U.S. laboratories cooperating with U.S. industry is misleading [13]. Therefore, Pho-

Table 1. Basic parameters of IITs from different generations.

Gen No.	Photocathode material	Photocathode sensitivity [μA/lm]	Design type	Luminance gain [lm/lm]	Resolution [lp/mm]	SNR
0	S1	< 60	inverter tube	< 200	20–60	–
1	S20	< 160	inverter tube	< 800	20–60	–
1+	S20	< 160	cascade inverter tube	< 20 000	20–30	5–8
2	S25	< 350	inverter MCP tube	< 50 000	24–43	12–17
2+	improved S25	< 700	proximity focus MCP tube	< 70 000	43–81	15–24
3	GaAs/GaAsP	< 1600	proximity focus MCP, tube with protecting film	< 70 00	36–64	18–25
3+ Thin Film	GaAs/GaAsP	< 1800	proximity focus MCP, thin film tubes	< 70 000	57–71	24–28
3 Film less	GaAs/GaAsP	< 2200	proximity focus MCP, filmless tubes	< 80 000	57–71	24–31

tonis (formerly also DEP) introduced its own generation numbering. The tubes are divided into four generations:

1. Gen II Plus®;
2. SuperGen®;
3. XD4®;
4. XR5®.

This division is based on tube performance characterized by two important parameters: resolution and SNR, or on the product of these two parameters called figure of merit (FOM). Typical values of resolution, SNR and FOM parameters used by Photonis to characterize mentioned above generations of image intensifier tubes are shown in Table 2 [13].

Table 2. Division of image intensifier tubes proposed by Photonis.

Generation code	Resolution [lp/mm]	SNR	FOM
Gen II Plus®	36	13	468
SuperGen®	51	21	1071
XD4®	64	23	1472
XR5®	72	28	2016

*Values of resolution and SNR are typical values from data sheets at Ref. 13.

The division of image intensifier tubes into several performance generations presented in Table 2 should be treated as a division used locally by only one of main manufacturers. However, the general concept to classify tubes into separate groups on the basis of values of two important parameters like resolution and SNR is quite popular.

U.S. Department of State guidelines for export of image intensifier tubes are nowadays based on FOM values. It is highly probable that the European Community (EU) authorities will follow this example and the old guidelines based mostly on photocathode luminous sensitivity will be revoked. A big advantage of FOM criterion is the fact that the FOM parameter of typical potted tubes can be measured without any damage to the tube in situation when measurement of luminous sensitivity is destructible to potted tubes.

Next, U.S. authorities generated division of image intensifier tubes into generation based on manufacturing technology as the main criterion. According to typical logic tubes of higher generation should be better than tubes of lower generation. Therefore, this official division discussed in Section has been used by U.S. manufacturers to promote U.S. made Gen 3 tubes against Gen 2+ tubes made almost exclusively by non-U.S. manufacturers. However, as it was shown earlier there is no clear precision relationship between generation number and tube performance. Therefore, even in USA, requirements for big purchase programs (coded Omnibus) carried out cyclically by US military have been based mostly not on manufacturing parameters but on performance parameters like resolution and SNR. Therefore, tubes manufactured by U.S. manufacturers are often divided into generations using requirements of Omnibus programs (up to Omnibus VII). Technical requirements on MX 10160 image intensifier tube purchased within Omnibus programs are presented in Table 3 [14]. As we see in this table performance of tubes of the same MX 10160 family purchased within different Omnibus program differ very significantly.

It was reported recently that contracts within new Omnibus program (OMNI VIII) were awarded [15]. However, technical details of OMNI VIII are not known and will not be discussed here.

To summarize, tube performance is not directly related to generation number. Situation when Gen 2+ tubes is better than Gen 3, or even to a lesser degree better than Gen 3+ is possible but inverse situation is equally probable. All tube manufacturers claim advantages of their tubes but often forget about drawbacks.

There are three technologies that are competing in market of hi-end tubes for ultra demanding military applications: improved Gen 2+ tubes (XR5 type or equivalents),

Table 3. Requirements on MX 10160 type image intensifier tube in Omnibus programs.

Contract	Omni I	Omni II	Omni III	Omni IV	Omni V	Omni VI	Omni VII
Resolution lp/mm	36	45	51	64	64	64	64
S/N	16.2	16.2	19	21	21	25	28
FOM	583	729	969	1344	1344	1600	1792
Photocathode sensitivity μA/lm@2856 K	1000	1000	1350	1800	1800	2000	2200
Gain [fL/fc]	20000–35000	40000–70000	40000–70000	40000–70000	40000–70000	50000–80000	50000–80000
MTF@2.5 lp/mm	0.83	0.83	0.9	0.92	0.92	0.92	0.92
MTF@7.5 lp/mm	0.58	0.6	0.7	0.8	0.8	0.8	0.8
MTF@15 lp/mm	0.28	0.38	0.45	0.61	0.61	0.61	0.61
MTF@25 lp/mm	0.08	0.18	0.2	0.38	0.38	0.38	0.38
Halo (mm)	1.47	1.47	1.47	1.25	1.25	0.90	0.70
Phosphor	P–20	P–20	P–20/P–43	P–43	P–43	P–43	P–43
Year	1982	1985	1990	1996	1999	2002	2006

Gen 3 Thin Film tubes, Gen 3 Filmless tubes. As we see in Table 4 each of these technologies has its strong points and weak points.

Table 4. Comparison of three competing technologies of hi-end IITs.

	Gen 2+	Gen 3 Thin Film	Gen 3 Filmless
Resolution	81 lp/mm	64 lp/mm	64 lp/mm
SNR	26	28	30
Reliability	15000 hours	15000 hours	10000 hours
Advantages	Very high resolution	High resolution, high SNR, high reliability	Very good SNR
Disadvantages	Medium SNR	No clear superior parameter	Modest reliability

*Attention: Values presented in the table refer to parameters of best tubes manufactured using compared technologies. Typical values are often lower.

As it was mentioned earlier the concept to characterize IITs using FOM criterion is becoming increasingly popular because FOM is directly related to tube performance. However, the readers should be warned that there is a significant drawback of this criterion: low accuracy of measurement of both resolution and SNR used to calculate FOM.

Low accuracy of measurement of resolution of IITs is caused by several factors: big steps (13%) between different resolution patterns of typical USAF 1951 resolution target used for resolution measurement, human subjective error, and influence of projection and observation system. It was reported by one of tube manufacturers that error of the measurement of resolution is often more than 10lp/mm [16]. In author opinion there are ways to minimize error of resolution measurement below mentioned above level, but still the error is noticeable.

Measurement error of SNR is often even bigger due to high technological challenges on light meters used for measurement procedure and slight differences between measurement procedures used by different manufacturers. The accuracy limits illuminance/luminance meters needed for SNR measurement are acknowledged by MIL standards that require only modest ±10% accuracy of such meters [17]. Due to these reasons differences between FOM values of the same tube measured by two test teams at the level of 20% are often met. Therefore, FOM values presented by different manufactures and measured by different teams using different apparatus should be treated cautiously. However, in spite of this limitation FOM criterion should still be treated as much better solution to characterize tube performance than generation number.

3.3. Tube input optics

Photocathode of image intensifier tube must be protected from direct contact with atmosphere by some kind of input optics. First proximity focus image intensifier tubes (most common type of Gen 2 and Gen 3 tubes) used fibre optics' tapers. The fibre taper was in direct contact with the photocathode and transmitted here an image created by the objective at input plane of the fibre taper (Fig. 18a). Nowadays tubes with input fibre optics are rarely met. Modern tubes are built using input glass optics (typical quartz, borosilicate glass, synthetic silica or rarely MgF_2). In the latter case the objective must create image at photocathode plane as shown in Fig. 18(b).

The difference between NVDs built using tubes having different input optics goes however much deeper than only difference in plane where the image is to be focused (typically about 5 mm difference). Two more important factors should be taken into account.

1. Fibre optics is characterized by almost two times worse transmission in comparison to transmission of input glass optics due to presence of dead areas in fibre tapers. The consequence is much lower luminous sensitivity of image intensifier tubes built using input fibre optics because photocathode of such tubes gets less photons than photocathode of a tube built using input glass optics at the same illumination conditions.
2. Size of fibre optics creates limit on maximal resolution of an image that can be transmitted.

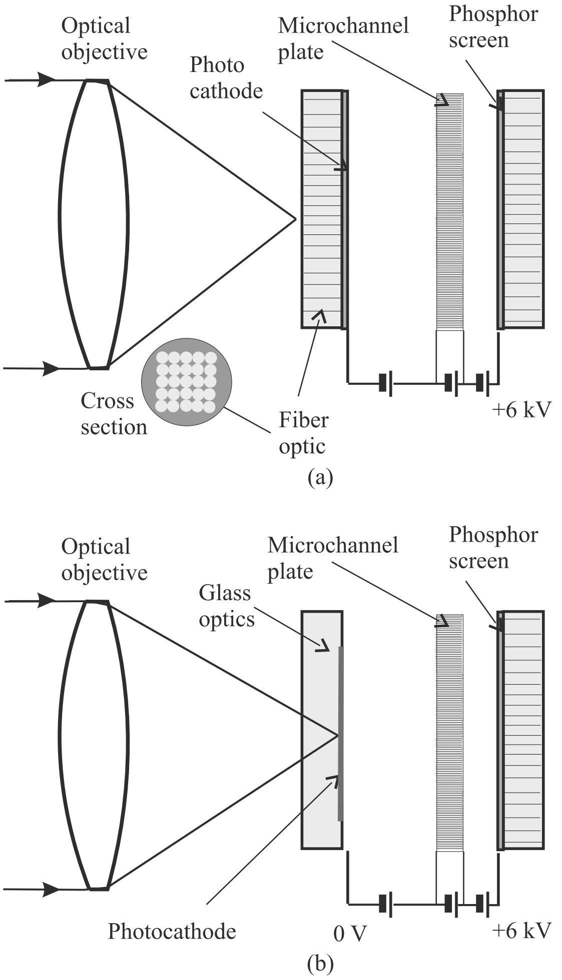


Fig. 18. Image creation process in NVDs: (a) case of a tube with input fibre optics, and (b) case of a tube with glass optics.

Because of these two discussed reasons the tubes built using input fibre optics are nowadays very rarely met and the tubes built using input glass optics are typically used in modern NVDs.

So far, only advantages of input glass optics were mentioned. It should be, however, also noticed that the tubes built using input glass optics create significant problems for designers of optical objectives for NVDs. The reason is a simple difference in location of image created by the objective (Fig. 18).

In case of NVDs built using tubes having fibre optics, the task of the objective is to create an image at input plane of the fibre optics plate. The fibre optics is as an external module not related to the optical objective.

In case of NVDs built using tubes having glass optics the task of the objective is to create an image at exit plane of the glass optics plate. Now, the glass optics becomes an internal part of the objective. Next, the glass optics distorts transmitted image and this distortion must be corrected by design of the objective.

The distortion added by the glass optics is particularly strong in case of ultra-bright objectives having low F-number (ratio of focal length to aperture). Therefore, design of aberration-free night vision objectives having F-number below one for NVD built using a tube with input glass optics is considered as a real challenge for optical designers.

Upgrading of old NVDs built using IITs having input fibre optics to modern devices built using tubes having input glass optics by simple tube replacement is usually not possible because of different requirements on optical objective. Replacement or modernization of an old optical objective is typically needed, as well.

