NVIS COMPATIBILITY
(A PRIMER)

Issue 2.01 – February 1997

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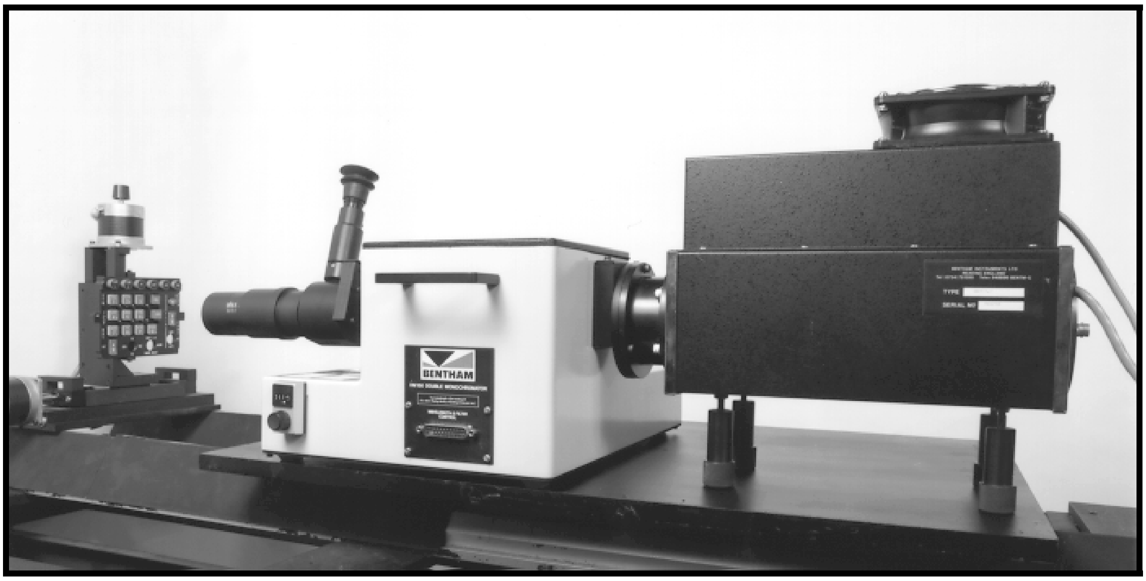
Night Vision goggles (NVG) are a very powerful aid to air crew vision which extend the conditions for successful missions into all night conditions. Light amplification by a factor of several thousand gives crisp, bright images from very low levels of natural illumination (such as overcast star light) under which the unaided human eye would be essentially blind. Thus the air crew, with NVGs mounted on a flying helmet, can look around and survey all the outside scene to study terrain, ground features, potential targets, other aircraft etc. almost as effectively as in normal day conditions.



Typical Bentham NVG Compatibility System

However, the utility of NVG can be compromised by the light from displays or any other light emitting components in cockpit unless their design has been subject to the disciplines of “NVG Compatibility”. These disciplines define, implement and validate the techniques that have evolved to allow displays and NVGs to co-exist in the aircraft in a manner which retains the utility of both NVGs and displays.

Most current purchasing specifications for avionics displays, backlit instruments, illuminated legends, warning lights etc. will have a clause requiring “NVG Compatibility”.

This report outlines the implications of such requirements for avionics design, testing, and test equipment.

The acronym "NVG" is in widespread use but it should be noted that in the USA the term "Night Vision Imaging System" or NVIS was introduced in the MIL-L-85762A specification and is the formally preferred term.