3.4. Tube output optics

Tube output optics that covers phosphor screen of image intensifier tubes is needed for two reasons. First, to protect the screen from direct contact with atmosphere. Second, to invert image created by the screen. The latter function is needed in great majority of NVDs built using non-inverting oculars to prevent situation that the user will see inverted image of observed targets (Fig. 19).

There are two main types of output optics: glass optics and fibre optics. The tubes with output glass optics do not invert images but such tubes are cheaper than tubes with output fibre optics.

Low cost tubes with output glass optics (plate made from quartz, or borosilicate glass) are used in applications where image orientation is not important (like astronomy) or image created at tube screen is inverted using special inverting oculars or other optical systems.

More expensive tubes with output fibre optics are used in great majority of NVDs. Such tubes are offered in two versions: tubes with inverting fibre optics and tubes with straight fibre optics. The inverting fibre optics is used in tubes for most of NVDs. Tubes with straight fibre optics are rarely used in NVDs built using non typical optical systems (non-inverting objective or inverting ocular).

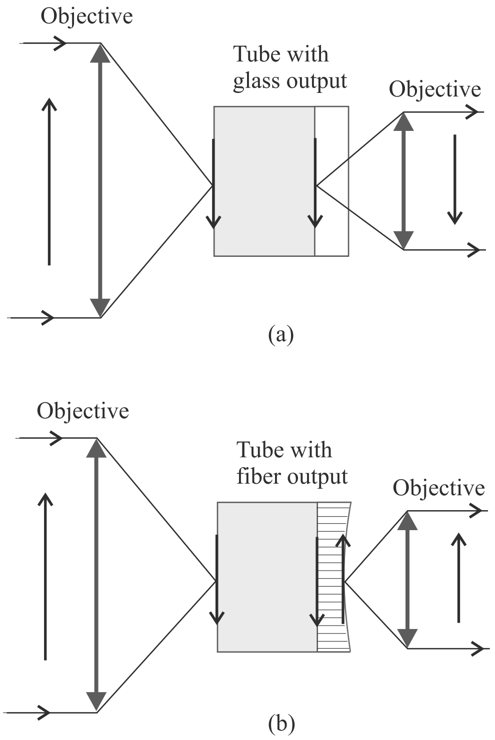


Fig. 19. Image inversion process: (a) NVD built using a tube with output glass optics, and (b) NVD built using a tube with output inverting fibre optics.

The output surface of the fibre optics is typically curved [(Fig. 19(b)]. The are two basic reasons to use such curved fibre tapers. First, it is easier to design aberration-free oculars for curved input plane than for flat input plane. Second, image of phosphor screen generated via curved fibre taper and seen by an ocular is more uniform for curved fibre tapers than in case of flat fibre tapers. In the latter case image of the centre looks significantly brighter than image of the outer sectors.

3.5. Phosphor screen

Phosphor screen is one of most important parts of an IIT. This part is used to convert the electrons, emitted by the photocathode and multiplied by the MCP incoming to the phosphor screen (the anode), into light, visible for human observer. The screen is typically a fibre optic plate coated with a phosphor and additionally coated with an external layer of aluminium. This layer of aluminium is needed as electrical contact to the phosphor layer using metal contact rings. The aluminium layer increases light efficiency up to almost 100% because light created by the phosphor is reflected back by the aluminium layer. The conductive aluminium layer reduces also the electrical charge from electrons and ions.

An electron acceleration energy of about 3 kV is required to pierce the aluminium layer. If this acceleration voltage is too high for a particular application then indium-tin-oxide (ITO) coated screens are used to provide the conductive base needed to minimize the electrostatic effects of charged particles [18].

Phosphors are made of rare earth oxides or halides (e.g., gadolinium, lanthanum, yttrium). Most phosphors are classified by using P letter and suitable number (from P1 to about P56). There are many known phosphors manufactured for cathode ray tubes (CRT tubes) that could be potentially used also for screens of IITs. However, two phosphors are used in majority of modern tubes: P20 and P43. There are also several other phosphors that are also used but much more rarely: P45, P46, and P47.

Table 5. Basic parameters of typical phosphors used in screens of IITs.

No	Phosphor type	Phosphor decay time (down to 1%)	Colour	Luminous efficiency
1	P20	60 ms	yellow-green	high
2	P43	3 ms	yellow-green	high
3	P45	5 ms	white	moderate
4	P46	3 μs	green	low
5	P47	0.4 μs	blue	very low

*P22 phosphor of similar parameters like P20 phosphor is also used.
**Parameters of phosphors depends on many factors. Data shown in Table 5 should be treated only as exemplary parameters.

There are four critical parameters of phosphors for image intensifier tubes: conversion factor, light spectrum (emitting colour), time decay, and resolution.

Typical conversion factors lie between 20 and 200 photons per electron, depending on the phosphor and the kinetic energy of the electrons, e.g., the acceleration voltage [19].

High conversion factor is not enough to guarantee that the screen shall produce a bright image perceived by human observer. The same number of photons can create totally different perception of brightness depending on wavelength of emitted light. Due to this reasons phosphors that emit light at green-yellow colour, where eye sensitivity is the highest, are preferred. Next, phosphors for image intensifier technology are typically evaluated using luminous efficiency as the evaluating criterion. The latter parameter is defined as a ratio of output luminance to number o input electrons.

Phosphor decay time is typically defined as time interval needed for phosphor screen to achieve low relative screen brightness (about 1%) from the moment when the input light is switched off. In case of tubes for night vision applications it is typically required that the phosphor decay time should be at least several times shorter than temporal inertia of human eye usually considered to be in 100–200 ms range. As we see in Table 5 there can be some doubts if P20 phosphor fulfils this criterion.

Resolution of phosphors, or in other words phosphor ability to create very fine images, depends mostly on median particle size. The latter parameter can vary from about 2 μm to about 12 μm. Bigger particles makes possible to built screens of higher conversion factor but phosphor resolution is reduced. In general manufacturers of image intensifier tubes try to keep resolution of the phosphor at the level about two times better than resolution of final image intensifier tubes. In practice it means that resolution of phosphor screen should be in the region from about 80 lp/mm to about 160 lp/mm.

Nowadays, image intensifier tubes built using P20/P43 phosphors dominate on market due to high luminous efficiency. Wavelength of maximal spectral emission of P43 (545 nm) nearly perfectly fits to maximal spectral sensitivity of human eye (555 nm) and high luminous efficiency this phosphor is the effect of this near perfect fit (Fig. 20). High spectral efficiency of P20 phosphor is a result of wide spectrum of P20 phosphor that almost fully overlap spectral sensitivity of human eye sensitive mostly in band from about 500 nm to 600 nm.

The P20 phosphor has been the preferred solution for several decades. However, it is also characterized by relatively long decay time that makes this phosphor less suitable for applications where short temporal inertia is important. Therefore, nowadays P43 phosphor is typically used in tubes targeted for airborne applications or other applications where night vision devices are supposed to be used for surveillance of dynamic phenomena.

P45 phosphor is a novelty in night vision technology introduced on the market by one of big manufacturers of IITs – Photonis – within the last several years. It is advertised that P45 phosphor makes images generated by image intensifier tubes more natural for humans who see targets at night in gray scale not in colours [13]. It is true that humans see images under dark conditions as monochromatic images of different gray level. Next, users of typical night vision goggles emitting greenish images see images in false colours for some time after goggles are removed from their eyes. The latter effect is eliminated when using goggles emitting black-white images.

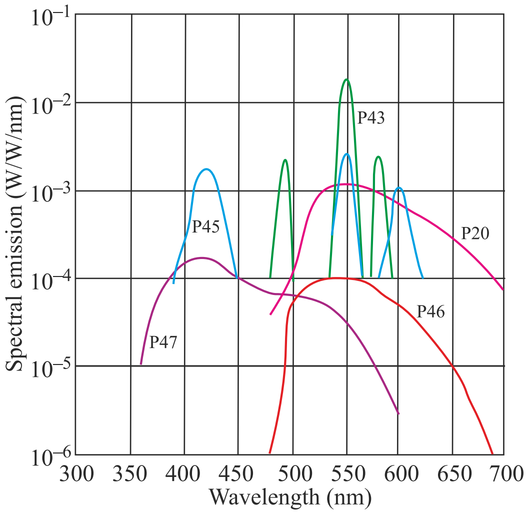


Fig. 20. Emission spectra of several phosphor screens (after Ref. 20).

However, in spite of advantages mentioned above, there are serious doubts whether P45 makes image intensifier tubes any better due to several reasons.

- Images generated by P45 screens look darker than images generated by typical P20/P43 screens for the same tube design due to lower luminous efficiency of P45 phosphor in comparison to typical P20/P43 phosphors. Therefore, luminance gain of tubes built using P45 screens is often almost two times lower than luminance gain of similar tubes built using P20/P43 screens.
- Tubes with P45 screens emit radiation at entire visible band including red/orange spectrum. Red/orange light sources are prohibited in airborne applications.
- Humans looking into greenish screens of IITs quickly adapt to mono-colour vision and start seeing in gray scale like during naked eye vision at night conditions.
- Human observes are less tired when looking on tubes that generate green-yellow images in comparison to tubes generating white-black images. The latter effect is because light spectrum of P20/P43 tubes better fits to eye spectral sensitivity curve than light spectrum of P45 tubes.
- It is easier to design optical oculars optimized for narrow spectral band of P43/P20 phosphors than for much wider spectral band of P45 phosphor.

Because of the reasons mentioned above the black-white images should not be treated as an advantage over classical green-yellow images. Inverse conclusion is more reasonable. Probability that P20/P43 screens in IITs shall be replaced in near future by P45 tubes is rather low. The same can be said about P46/P47 phosphors that are mostly used in some scientific applications where short temporal inertia of phosphor screen is crucial but are rarely used in main stream technology of night vision.

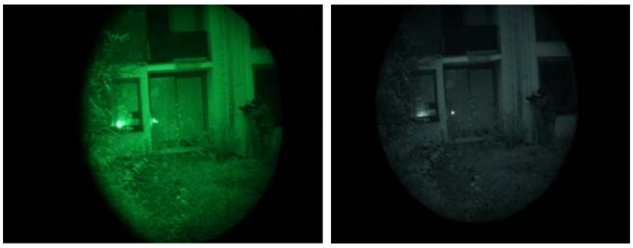

(a) (b)

Fig. 21. Images of the same scene generated by two tubes with different phosphor: (a) typical XR5 tubes with P43 phosphor, and (b) Onyx tube with P45 phosphor (after Ref. 21).

3.6. Photocathode diameter

All types of IITs are also differentiated by the nominal useful diameter of the photocathode. Typical diameter values are 18 mm, more rarely 25 mm. Tubes of bigger sizes are used sometimes in scientific applications.

However, recently a new 16 mm image intensifier tube was introduced by one of main manufacturers of IITs in order meet new requirements for reduced size, weight, and minimal power consumption [13].

The weight of the 16 mm tube has been reduced by 35 grams compared to standard ANVIS 18 mm tube while its volume size has been reduced by 40%. The 16 mm tube is available with an integrated auto-gated power supply [13].

The size difference in comparison to typical 18 mm tube mm tubes is not big. Therefore, the performance differences between new 16 mm tubes and typical 18 mm tubes are not big, too. It is risky to predict if the new size is accepted by other night vision manufacturers and if 16 mm tube becomes a new standard for applications where size and weight are of crucial importance. However, some manufacturers of NVDs have already started production of ultra-weight night vision monoculars using these new ultra small tubes [22]. Therefore, it can be rather expected that most manufacturers of IITs will soon offer these new miniaturized 16 mm tubes.

4. Optics of NVDs

Image intensifier tube is rightly considered as the most important module of night vision devices. Because of this unquestionable importance of the tubes there is a tendency to decrease design complexity of optical modules of NVDs and influence of optical modules on overall performance of NVDs.

4.1. Design requirements

The night vision optical modules (objective, ocular) looks apparently simple and similar to low cost optics used in binoculars, close circuit television (CCTV) cameras, and photography. Two optional modules (beam splitter and optical filter) look also apparently simple. However, practically design of high performance night vision optical modules is a technological challenge due to a set of different reasons.

4.1. 1. Objective

There are five main requirements on objectives for modern NVDs:

1. Field of view (FOV) optimized for type and applications of NVD. Typical FOV of night vision goggles and monoculars is about 40° but objectives of bigger FOV up to about 50° are sometimes used, too. Objectives of FOV in the range from about 4° to about 12° are used in night vision sights or binoculars. Possibility to change FOV of the objective by adding additional lens is also sometimes required.
2. Low F-number. It is typically required to design objectives of F-number (ratio of focal length to aperture) lower than 1.2. However, objectives of F-number equal to 0.9 or lower are used, as well. It should be noted that that F-number of photographic objectives is rarely lower than 1.8.
3. Optimization for wide spectral band. Objectives for NVDs should be optimized for spectral band from about 500 nm to about 900 nm. This is a significant increase in requirements in comparison to typical photographic objectives optimized for spectral band from about 450 nm to about 630 nm.

4. Optimization for input glass optics of IITs. As it was explained in Sect. 3.3 optical objective of NVD must correct influence of input glass optics of IIT on image created at photocathode of this IIT.
5. High resolution. It is typically expected that resolution of objective for NVDs should be about two times better that resolution of IITs. In case of IITs of resolution equal to 64 lp/mm it means that resolution of optical objective should be at least 128 lp/mm. For comparison it should be noted that photographic objectives of resolution higher than about 100 lp/mm are considered as very good.
6. Optimization for cooperation with large sensors. Optical objectives for NVDs should generate sharp image on entire area of photocathode of IITs. Typical diameter of IITs is 18 mm but tubes of 25 mm photocathode diameter or bigger are sometimes used. It should be noted that sensors used in most of electronic CCTV cameras are much smaller. Sensors of size equal to 4.8×3.6 mm are used in great majority of CCTV cameras.
7. Low mass. The latter requirement is less important in case of NVDs used as observation systems or as sights in mechanical vehicles but is of crucial importance in case portable goggles or sights carried by humans.

It is extremely difficult to fulfil all these requirements at the same time and design of high performance objectives for NVDs is considered as one of most challenging tasks for optical designers.

4.1.2. Ocular

There are five main requirements on oculars for modern NVDs:

1. Large exit pupil. It is typically expected 14 mm pupil at 25 mm distance from input plane.
2. Wide field of view. It is typically required that the oculars should project high resolution image of the tube screen in wide field close to 40°.
3. Optimization for curvature of output optics of IITs. Majority of tubes used on modern NVDs use curved output optics and oculars must be optimized for such an input curvature in order to project a sharp image generated at screen of such tubes.
4. High resolution. The latter parameter of optical oculars should be significantly higher (typically two times better) than resolution of image intensifier tubes. In case of oculars for NVDs built using high-res tubes it is required that ocular resolution is higher that about 120 lp/mm.
5. High transmittance. In order to minimize light losses on oculars transmittance higher than about 0.95 is expected. The requirement is typically fulfilled by reducing number of lenses (replacement of spherical lenses by aspherical lenses) and improved antireflection coatings.
6. Low mass. The latter requirements is achieved by using thin glass lenses or by using ultra light plastic lenses.

Fulfilling all these requirements on oculars for NVDs at the same time is difficult and design of such oculars is typically a compromise between these requirements.

4.1.3. Beam splitter

Beam splitter is used in monocular NVG to split and project image from screen of a single IIT into two optical channels optimized for two human eyes [(Fig. 6(b)]. Splitting image generated by IIT into two images automatically reduces perceived brightness gain of NVG by a factor of two. Practically, there are some additional losses due to limited transmittance of the beam splitter. Therefore, high transmittance of this optical module at a level over 90% is critical to assure acceptable brightness gain of such goggles. Next, beam splitter should be designed in a way that minimizes the vignetting of propagated optical beam. If the latter condition is not fulfilled the centre of FOV is significantly brighter than peripheral parts of image seen by human observer.

4.1.4. Optical filter

Optical filter is an optional module used to modify spectral sensitivity of NVD in comparison to spectral sensitivity of IIT.

Spectral sensitivity of majority of NVDs is the same as spectral sensitivity of IIT used in NVD. Such situation occurs because most NVD are built by using optical modules of flat spectral transmittance in VIS/NIR range. Practically, it means that typical NVDs are sensitive in spectral band from about 400 nm to about 850 nm, if Gen 2 tube is used, or in spectral band from about 500 nm to about 900nm if Gen 3 tube is used.

This wide spectral sensitivity band is not acceptable in two cases:

1. NVDs are to be used to help pilots to navigate helicopters/aircraft at night conditions;
2. NVDs are to be protected against common lasers.

Reasons for modification of spectral sensitivity of aviator NVGs are explained in Sect. 7.2. Aviator NVG are typically equipped with a long bandpass filter that blocks light of wavelength below about 630 nm (Class A filters), below about 650 nm (Class B filters). Class C filters are more sophisticated as these filters are a combination of a long bandpass filter (blocking below about 680 nm) and a bandpass filter (partial transmission in band from about 530 nm to 570 nm).

Protecting NVDs against lasers is needed to eliminate possibility that pilots, drivers, snipers or other peoples using NVDs are blinded using commonly available lasers; or even that NVDs are destroyed. Such a protection is achieved using special optical filters that are expected to attenuate incoming laser radiation. Precision requirements on such protecting filters in military NVDs are not known publicly. Such data are considered as a secret in USA and dissemination of any information related to this technology is prohibited [23]. However, it can be logically expected that these protecting filters are manufactured as a combination of an interference filter with a substrate of absorptance depending on power of incoming light.

The interference filter should have several absorption peaks optimized for wavelengths of typical lasers in visible/NIR range. The substrate should offer broadband absorption covering spectral band of NVD and attenuation of this substrate should be at least proportional to power of incoming light. Short temporal inertia at a level of several milliseconds is also a critical condition. It is possible that protecting filters in high-tech military NVDs are modified filters used for protecting eyes of welders.

Protecting filters to be used in NVDs for civilian market are much simple. Here requirements are generally limited to attenuation of green and blue lasers. Practically, these are requirements for long pass filter blocking visible light with exception of red light. Such protecting filters are commercially available and can be easily added to typical NVGs [24]. However, practically such commercial-grade protecting filters offer very limited protection because NVD equipped with a such filter is still vulnerable to red lasers and lasers operating in NIR range.

4.2. Influence on NVD performance

NVD is a system built from the main modules: optical objective, IIT, and optical ocular. Both photometric parameters [brightness gain (BG), SNR] and image quality parameters [modulation transfer function (MTF), resolution] of complete NVD depend on parameters of all these modules.

Brightness gain (BG) of complete night vision devices can calculated as

$$BG = \frac{LG \cdot \tau_{ob} \cdot \tau_{oc}}{4F^2 + 1} \tag{1}$$

where LG is the luminance gain of IIT, τ_{ob} is the objective transmittance, and τ_{oc} is the objective transmittance.

A similar equation can be used to calculate SNR of complete NVD

$$SNR_{NVD} = SNR_{IIT}\sqrt{\frac{\tau_{ob}}{4F^2 + 1}} \tag{2}$$

where SNR_{NVD} is the signal to noise ratio of the complete NVD, and SNR_{IIT} is the signal to noise ratio of the tube.

Both equations show importance of F-number of optical objective for photometric parameters of NVD. By using such ultra bright objectives both BG and effective SNR complete of NVD can be improved several times. If typical F = 1.2 objective is replaced for brighter F = 0.9 objective than both parameters can be improved 1.6 times. If ultra bright F = 0.65 objective is used, then improvement equal to 2.5 times can be achieved. Practical improvements are lower than values stated above but this data clearly show a method to design ultra sensitive NVDs. The method is practically used by some manufacturers, mostly to design night vision goggles for aviators and special operation teams [25]. There are, however, several drawbacks of such ultra bright objectives: higher price, higher dimensions, higher mass. These drawbacks limit present applications of these objectives but it should be expected that such objectives become more popular in near future.

MTF is a parameter that can be used to describe the ability to generate perfect images by both complete NVD, IIT, optical objective, and optical ocular.

Relationship between MTF of a complete NVD and MTF of modules of NVD can be presented in the following form

$$MFT_{NVD}(\nu) = MFT_{ob}(\nu) \cdot MFT_{IIT}(\nu) \cdot MFT_{oc}(\nu), \tag{3}$$

where MTF_{NVD} is the MTF of complete NVD, MTF_{ob} is the MTF of optical objective, MTF_{NVD} is the MTF of IIT, MTF_{oc} is the MTF of optical ocular, and ν is the spatial frequency.

Practical experience of the author shows that MTF of both NVD and their modules can be usually well approximated by function below

$$MFT(\nu) = \left(1 - \frac{\nu}{\nu_{\max}}\right)^2 \tag{4}$$

where $\nu_{\max}$ is the spatial frequency when MTF is zero.

Next, resolution of both NVD and IIT can be approximately determined as spatial frequency when MTF is about 0.04. Further on, resolution of optical modules can be approximately determined as spatial frequency when MTF is about 0.02. Higher value of required MTF needed to resolve resolution target in case of NVD and IIT is due to presence of significant noise in images generated by these two devices.

Finally, resolution of NVD can be presented in both lp/mm units or lp/mrad units. If the latter unit is to be used then resolution in lp/mm units should be multiplied by objective focal length presented in meter unit.

Table 6 and Figs. 22–23 present results of an analysis of two NVDs built using the same IIT but using two different optical modules: a) high-res optics and b) typical optics. The results show clearly that by using high quality optics' improvements in resolution of NVD at a level of at least 20% can be achieved.

Table 6. Resolution of two NVDs built using the same IIT but different optical modules.

Resolution	Hi-res NVD	Typical NVD	Comments
IIT [lp/mm]	64	64	Assumed input data
Objective [lp/mm]	128	86	
Ocular [lp/mm]	170	105	
NVD [lp/mm]	48	40	Calculated parameters of NVD
NVD [lp/mrad]	1.2	1	

Resolution of NVD in lp/mrad units showed in Table 6 is calculated for a case of an objective of 25 mm focal length. This is a typical objective in night vision goggles of 40° FOV built using 18 mm tube. The obtained resolution of NVD built using high quality optics (1.2 lp/mrad) corresponds quite well with resolution value (1.3 lp/mrad) of real goggles presented in a catalogue by one of big manufacturers of NVDs [4].