2.1 NVG Technology

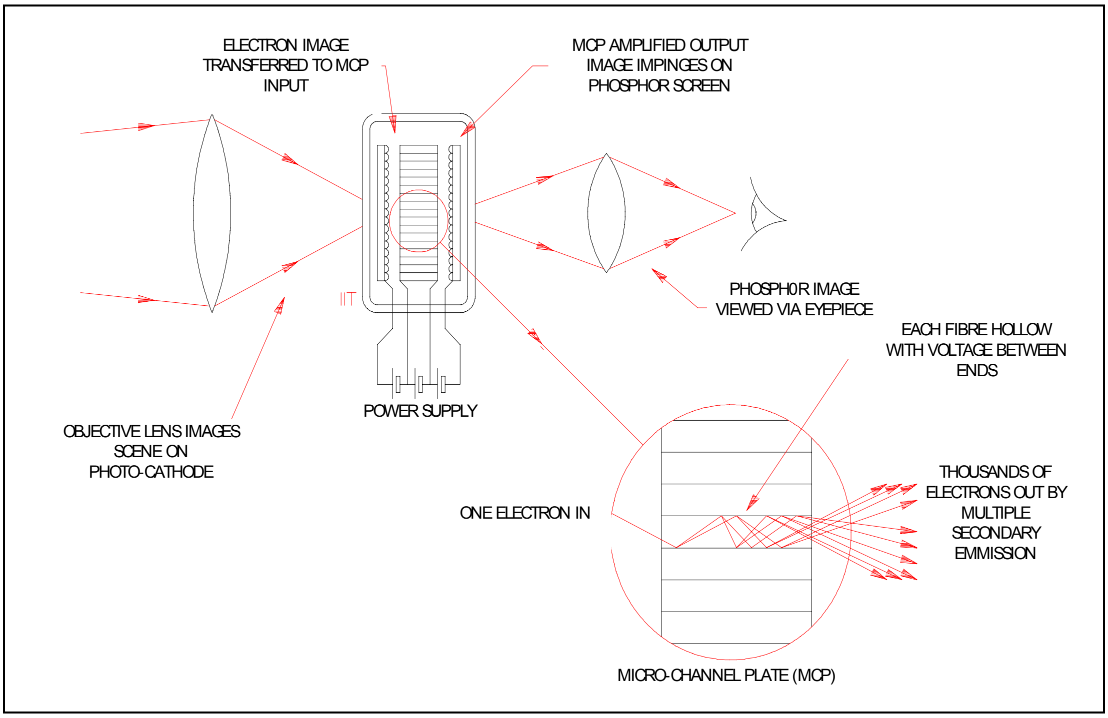


Fig. 1 NVG Operation

There are many configuration variations but all NVGs have as their key component an image intensifier tube (IIT) which provides the light amplification function. The basic NVG is depicted in Fig. 1. An object lens images the outside scene, via the IIT input window, on to the photocathode. Each part of the photocathode emits electrons in proportion to the local illumination and the resultant electron image is transferred by a voltage gradient to the input surface of the micro-channel-plate (MCP). The MCP comprises a multiplicity of hollow glass tubes fused together to form a plate but with each tube acting independently as an electron multiplier. Input electrons impinging on the inner wall emit secondary electronics with a modest electron gain but each secondary is accelerated along the tube to the next impact to give a further electron gain. This process is repeated many times until a shower of electrons exit from the tube with a net electron gain of thousands.

The amplified electron image from the MCP is accelerated across a small gap to a phosphor screen to yield a visible image which is the same size as the image on the input window but very much more bright.

The Image Intensifier Tube requires some applied high voltage which comes from a DC/AC converter wrapped around the IIT. The detail of NVG design and manufacture are very complex and various configuration options have arisen.

The detail features that have a place in compatibility discussions are:-

a) Wavelength Range

The wavelength responsivity of NVGs, an important issue for compatibility, is determined partly by the IIT technology and partly by the filters in the NVG input optics.