The results presented in this section show clearly that it is possible to design a high performance NVD only if all its modules perform very well. It is possible to find on market

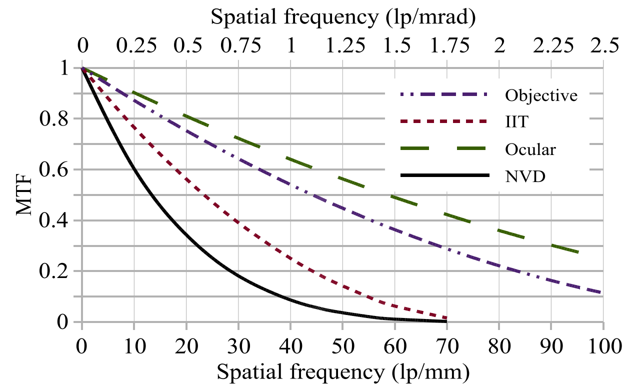


Fig. 22. MTF of NVD built using IIT of 64 lp/mm resolution, and hi-res optical modules (objective of 128 lp/mm resolution, and ocular of 170 lp/mm resolution).

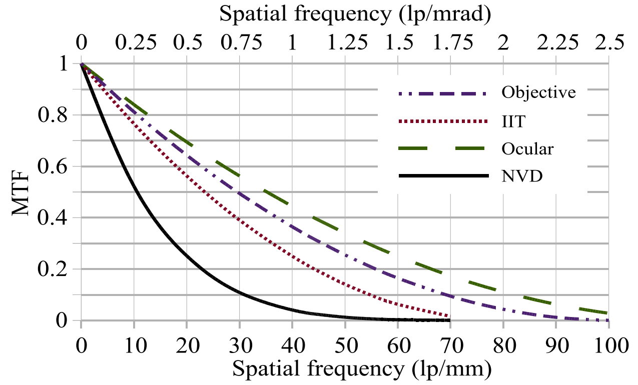


Fig. 23. MTF of NVD built using IIT of 64 lp/mm resolution, and typical resolution optical modules (objective of 86 lp/mm resolution, and ocular of 105 lp/mm resolution).

NVDs built using expensive, high performance tubes and rather poor quality optical modules. The effect is no more than Medium performance of such a NVD. Inverse situation is also possible. Medium performance tubes cooperating with high performance optical modules can produce quite good NVD, as well.

To summarize, it is recommended to treat very seriously night vision optics, measure most critical parameters of optical modules (on-axis MTF, off axis MTF, transmittance, F-number, FOV, vignetting). This measurement data combined with parameters of IIT enables to carry out design optimization NVD and development of devices with high ratio of image quality to cost.

5. Targeted market

The origin of night vision technology is clearly military. Several decades ago night vision devices were manufactured almost exclusively for military market. Nowadays the situation on the market has changed significantly. Military customers are still very important for the manufacturers especially that they usually purchase most expensive units but other markets have become important, too. It can be even said that there are some manufacturers of NVDs that specialize in non-military markets.

Market of night vision devices can be divided into three major sectors: military applications, law enforcement applications, and commercial applications (hunting, recreation, astronomy, science).

Theoretically, the border between the first two sectors (military and law enforcement) and the third sector (commercial applications) has been relatively precisely determined by regulations on export control of NVDs issued by U.S. or EU authorities. Practically, this border can be sometimes blurred due to several reasons:

1. Some technically backwards military still use old type NVDs of parameters below level of good commercial night vision devices;
2. Some dealers of NVDs active on commercial market advertise their products as military grade goods in situation when parameters of their devices are below the level mentioned in export control laws;
3. Law enforcement agencies often purchase on commercial market in order to save funds as military grade NVDs are more expensive;
4. There has been little progress in night vision metrology within last several decades in spite of big progress in night vision technology. It is quite common to find on the world market two NVDs (or two IITs) of the same data sheet parameters but of a totally different performance. Inverse situation is possible, too. Next, it is quite common that test systems used by different manufactures of NVDs or IITs generate significantly different measurement results due to a series of reasons [53].

To summarize, different claims about ultra performance of so called military grade NVDs should be treated with caution unless the claims are verified by practical tests.

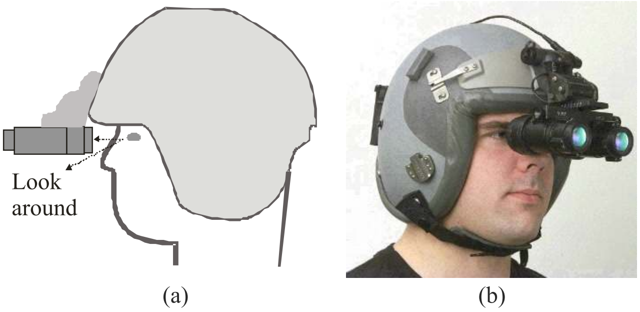
6. NVD for airborne applications

6.1. Types of aviator NVG

Night vision goggles for airborne applications can be classified as two basic types:

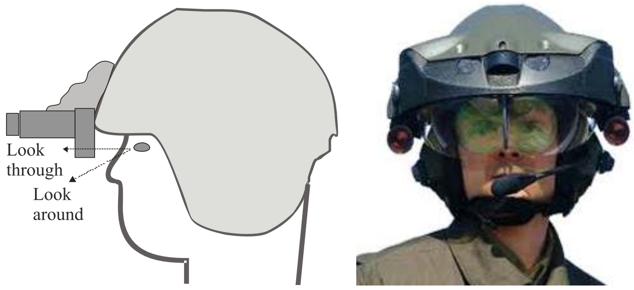
1. Direct view image NVG (Type I);
2. Projected image NVG (Type II).

Type I goggles are NVG that display the intensified image on a phosphor screen in the user's direct line of sight (Fig. 24). These goggles are often called aviator's night



(a) (b)

Fig. 24. Type I (direct view) night vision goggles with "look-around" vision into the cockpit: (a) diagram and (b) photo (after Ref. 3).



(a) (b)

Fig. 25. Type II (projected image) night vision goggles with “look-through” outside viewing and optional “look-around” vision into the cockpit: (a) diagram, and (b) photo (after Ref. 26).

vision imaging system (ANVIS). Type I look very much likes like a pair of binoculars attached to a helmet. These goggles represent a majority of airborne NVGs, particularly in case of helicopter pilots.

Type II goggles are NVG that projects the intensified image through medium in the user’s line of sight (Fig. 25). This configuration allows for simultaneous viewing of the intensified image and visual cues such as head-up display (HUD – a semi transparent display that generates data) symbology [8]. In the past Type II goggles were used exclusively for pilots of fixed-wing aircraft. Nowadays they are used also by a growing number of helicopter pilots.

The design of Type I goggles is a cost optimized solution that is characterized by one most important disadvantage: a pilot must constantly change its attention from image generated by the goggles to images from other imaging systems (FLIRs etc) or just to look on helicopter controls. Therefore, during last several decades a dozen or more Type II goggles were proposed to eliminate the earlier mentioned disadvantage of Type I goggles.

The Cats Eyes goggles were the first relatively widely used Type II goggles. The goggles allowed for the combination of both a direct visual and an intensified image to be presented to the pilot’s eyes. The two images are combined in a 1:1 relationship and complement each other. The head-up display and helicopter control panel is seen through the direct visual path. Additionally, the direct vision path through the optical combiner arrangement makes easy monitoring of cockpit displays. The direct vision path also removes problems normally associated with light to dark transitions as the intensified image becomes progressively more noticeable as the direct visual image fades. The system is compact and rugged and the restrictions on head mobility imposed by the depth of conventional NVG systems is avoided [27]. However, the folding of the Cats Eyes optical system results in reducing FOV to a circular 30° FOV with some clipping of the image in the lower right and lower left. This creates a situation when pilot is looking like via narrow tunnel. In addition the beam splitter used to combine two images reduces also significantly luminance gain of the night vision goggles.

TopOwl® helmet is the latest type of Type II imaging system developed for airborne applications by Thales. The Helmet Mounted Sight and Display is based on a unique concept incorporating a night vision system with a 100% overlapped projection of a binocular image on the visor. TopOwl projects the night scene and associated symbology onto two circular reflective surfaces with a fully overlapped, 40-degree, binocular FOV [28]. With training, the pilots also can look through the visor to read moving maps and other information on head-down displays. The system’s true binocular presentation and the spreading of the image intensification tubes at a distance wider than the spacing of the pilot’s eyes help to give a “3-D feel” to the 2-D night vision imagery. TopOwl has the ability to project thermal and night vision imagery to the visor, so that pilots and co-pilots can select either view. Standard symbology is used to display flight and weapon management data, helping to reduce crew workload. TopOwl’s head position sensor, used during target designation and weapon firing sequences, enhances operational effectiveness. This system is also characterized by low weight and perfect balance of the ergonomically designed helmet sight.

6.2. Compatibility to aviation regulations

IITs used in night vision NVGs are sensitive to radiation in both visible and near infrared range. Gen 2 tubes are usually sensitive from about 400 nm to about 880 nm when Gen 3 tubes are sensitive from about 500 nm to about 920 nm. This means that NVGs are potentially sensitive to visible light emitted by helicopter/aircraft control panel.

The light emitted by control panel reflected by glass window can produce severe veiling glare that can obscure the overall image for goggles looking through such helicopter/aircraft window. If light level from the control panel is high then automatic gain control mechanism built in NVG reduces luminance gain of the goggles. The final effect is that the pilot can see only image of the control panel reflected by the window – image of real targets outside the widow becomes dark. In order to prevent such a situation NVGs for airborne operations must be compatible with cockpit lights of helicopters/aircraft.

To achieve compatibility of the cockpit lighting with the night vision goggles, the cockpit lighting should have a spectral radiance with little or no overlap into the spectral sensitivity band of NVG. In other words the cockpit lights should emit very little light in the spectral region in which the goggles are sensitive. At the same time the lights must also be visible to the unaided eye in order to enable the pilot to easily view the cockpit. Such a situation can be achieved when both cockpit lights and NVGs are optimized for airborne applications as shown in Fig. 26 [29].

Compatibility of NVG with cockpit lighting can be achieved in different ways. NVGs compatible with aircraft/helicopter cockpit lighting are divided into three classes: Class A, Class B, and Class C [29]. Spectral sensitivity curves of these three classes of NVG are shown in Fig. 27.

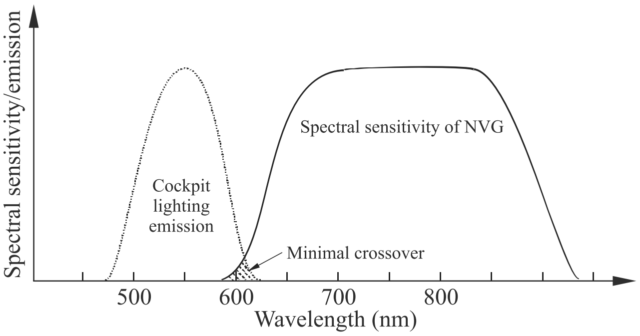


Fig. 26. General concept of compatibility of night vision goggles with cockpit lights.

Class A NVG are built like typical goggles with additional so called 625 minus-blue filter. Such goggles are not compatible with red lights because of the overlap between the spectrum of red light and the sensitivity of Class A goggles. Other colour lights as blue, green, orange are acceptable. Most NVGs for airborne applications are Class A goggles.

Class B goggles are built using 665 minus-blue filter. Such goggles are compatible with all colours of visible light: blue, green, orange and red and typical cockpit lights can be used. Such a situation was achieved because there is practically no overlap between spectral sensitivity curve of filtered night vision goggles and visible band. However, sensitivity (and related parameters like luminance gain, SNR) of Class B goggles is lower than sensitivity of Class A goggles because of more narrow spectral sensitivity band.

Class C goggles are built using special filters that suppress blue, orange and red light but transmit partially green light. Class C was introduced to allow the night vision goggles to see HUD symbology presented usually in green colour. If Class A goggles or Class B goggles are used then this symbology cannot be seen.

7. Parameters of night vision devices

NVDs generate images that can be seen by humans and it is possible to evaluate such devices using human sight. However, it is surprisingly difficult even for an expert to precisely evaluate NVDs only by looking on images of typical scenery. Measurement of a series of parameters is needed in order to accurately evaluate quality and possible performance of these devices.

Different sets of parameters of NVDs are used in different documents: data sheets presented in websites of manufacturers of NVDs [2,4,5,6,25,30,31], military standards [32–44], tender technical specifications [45–47], export control regulations [48,49], in aviation technical recommendations [50], or in educational sections of manufacturers' websites of NVDs' testing equipment [51,52]. On the basis of analysis of these literature sources, parameters of NVDs can be divided into twelve groups: parameters of IITs, parameters of optical modules, image quality parameters, photometric parameters, geometrical parameters, blemishes, binocular parameters, operational defects, environmental parameters, mechanical parameters, electrical parameters, and function checks. Detailed list of parameters of night vision devices is shown in Table 7.

It is beyond scope of this paper to present here a review of parameters of night vision devices. The readers should be however warned that characterization and testing NVDs is a difficult task, probably more difficult than testing thermal imagers. Present situation in night vision metrology is not optimistic in spite of significant technological advances in night vision technology during last several decades [53]. The readers interested in characterization and testing NVDs/IITs are encouraged to read literature sources mentioned above in this section.

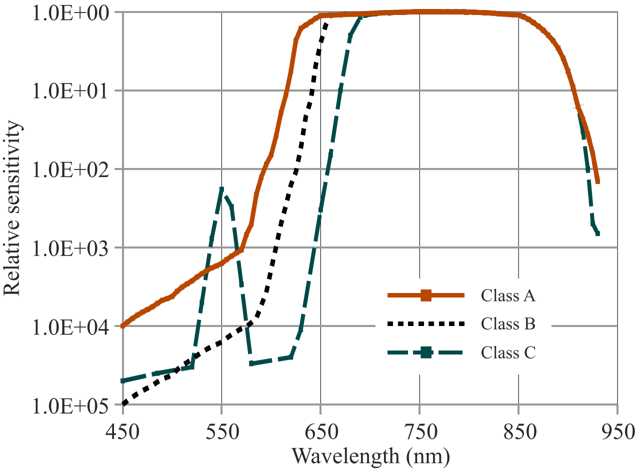


Fig. 27. Relative spectral sensitivity of night vision goggles compatible to lighting in aircraft/helicopter cockpits (after Ref. 29).

8. Technology trends

Forecasting technology trends in night vision technology is risky. However, on the basis of analysis of data available from manufacturers of NVDs and manufacturers of IITs, seven separate development trends can be determined:

1. Digital NVDs;
2. Enhanced (dual sensor) NVDs;
3. Active NVDs;
4. Ultra sensitive NVDs;
5. NVD of enlarged field of view;
6. Ultralight NVDs;
7. Low cost NVDs.

The first three trends represent basically new types of night vision systems. The latter four trends are generally improvements of classical NVDs.

8.1. Digital NVDs

Classical night vision devices built by using image intensifier tubes are sensitive in similar spectral range as surveillance visible/NIR cameras built by using solid state silicon sensors. At the same time visible/NIR cameras are elec-

Table 7. Parameters for characterization of night vision devices.

No	Group of parameters	List of parameters
1	Parameters of image intensifier tubes	resolution, MTF, SNR, blemishes, image alignment, halo, etc – these parameters are to be evaluated using tube certificates
2	Parameters of optical modules	resolution, MTF, FOV, transmission – these parameters are to be evaluated using certificates
3	Image quality parameters	resolution, MRC (minimal resolvable contrast), range of focus, eyepiece diopter range
4	Photometric parameters	brightness gain, saturation level
5	Geometrical parameters	field of view, magnification, distortion
6	Blemishes	dark spots, white spots, fixed pattern noise, chicken wire, output brightness variation
7	Binocular parameters	collimation error, gain balance, magnification balance, distortion balance image rotation balance, inter-pupillary distance
8	Operational defects	shading, edge glow, flashing/flickering/intermittent operation, and emission points
9	Environmental parameters	extreme temperatures, temperature shock, altitude, humidity, vibration, shock, sand and dust, fungus, immersion, salt fog, explosive conditions, transportability, electromagnetic interference (EMI)
10	Mechanical parameters	weight, size, centre of gravity
11	Electrical parameters	power voltage, battery type, battery operational time
12	Function checks	electrical switch, objective torque, Eyepiece torque, LED indicator, high light cut off, low voltage indicator, inter-changeability, flip-up/flip-down (aviator goggles), automatic breakaway (aviator goggles)


(a) (b) (c)

Fig. 28. Digital NVDs: (a) Pulsar Hindsight N550 digital sight, (b) Ghost Hunter 5×50 monocular (after Ref. 54), and (c) Monie-D goggles (after Ref. 55).

tronic imaging devices that inherently possess some important advantages as image processing, storing, automatic focusing, automatic target recognition, ability for electronic communication, etc. Next, some of visible/NIR cameras offer sensitivity similar to classical NVDs. Therefore, digital night vision devices built by using high sensitive silicon imaging sensors and miniature electronic displays should be theoretically a much better alternative to classical night vision device based on optical image intensification.

Digital NVDs are already offered on commercial market as sights, monoculars, and goggles [54]. There are manufacturers of classical NVDs for military sector that offer also digital monocular goggles [55]. However, so far a share of digital NVDs on commercial market is small (it can be estimated below 1%); a share of digital NVDs in military market is even smaller. Digital NVGs are treated on both markets as an interesting novelty that must be verified both technically and economically.

Digital NVDs looks externally the same as their classical analogues (Fig. 28). Such a situation occurs because external modules (objective, ocular, mechanical case) are the same for both types of NVDs. However, practically there are big differences between internal modules used by these two types of NVDs. As it is shown in Fig. 29 new modules (image sensor, signal processing, and display) are used in digital devices to replace a single module (IIT) used in classical NVDs.

Image sensor (typically integrated with signal processing electronics) and miniaturized display are two most important modules of digital NVDs.

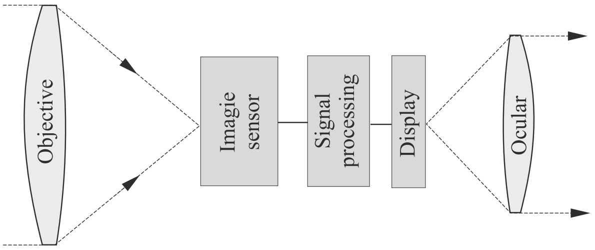


Fig. 29. Block diagram of digital NVDs.

8.1.1. Image sensors

There are at least seven technologies of silicon imaging sensors that compete in digital night vision:

1. Intensified CCD (ICCD);
2. Intensified CMOS (ICMOS);
3. Electron multiplied CCD (EM CCD);
4. Electron bombarded CMOS (EBCMOS);
5. Microchannel plate complementary metal-oxide semiconductor (MCPCMOS);
6. Scientific CCD (sCCD);
7. Scientific CMOS (sCMOS).

ICCD/ICMOS module is basically an IIT coupled to classical CCD (or CMOS) imaging sensor by fibre optics with additional some electronics for processing signal generated by CCD/CMOS sensor (Fig. 30). Digital NVDs based on ICCD sensor are the oldest type of these digital devices.

EMCCD is a technology that uses a solid state electron multiplying (EM) register at the end of the normal serial register [57]. The EM register allows weak signals to be multiplied before any readout noise is added by the output amplifier. The EM register has several hundred stages that use higher than normal clock voltages. As charge is transferred through each stage, the phenomenon of impact ionization is utilized to produce secondary electrons, and hence the name of EM gain. In this way EMCCD sensors are capable of detecting single photon events. In this way EMCCD eliminates important shortcoming of conventional high-performance CCD cameras that very low signal levels typically fall beneath the read noise floor of the sensor.

EMCCD technology originated at beginning of 2000s. Now it is a fully matured technology offered by a series of companies. The problem is however that EMCCD sensors are typically cooled by using thermoelectric cooler (or other types of coolers) in order to reduce its temperature and consequently its noise. The latter feature makes EMCCD cameras rather bulky. Due to big size, mass and high power consumption EMCCD sensors have no chance to find mass applications in portable digital NVDs but can be potentially used in digital NVDs as observation systems in mechanical vehicles.

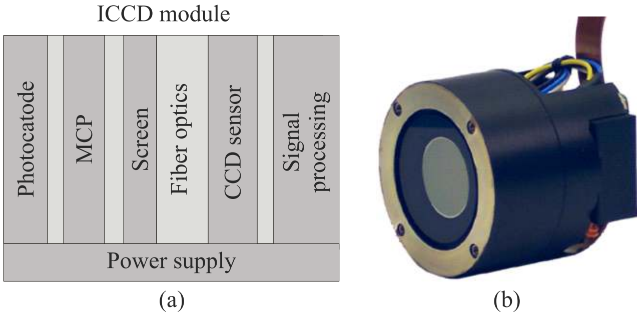
Electron bombarded active pixel sensor (EBAPS sensor) is an ultra sensitive imaging sensor based on a III–V semiconductor photocathode in proximity-focus with a high-resolution, backside-thinned, CMOS chip anode [58]. The electrons emitted by the photocathode are directly injected in the electron bombarded mode into the CMOS anode, where electrons are collected, amplified and read-out to produce digital video directly out of the sensor. This technology enables a design of a compact, lightweight and low power sensor offering high quality images even at a very low illumination level. Low power consumption of EBAPS sensors is a significant advantage over EMCCD technology. Due to low mass and power consumption EBAPS technology enables design of portable NVDs.

EBAPS is a patented technology and EBAPS sensors are manufactured by only one manufacturer Intevac Corp. This company has already started production of both digital night vision monoculars and digital binocular NVGs [58].

Microchannel plate complementary metal-oxide semiconductor (MCPCMOS) is a technology developed similar to EBAPS technology. MCPCMOS sensor uses modified CMOS chip directly into the vacuum envelope of a proximity focused image tube like typical EBAPS sensor. The primary difference is that the MCPCMOS sensor contains a microchannel plate and, therefore, can offer higher luminous gain capability [59]. This technology has been developed by ITT Night Vision - a big manufacturer of classical IITs – that clearly shows interest of this company in digital night vision.

sCCD/sCMOS sensors are so called scientific grade CCD (or CMOS) imaging sensors of significantly reduced defects and blemishes, reduced several times internal noise, improved image resolution and expanded dynamic range in comparison to typical CCD/CMOS sensors used in commercial video cameras. The price of scientific grade CCD/CMOS sensors can be even over 100 times higher than the price of typical sensors.

sCCD/sCMOS sensors are often used in high end imaging systems used in science and industry. Due to recent improvements in sensitivity sCCD/sCMOS both sCCD and sCMOS sensors are considered as serious competitors of the earlier mentioned sensor technologies in digital night vision. sCMOS sensors have already found mass applications in high-end colour surveillance cameras for night applications. These small, rugged, low-power cameras can generate



(a) (b)

Fig. 30. ICCD module: (a) block diagram and (b) photo (after Ref. 56).