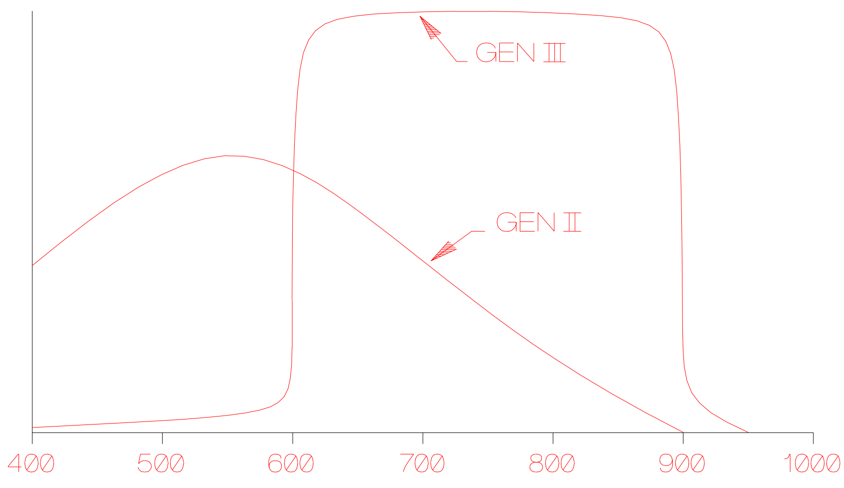


Fig. 2 Raw Intensifer Response

The latest IIT technology, known as “Gen. III”, uses a gallium arsenide photocathode and exhibits wavelength responsivity as indicated in Fig. 2 which shows that the major part of the response is in the red end of the visual spectrum and in the infra-red out to 900nm. The responsivity is relatively low in the green and blue part of the visual spectrum but the very high gain of the MCP results in a green/blue sensitivity which is far from negligible.

The earlier “Gen II” IIT technology uses a multi-alkali photocathode with lower overall sensitivity and wavelength responsivity peaking in the visible range as indicated in Fig. 2.

The advantage of Gen III is more pronounced than indicated by Fig. 2 because moonlight and starlight spectral distribution is biased towards the IR region and because natural foliage has higher reflectivity in the IR.

The Gen III based NVGs are now universal in military aircraft applications, but the Gen II devices continue to be used by ground troops.

Most NVGs also include a filter in the input optics to control or sharpen the short wavelength cut-off (a "minus-blue" filter) as part of the strategy for allowing NVGs and displays to co-exist. The details are discussed in section 2.3

b) Optical Configuration

The direct-view optical configuration as used in the US ANVIS devices is like the scheme shown in Fig.1 but with two identical systems in binocular style.

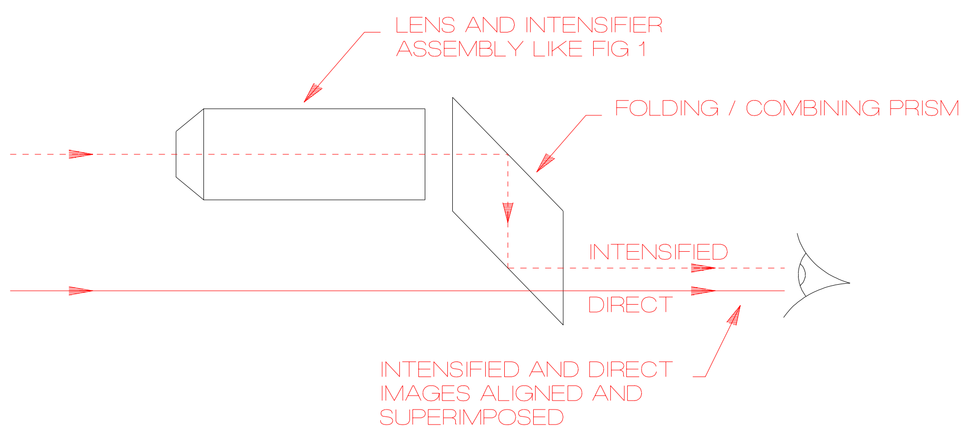


Fig. 3 The Projected Image Configuration

The eye-piece design allows sufficient eye-relief to allow viewing of the aircraft instrument panel by looking under the NVGs.