Fig. 31. Digital sCMOS sensor called Lynx offered by Photonis (after Ref. 61).

1280×960 high-definition (HD) image, offer ultrahigh 25000:1 dynamic range and less than 2e- (rms) read noise [60]. One of big manufacturers of classical IITs is offering also sCMOS sensors of 1280×1024 resolution for digital night vision designed to provide excellent performance in low light level conditions (read noise below 4e, power consumption under 200mW) [61].

Simpler imaging modules built by using the technologies mentioned above generate output image in typical analogue television formats: PAL or NTCS (720×576 at 25 frame rate for PAL format or 640×480 at 30 frame rate for NTSC format). Additional analogue/digital module is used to convert analogue images to digital form that is later sent to a display module. More advanced imaging modules generate output image using digital image formats: DVI, USB 2.0 or Camera Link. Images of resolution over 1280×1024 at 25 frame rate can generated and sent directly to the display module.

8.1.2. Miniaturized displays

There are two main technologies of miniaturized displays used in digital NVDs: thin film transistor liquid crystal display (TFT-LCD) and organic light emitting diode displays (OLED).

TFT-LCD displays or more accurately active matrix TFT LCD (AM TFT LCD) are electronic devices that generate image on array of LCD pixels using for control active matrix of thin film transistors. Voltage dependent optical polarisation of LCD crystal is used as a basic phenomenon that enables image generation on LCD array.

OLED displays use of electroluminiscence phenomenon of some organic compounds. A film of organic compound that emits light in response to an electric current is used to generate image.

There are two main families of OLEDs: those based on small molecules and those employing polymers [83]. Adding mobile ions to an OLED creates a light-emitting electrochemical cell (LEC), which has a slightly different mode of operation. Next, OLED displays can use either passive-matrix (PMOLED) or active-matrix addressing schemes. Active-matrix OLEDs (AMOLED) require a thin-film transistor backplane to switch each individual pixel on or off, but allow for higher resolution and larger display sizes.

Both TFT-LCD and OLED technologies are now used to manufacture big numbers of mini-displays for commercial and military applications. However, it is typically considered OLED displays are a better choice for both these application areas.

Commercial OLED displays are thinner, lighter and more flexible. Next, the OLED displays offer higher viewing angle, brighter images, more vivid colours, higher contrast (both dynamic range and static), faster colour switching, reduced ghosting or blurring effects, short response time (~ 0.01ms,) and consume less power in comparison to LCD. However, OLED displays are characterized by more limited life time than LED displays [62]. Ability of OLED display to work at low temperatures without heaters, elimination of backlights, display flexibility are considered as a big advantage of OLED displays in military applications [63].

8.1.3. Technological challenges

The presented earlier long list of technologies used in digital night vision looks impressive but practically there are serious problems to design digital NVDs of sensitivity, image resolution, compactness, power consumption and cost similar to parameters offered by classical NVDs.

The requirement on similar sensitivity is not a big technical challenge. Cameras manufactured using all technologies mentioned earlier generate images of minimal degradation of image quality at illumination as low as 10 mlx (Quarter Moon) [64]. Next, CCD/ICMOS/ EMCCD/EBAPS technologies offer sensitivity similar to typical NVDs and potentially enable surveillance at illumination as low as 1 mlx.

The biggest technical challenge for designers of digital NVDs is to achieve image resolution similar to resolution of classical NVDs. It should be remembered that classical IITs generate images of equivalent resolution of about 2 500 000 pixels (IIT of 18 mm photocathode, and modest resolution equal to 50 lp/mm) at the frame rate at about 25 frame per second. In order to enable design of digital NVD offering image of resolution equivalent to classical NVD two crucial modules are needed: high resolution imaging sensor and miniaturized high resolution display.

There are available imaging sensors of resolution exceeding 2 500 000 pixels' limit. However, such sensors are very expensive and not suitable to be used in digital NVDs for mass applications. Imaging sensors of pixel number 1280×1024 (about two times less than earlier mentioned number of equivalent pixels of an image in typical NVDs) can be considered as current resolution limit of imaging sensors that can be used in digital night vision.

Ten years ago miniaturized displays were considered as the main obstacle to design digital NVDs even of modest resolution of typical analogue TV images. Nowadays, situation on market of miniaturized OLED displays looks much better, even impressive due to recent dramatic improvements in resolution of miniaturized OLED displays [65]. Bicolour and tricolour OLED displays of resolution up to 5 bilion dots are now commercially available.

Requirement on compactness represents another technical challenge for designers of digital NVDs. It should be remembered that weight of classical monocular NVDs can be as low as 250 g. Size of imaging sensors was never a big limitation for digital night vision. Situation with size of displays was inverse. Display size was one of factors that made impossible to design a portable NVD one decade ago. However, last decade is a period of big achievements in miniaturization of both TFT-LCD and OLED displays. Nowadays, displays of sizes smaller than screens of IITs are manufactured and are commercially available (Fig. 32) [65].

Power consumption of imaging sensors and displays in digital NVD is a difficult problem, not fully solved, so far. Power consumption of typical NVD is often below 0.1W.

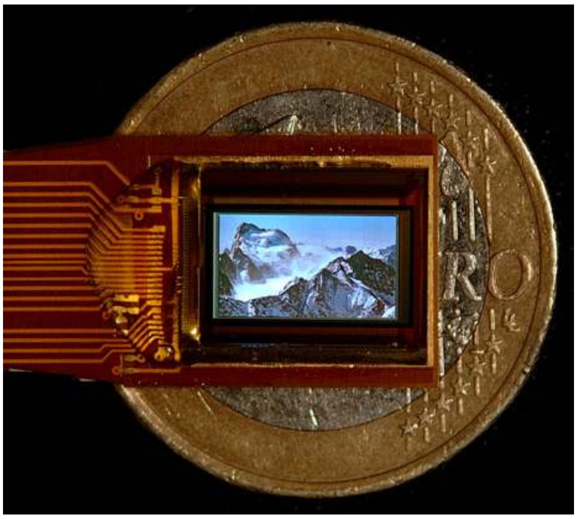


Fig. 32. Photo of a microdisplay of diagonal size equal to 0.38 inches (after Ref. 65).

Power consumption of digital NVDs is typically in a range from about 500 mW to about 1200 mW. It means that currently power consumption of classical NVDs built by using IITs is at least five times smaller than power consumption of digital NVDs. The problem of power consumption of digital NVDs is only partially neutralized by big progress in technology of miniaturized batteries in the last decade.

Cost is another, probably, the biggest problem for digital night vision. At present, it is not possible to replace a single IIT module by an equivalent set of three modules (imaging sensor, signal processing electronics, miniaturized display) and keep the same manufacturing price.

To summarize, digital NVDs are an interesting novelty on market that present several potential advantages over classical NVDs. However, these potential advantages of digital night vision are not so far fully materialized because of both technical and economical challenges. Practical tests often show clear superiority of classical NVGs from the point of view of sensitivity, image resolution, compactness, and power consumption. There are rumours that users of digital goggles loose more quickly orientation or balance when wearing such goggles. At the same time manufacturing costs of high performance digital NVDs are higher than in case of equivalent classical NVDs. Therefore, probability that digital NVDs will eliminate classical NVDs is low. However, digital night vision technology is making fast progress, technical performance of digital NVDs is quickly improving and it can be expected that market share of digital NVDs will grow steadily in future.

8.2. Enhanced NVDs

Enhanced NVDs (dual sensor NVDs) are probably the most important trend in night vision technology.

Digital NVDs presented in the previous section offer some advantages over classical NVDs due to image processing, storing, automatic focusing, automatic target recognition, ability for electronic communication, etc. However, both classical NVDs and digital NVDs suffer from the same limitation because both technologies use the same spectral band. Both devices are practically blind in dense fog, smoke, sand storms, or at very low illumination conditions. Next, these devices are also not effective against classical camouflage techniques.

Fusion of classical night vision with thermal imaging is very interesting for both military and commercial users of NVDs because these new fused devices combine advantages of both two technologies:

1. Ability to generate high contrast images of warm targets of interest at low illumination/poor atmosphere conditions (detection task);
2. Ability to generate high resolution image of both targets and background (identification task).

There is a huge interest in enhanced night vision due to advantages mentioned earlier. Enhanced NVDs are already commercially available (Fig. 33). These new devices offer high contrast images like images shown in Fig. 34. Human users can easily see high contrast warm features (typically bright orange or red colour) over typical green background in a single image and can easily recognize hidden targets.

There is a bright future for enhanced night vision technology due to earlier mentioned advantages. However, at present there are big technical and economical challenges that this technology must overcome in order to be used in high numbers.

(a)

(b)

Fig. 33. Enhanced night vision devices: (a) enhanced monocular goggles (after Ref. 4) and (b) enhanced binocular goggles (after Ref. 66).

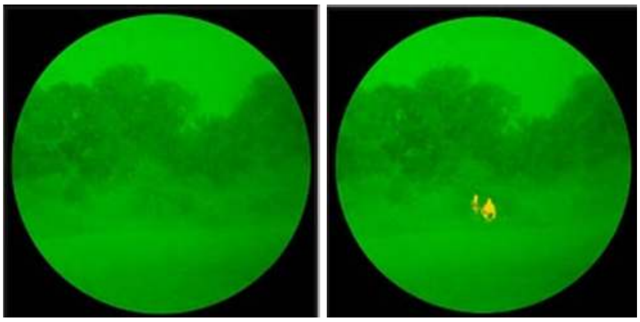


Fig. 34. Images of forest scenery at foggy conditions generated by classical NVGs (left) and ENVG (right) (after Ref 67).

Details of design of enhanced NVDs shown are considered as secret [68]. Monocular goggles designed as a combination of two optical channels (digital night vision channel and thermal imager channel) shown in Fig. 35 are one of possible design solutions.

All technical challenges for digital night vision are still valid for enhanced night vision because digital NVD is one of channels of enhanced NVD. Therefore, only additional technical problems specific for enhanced NVDs will be presented in this section.

Resolution of IR FPA sensors used in thermal imagers has always been behind resolution of silicon arrays (CCD/CMOS/ICCD/EMCCD/EBAPS/sCCD/sCMOS) used as imaging sensors in a visible and near infrared range. IR FPAs of 1024×768 resolution can be considered as current technology limit for sensors to be used in enhanced night vision. It is several times below resolution of classical NVDs but still acceptable due to ability of IR FPA sensors to produce high contrast images.

Non-cooled IR FPA sensors are the only option for enhanced night vision due to too high power consumption and price of cooled IR FPAs. Power consumption of modern non cooled IR FPA of 1024×768 resolution can be as low as about 100 mW [69], but overall power consumption of complete thermal module is much higher and limiting power consumption below about 400 mW is a real technical challenge.

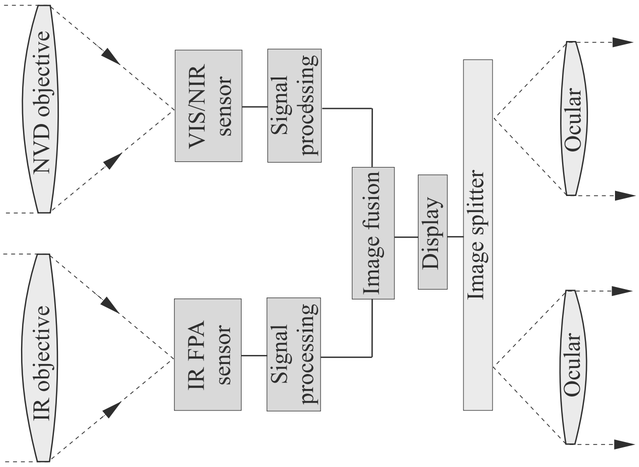


Fig. 35. Simplified block diagram of enhanced NVDs.

Next, it is technically possible to use two displays for two channels in enhanced NVDs but solution with a shared display and optical image splitter (shown in Fig. 35) is preferred due to effort to limit power consumption.

Design and manufacturing of high resolution, ultra light, ultra bright (F number about 1) objective capable to cooperate with high resolution of 1024×768 (17 µm pixel) in full FOV is another difficult problem for designers of enhanced NVDs. There are on market very few IR objectives that can fulfil at the same time requirements on wide FOV, high modulation transfer function (MTF), low F-number, high transmittance and low weight.

The most difficult challenge specific for enhanced night vision is fusion of images generated by two channels working at two different spectral ranges.

Humans are equipped with an optical system in form of two eyes sensitive to light in a visible range. Human brain is doing image fusion from these two optical channels and creates a single two dimensional image (but with some depth perception) of targets located at distance from a dozen of centimeters to several kilometers.

Enhanced NVDs are expected to work in the same way as the human sight. The challenge is that images of the same target seen by two channels of enhanced NVD are slightly different and this difference depends on distance to the target. Advanced processing of images from two channels of enhanced NVD is needed to find optimal overlaying of images from these two channels. Next, advanced image processing is needed to determine which parts of thermal image should be used in the final fused image, which parts of visible image are eliminated, and how to blend thermal image with a visible image without decreasing sharpness of final fused image.

To summarize, enhanced night vision combines advantages of two classical technologies (image intensification and thermal imaging) and is potentially very attractive for both military and commercial users. However, technological difficulties are higher than in case of digital night vision.

Present prices of ENVGs can be estimated at a level over 20–50 times higher than price of classical NVGs. Price of NVGs manufactured in mass production is expected in the future to go up to a level about three times higher than price of classical NVD [70]. This reduced but still high price combined with reduced sensitivity and image resolution of ENVGs in comparison to classical NVDs rather eliminate possibility that ENVGs will dominate night vision market. However, it can be expected that ENVGs will take a big share of night vision market in near future due to a several of advantages of enhanced night vision.

8.3. Active NVDs

First NVDs were active systems that required artificial illumination in near infrared range (powerful tungsten search lights). Such a feature is a significant drawback in military applications and passive NVDs were developed several decades ago. Therefore, modern classical NVDs are fully

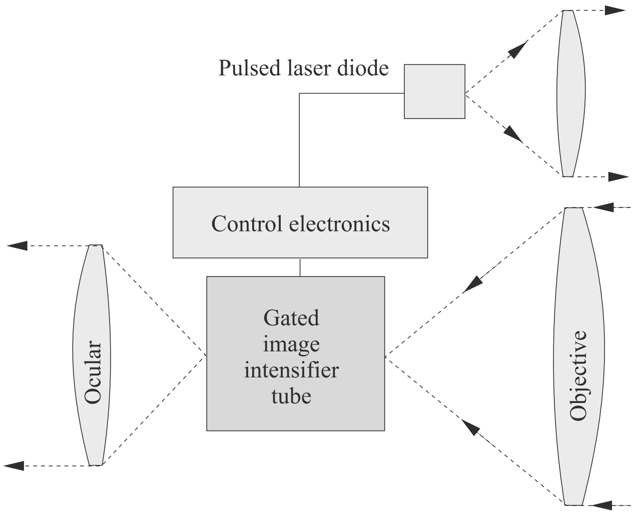


Fig. 36. Block diagram of an active night vision device.

passive surveillance systems using only in exceptional situation small short range illuminators (map reading).

There are, however, on the market some advanced active NVDs taking advantage from technological improvements in laser technology. Modern active night vision devices are built, like old NVDs, from two main modules: active light source and passive imaging device. However, simple tungsten/halogen bulb working in direct mode (the light level is quasi constant) in old active NVDs is replaced by powerful laser diodes emitting pulsed light in NIR range in modern active NVDs. Next, the passive imaging device is now working in gated mode (sensing device is active only at short time durations) and is synchronized with the active light source. This means that the receiver is active only at time intervals when the pulses emitted by the light source and reflected by the observed targets are supposed to reach back the imaging device.

In this way the drawbacks of old active NVDs are almost eliminated. Due to directional character of emitted light and short time when the new active night vision systems emit light probability of detection of these systems is much lower than case of old active night vision systems. Gating mode used in modern active night vision systems makes them less vulnerable to fog, rain or in general to atmosphere conditions. Higher range of effective observation can be achieved. Further on, modern active night vision system can generate sharp images of targets located close to strong light sources are located in situation when typical passive night vision devices or typical passive visible/NIR electronic cameras generate only blurred images of the light sources and black background. Finally, some of modern active NVDs can work as low accuracy range finders (they produce sharp image only of targets at regulated expected distance).

Fig. 37. Photo of an active night vision device type DM 740 from Dedal, Russia (after Ref. 71).

In spite of earlier mentioned important advantages these new active NVDs are not popular in comparison to typical passive NVDs. However, situation can change in the future because portable, active range gated NVDs are a small offspring of a much wider active imaging technology.

Laser detection and ranging (LADAR) cameras, time of flight (ToF) cameras, active range gated night vision cameras are three important groups of active imaging technology that differ in technical solutions but use the same principle as earlier discussed active NVDs. The latter three main groups of active imaging have found mass applications in automotive industry, surveillance, 3D modelling, robotics etc [72–74].

It is beyond the scope of this paper to discuss in details groups of active imaging system but should be noted that further development of this technology will bring improvements in active NVDs.

8.4. Ultra sensitive NVDs

Recent military conflicts have shown that present generation of NVDs still performs rather poorly at very dark night conditions (overcast starlight) or even at relatively good illumination conditions (quarter moon) but in areas of low terrain reflectance (like mountains of Afghanistan). At present level of night vision technology dark nights can still significantly reduce military activities. Some elite units equipped with ultra-high sensitivity NVDs can carry out operations even at overcast starlight illumination conditions but effectiveness of surveillance is limited.

Present ultra-sensitive NVDs are built by using Gen 3 Filmless/Gen 3 Thin Film tubes and ultra bright optical objectives of F-number as low as 0.9. It can be expected that further technological improvements of sensitivity of Gen 3 Filmless tubes or Gen 3+ Thin Film tubes (SNR as high as 35) combined with improvement of high resolution ultra-fast objectives of ultra low F-number (as low as 0.65) will improve sensitivity of NVDs even more.

As it was shown in Fig. 38 there is a big difference in performance in dark night conditions between a typical NVG and an ultra sensitive NVG. The latter NVGs enable safe flights for helicopter pilots when use of the first ones can lead to accidents.

Ion barrier film is the main factor that limits further improvement of Gen 3+ Thin Film tubes and it is doubtful if these tubes can ever achieve earlier mentioned level of SNR parameter. It is more probable that the best of Gen 3 Filmless tubes will offer SNR equal to 35 or higher in near future.

Significant aberrations, strong vignetting effect, narrow focus range, big sizes and mass are four main technological

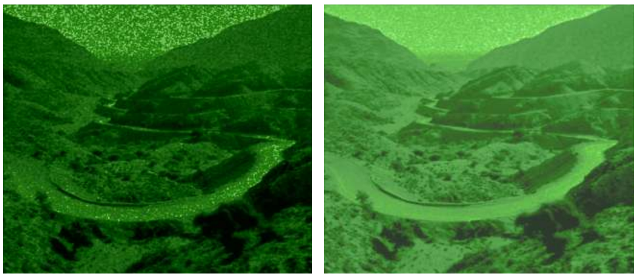

(a) (b)

Fig. 38. Photo of low contrast mountain landscape at moonless night obtained using two NVG of different design: (a) NVG built by using typical F1.2 optics and typical IIT of SNR equal to 22 and (b) NVG built using F0.9 optics and IIT of SNR equal to 32.

challenges in a design of ultra bright objectives needed for new generation of ultra sensitive NVDs. Design of high resolution (aberration blur below about 3 micrometers), ultra bright (F number as low as 0.65) small, compact, light objectives of wide FOV (over 40°) cooperating with big 18 mm sensors is a very high challenge for optical designers. However, sooner or later these optical objectives will be developed and increase significantly sensitivity of NVDs.

8.5. NVDs of enlarged FOV

Horizontal field of view of a human eye is about 40° and vertical field of view is about 30°. Due to its ability to rotate, a human eye can effectively see (detection of movement) almost in full hemisphere. Therefore, narrow FOV in comparison to human eye FOV has always been considered as one of basic limitations of night vision devices.

The efforts to increase FOV of NVD have always been present in vision technology. Old standard FOV of NVG used until about the end of 1980s was 30°. Nowadays, great majority of short range NVDs (goggles, monooculars) offer 40° FOV. However, there are also on market goggles of wider FOV. Night vision goggles Lucie from Thales Angenieux having FOV equal to 50° is an example of this trend (Fig. 39). It is possible that such goggles become popular in future and 50° will become a new standard FOV.


Fig. 39. Night vision goggle Lucie of enlarged field of view from Thales Angenieux (after Ref. 75).

It should be noted that FOV and resolution are connected. Increasing FOV means to sacrifice resolution and inverse. Therefore, goggles of enlarged 50° FOV are characterized by slightly lower resolution than typical goggles of field of view about 40°. Next, one of tricks of sellers of low cost NVGs for civilian applications of 30° FOV is to advertise their high resolution comparable to resolution of expensive military grade NVGs of 40° FOV without mentioning difference in FOV. Table 8 presents the relationship between resolution of IIT, FOV and resolution of NVD and shows clearly how it is easy to manipulate with resolution of NVDs if information about FOV is not available.

Table 8. Relationship between resolution of IIT, FOV and theoretical (case of ideal optics) resolution of NVD.

Resolution of IIT [lp/mm]	Resolution of NVD for 30° FOV [lp/mrad]	Resolution of NVD for 40° FOV [lp/mrad]	Resolution of NVD for 50° FOV [lp/mrad]
45	1.20	0.90	0.72
64	1.71	1.28	1.02

Panoramic NVG represents another version of a trend to enlarge FOV of NVGs but without sacrificing resolution because panoramic goggles are built by using several tubes. Modern panoramic NVGs are typically built by using four 16 mm tubes and offer FOV about 80°–100° (horizontal) to about 35° (vertical).

Experimental projects to design panoramic NVG to double typical horizontal FOV have been carried out for decades. A series of panoramic NVGs for pilots of fixed-wing aircraft has been developed. Tests have confirmed big potentials of such goggles due to enlarged FOV but also have showed a series technical problems encountered in practical use of panoramic NVGs [76–78].