The projected - image configuration, used in the GEC "Cats Eyes" NVGs, was devised to solve an NVG compatibility problem particular to Head-Up Displays (HUDs) by providing two superimposed image paths as depicted in Fig. 3.

The rationale for this configuration is discussed later in section 2.5.

c) Gain

A parameter which is often useful but which must be used with some care is the ratio of the output image luminance to the scene luminance known as the "NVG gain".

The need for care arises because the NVG Gain is not just a property of the NVG device but is joint property of the NVG and the scene. Two extreme examples illustrate this:-

- The scene emits only blue light at 450nm where the NVG has very low response. The NVG Gain parameter will therefore be near zero.

- The same NVG but with a scene emitting only at 800nm. By definition the scene luminance is zero so the NVG Gain is infinite!

A benchmark test for NVG evaluation is based on a source having the characteristics of a Black-Body Radiator at 2856K and the NVG Gain with such a source is termed the System Gain.

The 2856K Black-Body is a convenient source because:-

- It is a universally understood definition with a well defined ratio between infra-red energy and visible energy.

- It is a rough approximation to natural moonlight spectral distribution.

- A practical embodiment in the form of CIE Illuminant A will be found in many lighting laboratories.

For current NVGs used in military aircraft a System Gain in the range 2000 to 4000 will be encountered.

d) Automatic Gain Control (AGC)

The high voltage supply to the micro-channel plate is configured such that when the current drawn exceeds a fixed threshold value the applied voltage, and hence the gain, is progressively reduced so that the brighter scenes can still show a range of grey-shades. This AGC action limits the output image luminance to something in the region of 5 cd/m^2.

2.2 How Does Incompatibility Arise?

First, it must be emphasised that the concern is about emissions from displays interfering with the performance of the NVGs and it is not a concern about how the displays look when viewed through NVGs. Apart from two special cases the usual mode of use is to view the displays or anything else in the cockpit by looking under the NVGs via the eye-relief.

The incompatibility arises because of the extreme disparity between the luminance of the out-front scene (maybe 0.001 cd/m^2) and the luminance of displays and controls (maybe 2 cd/m^2) giving rise to effects such as:-

a) False Targets

Direct reflections of the display in the cockpit canopy or even reflections of passive objects in the cockpit which are illuminated by the display can yield spurious out-front images through the NVG which can either be mistaken for real targets or can obscure features of interest. Because of the disparity of levels troublesome false images can arise even from reflection paths with very low reflectance factors.

b) Loss Of Image Contrast

If radiant energy from sources other than the target of interest can reach the IIT photocathode and if those sources are bright they will have the capability of invoking the AGC action (see section 2.1(d)) thus reducing the gain even if the brightness of the target of interest does not warrant gain reduction. Unwarranted gain reduction of course leads to loss of contrast in the target of interest.

This type of AGC invocation can arise from:-

- Having the NVG point-of-gaze just above the coaming so that the typical 35 degree field of view embraces some of the light emitting items on the instrument panel.
- Internal reflections within the NVG objective lens assembly which allow energy from well outside the NVG field of view to get to the IIT.

c) Loss Of Security

A cockpit full of displays, warning lights, illuminated controls etc. radiates a lot of light out through the canopy and announces the aircraft presence very clearly to hostile forces either in the air or on the ground especially if they are equipped with NVGs. This factor is not strictly an NVG compatibility issue but it is obviously related and will need to be taken into account in the cockpit lighting design.

2.3 Wavelength Partition

The co-existence problems discussed in paragraph. 2.2 have been addressed successfully by introducing the wavelength partition concept sometimes called Complementary Filtering. This concept recognises that best utilisation of the human eye performance requires wavelengths in the range 400 to 650nm and that the strongest signals from moonlit foliage are in the region above 650nm. Thus if the wavelength utilisation is partitioned into an “eye-domain” and an “NVG domain” and two rules are strictly enforced:-

a) Displays and light-emitting devices shall emit no radiant energy outside the “eye-domain”.

b) NVGs shall have zero response outside the “NVG domain”.