After a long period of experimental tests panoramic NGVs are nowadays used as standard imaging systems in several fixed-wing aircraft [79]. Panoramic NVGs for aviators are commercially available, too [80].

Panoramic NVGs were developed and are mostly used by aviators. However, it should be noted that panoramic NVGs for land applications are recently also offered (Fig. 40). It means that in near future panoramic NVGs can be used in much higher numbers than they were used in past.


Fig. 40. AN/AVS-10 panoramic night vision goggle offered by L-3 Warrier Systems (after Ref. 81).

8.6. Ultralight NVDs

Fatigue of soldiers or other users of NVDs wearing heavy goggles attached to helmets or masks was always considered as a drawback of night vision technology. An ideal NVD should be of mass comparable to human eyes. Ultra light NVG or monoculars built by using new small 16 mm tubes are a potential solution to this limitation. There are already on market night vision monoculars as light as 250 g of a very ergonomic design (Fig. 3) [31]. The same can be said about size and weight as even modern NVDs are very big and heavy in comparison to human eye.

8.7. Projected image NVDs

Projected image NVG (Type II goggles) are devices that projects the intensified image on a see through medium in the user's line of sight. These goggles allow for simultaneous viewing of the intensified image, control panel, HUD symbology and images from other electronic imaging systems like thermal imagers etc. Nowadays Type II goggles are part of highly sophisticated systems that combine modules of NVG, projection optics, image combining optics, helmet, position sensing electronic system, and image processing electronics. TopOwl® system developed by Thales (Fig. 25) can be treated as a prime achievement in this trend of night vision technology. It can be expected that simplified, lower cost projected image NVDs will be offered on market in near future.

8.8. Low cost NVDs

Price is a prime factor for NVDs at commercial market. Due to this factor devices built by using Gen 1 tubes are still used. High price of Gen 2/Gen 3 tubes is the main obstacle for wider use of NVDs built by using these more modern tubes for commercial applications. Therefore, efforts to decrease costs of manufacturing of Gen 2 tubes are continued and some Gen 2 tubes of lower luminous sensitivity (below about 350 μA/lm) and resolution (below about 45 lp/mm) are manufactured for commercial market as non military goods.

Improved Gen 1 tubes represent another direction in trend to lower cost of IITs for commercial market. Ceramic optical ruggedized engine (CORE) tubes represent the latest novelty on commercial market. Gen 1 tubes are characterized by three important drawbacks: low sensitivity, medium resolution, and vulnerability to mechanical shocks. Gen 1 tubes made in CORE technology almost eliminate these drawbacks. The CORE tubes are manufactured by means of fusion of metal alloys with ceramic compounds similar to Gen 2 tubes and unlike classical Gen 1 tubes manufactured using glass technology. In this way ability to produce of robust night vision weapon sights for restricted budgets was achieved because CORE tubes shock-proof against middle-size riffle calibers. The latter feature is extremely important for hunters that form significant group of commercial market. At the same time these new tubes offer images of much better quality than typical Gen 1 tubes. It is reported that luminous sensitivity of CORE tubes can be as high as 350 μA/lm and resolution close to 60 lp/mm [82]. This performance level makes CORE tubes a serious rival of low cost Gen 2 tubes.

9. Conclusions

Night vision based on technology of image intensifier tubes is the oldest electro-optical surveillance technology. However, in spite of strong competition from thermal imagers, visible/NIR cameras and digital night vision, this old mature technology is still in a phase of growth. There are no signs of possible demise of classical optical NVDs in near future.

Night vision is a fully matured technology that has found mass applications in both military, security and defence sectors. NVDs are offered on international market in form of a long series of devices of different design configuration, type of image intensifier tube, type of night vision optics, and performance. Proper understanding and evaluation of NVDs is a complicated task as many details are to be taken into account.

This review of modern night vision technology can help readers to understand sophisticated situation on international night vision market. However, reading of literature on characterization and testing of night vision devices, and analysis of dynamic situation in trends of night vision technology is recommended as a supplement to this paper.

References

1. A. Rogalski, "History of infrared detectors", *Opto-Electron. Rev.* 20, 279–308 (2012).
2. www.atncorp.com
3. International military catalogue – Night vision products, ITT Night Vision, 2010
4. www.nightvision.com
5. www.vectronix.ch
6. www.optixco.com
7. www.inframet.pl/computer_simulators.htm
8. *The Avionics Handbook*, edited by Cary R. Spitzer, Boca Raton, 2001.
9. www.nightvisioncn.com/sdp/625512/4/cp-3235901/0/Evaluating_Night_Vision.html
10. en.wikipedia.org/wiki/Image_intensifier
11. Image Intensifiers catalogue no. TII 0004E02 IP, Hamamatsu Photonics K.K, 2009
12. www.nightvision.com/products/military/case_study-gen3.htm
13. www.photonis.com/en/night_vision
14. aunv.blackice.com.au/cgi-bin/nightvision/forum?index=discussions&story=omni
15. www.exelisinc.com/News/PressReleases/Pages/Omni-VIII.aspx
16. L. Bosch, "Tube performance that matters", *Proc. SPIE* **4128**, 65–78, (2000).
17. MIL-I-49453 CR, Image intensifier assembly, 18 millimiter microchannel wafer, MX 10130/UV, 1989
18. www.colutron.com

19. www.stanfordcomputeroptics.com
20. *Introduction to scientific imaging*, Roper Scientific Inc., 2002
21. www.night-tronic.de/Seite-116
22. www.vectronix.ch/#/en/news_press/current_news/indotarsius
23. www.sidley.com/db30/cgi-bin/pubs/Statement_of_Facts.pdf
24. nightflightconcepts.com/pdf/LaserDefense/LaserArmorLIF_Datasheet_v4_LowRes.pdf
25. www.angenieux.com/zoom-lenses/index.php?rub=5
26. www.thalesgroup.com/TopOwlH.aspx
27. H. L. Task, Night vision devices and characteristics, *Amstrong Laboratory Report* ASC, 91–2961 (1992).
28. www.aviationtoday.com/av/categories/military/Two-Ways-to-See_1159.html
29. MIL-STD-3009, Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible, 2001.
30. www.transvaro.com.tr
31. www.vectronix.ch/#/en/products/handheld_equipment/image_intensifiers
32. MIL-G-49313CR, Goggles – night vision AN/PVS-7B, 1989
33. MIL-A-49425(CR), Aviator's night vision imaging system AN/AVS-6, 1989
34. MIL-PRF-49082E, PERFORMANCE SPECIFICATION VIEWER, DRIVER'S, NIGHT VISION, AN/VVS-2(V, 1999
35. MIL-PRF-49063E, NIGHT VISION SIGHT, INDIVIDUAL SERVED WEAPON AN/PVS-4, 1999.
36. MIL-PRF-49065F, NIGHT VISION GOGGLES, AN/PVS--5, 1999.
37. MIL STD 1858, Image intensifier assemblies, performance parameters of, 1983.
38. MIL-PRF-49052G "Image intensifier assembly, 18 millimiter microchannel wafer, MX-9916/UV, 1999.
39. MIL-PRF-49428 "Image intensifier assembly, 18 millimiter microchannel wafer, MX-10160/AVS-6, 1995.
40. MIL-STD-1858, Image intensifier assemblies, performance parameters of; 1981
41. MIL-I-49453 CR, Image intensifier assembly, 18 millimiter microchannel wafer, MX 10130/UV, 1989
42. GOST 21815.0-86-GOST 21815.17–86 Image intensifier tubes – Measurement methods of optical and photometric parameters, 1987 (in Russian).
43. Stanag no. 4348, Definition of nominal static range performance for image intensifier systems, 1988 (annulled in 1996).
44. STANAG No. 4351, Measurement of the minimum resolvable contrast (MRC) of image intensifiers,1987 (annulled in 1996).
45. Tender Enquiry No 2/Tech/2007(1)– for Night Vision Device, Ministry of Home Affairs Government of India.
46. Request for Proposal (RFP) No : PC-28706/ACSFP/PNVB/A/ARTY dated 01 Dec 10., GOC-in-C, Northern Command, C/o 56 APO, India.
47. Global tender inquiry no TE No. U.II. 871/2010-11-PROC--IV dated the 02 August, 2010, India.
48. International Traffic in Arms (ITAR) per title 22, Code of Federal Regulations (CFR), Parts 120–130.
49. EC Regulation No WE 428/2009: Community regime for the control of exports, transfer, brokering and transit of dual-use items.
50. Addendum to GEN-09-ASAM-01, Aviation Safety Action Message, Updated Night Vision Device (NVD) Maintenance, 151130Z OCT 09, 2009.
51. www.hoffmanengineering.com
52. www.inframet.com
53. K. Chrzanowski, "Present status of night vision metrology", *OPTRO 5th Int. Symp. on Optronics in Defence and Security*, Paris, 2012.
54. www.nightvisionstore.com
55. www.angenieux.com/zoom-lenses/index.php?txt=38
56. www.armedforces-int.com/suppliers/defence-vision-systems.html
57. www.emccd.com/what_is_emccd
58. www.intevac.com
59. www.photonics.com/Article.aspx?AID=25144
60. www.flir.com/cvs/cores/view/?id=54460
61. www.photonis.com/en/ism/106-l.html
62. www.jayceooi.com/2009/10/04/tft-lcd-vs-oled-which-one-to-choose/
63. www.printedelectronicsnow.com/articles/2012/06/emagins--amoled-displays-enjoy-success-in-military
64. C.V. Driessche, F. Coursaget and F. Berthault, "IR-CMOS fusion for night vision", *5th Int. Symp. on Optronics in Defense and Security*, Paris, 2012.
65. www.microoled.net/news/news-from-microoled
66. www.insighttechnology.com/products-insight/fgs
67. airsoftinformations.blogspot.com/2010/04/envg-enhanced--night-vision-goggle-anpsq.html
68. www.sidley.com/db30/cgi-bin/pubs/Statement_of_Facts.pdf
69. www.ulis-ir.com
70. www.globalsecurity.org/military/systems/ground/envg.htm
71. www.altaoptica.ru
72. www.obzerv.com
73. www.sensorsinc.com/LADAR.html
74. S. May, S. Fuchs, D. Droeschel, D. Holz, and A. Nuchter, "Robust 3D-mapping with time-of-flight cameras", *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, St. Luis, 2009.
75. www.angenieux.com/zoom-lenses/index.php?txt=38
76. J.L. Craig and H.L. Task, "Development and evaluation of the panoramic night vision goggle", Air Force Research Laboratory Human Effectiveness Directorate, Report DTIC no. ADA400115, 1999.
77. Peter L. Marasco and H.L. Task, "Optical characterization of wide field-of-view night vision devices", Air Force Research Laboratory Human Effectiveness Directorate, Report DTIC no ADA430272, 1999.
78. Eric E. Geiselman and Jeffrey L. Craig, "Panoramic Night vision goggle update", Air Force Research Laboratory Human Effectiveness Directorate, Report DTIC no ADA430243, 1998.
79. en.wikipedia.org/wiki/Night_vision_device
80. www.elbitsystems-us.com/sensor-electro-optics-solutions/land/soldier/helmet-mounted/quadeye
81. www.insighttechnology.com/image-intensified-systems--products
82. www.nightvisionstore.com/Armasight%20SPARK%20Night%20Vision%20Monocular.htm
83. en.wikipedia.org/wiki/OLED