Then displays and NVGs can co-exist without mutual interference.

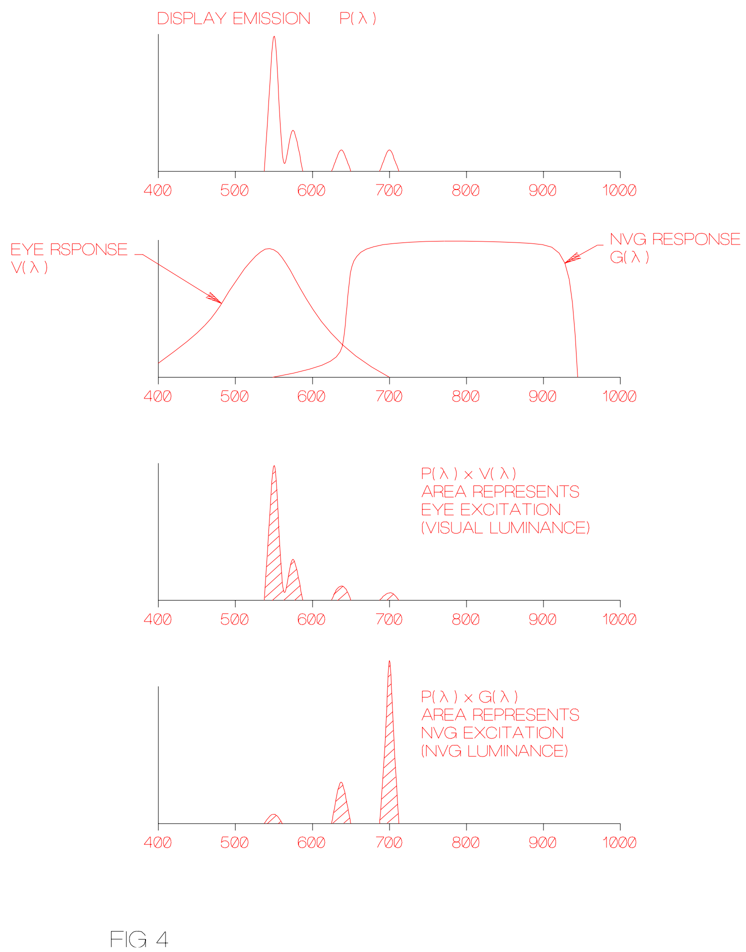


Fig. 4

In practice of course features like "zero emission", "zero response" and sharp domain edges can not be implemented. There is also complication arising from differing areas of application preferring differing compromises on where the dividing line between "eye" and "NVG" is put, resulting in a multiplicity of compatibility specifications.

The intent of the specifications is to define the wavelength partition rules and means of enforcing the rules which is usually done in the following manner:-

a) An NVG wavelength response function is defined numerically over a range which includes the visible wavelengths where the NVG response may be small, but not zero. Note that this response function is some sort of nominal that is deemed to apply for the purpose of quantifying compatibility for that type of NVG, but which may not actually match any particular sample of NVG.

b) A limit is put on the display total emission in the NVG region when the emission is weighted by the NVG response in (a) above.

c) The emission in the NVG region is dependant on a brightness control setting which may cover a wide range so it is usual to define some type of normalisation process to yield a figure of merit which is the ratio of emission in the NVG region to luminance.

The concept described here and illustrated in Fig. 4 is sometimes referred to as “Complementary Filtering”. In this way of describing the solution the starting point is a raw lighting component with emissions in the NVG domain, a raw NVG response which extends into the visible domain. Compatibility is achieved by imposing a short-pass filter on the lighting component and a long-pass filter on the NVG. The two filters are complementary in the sense that one pass-band takes over where the other leaves off as illustrated in Fig.4(a).

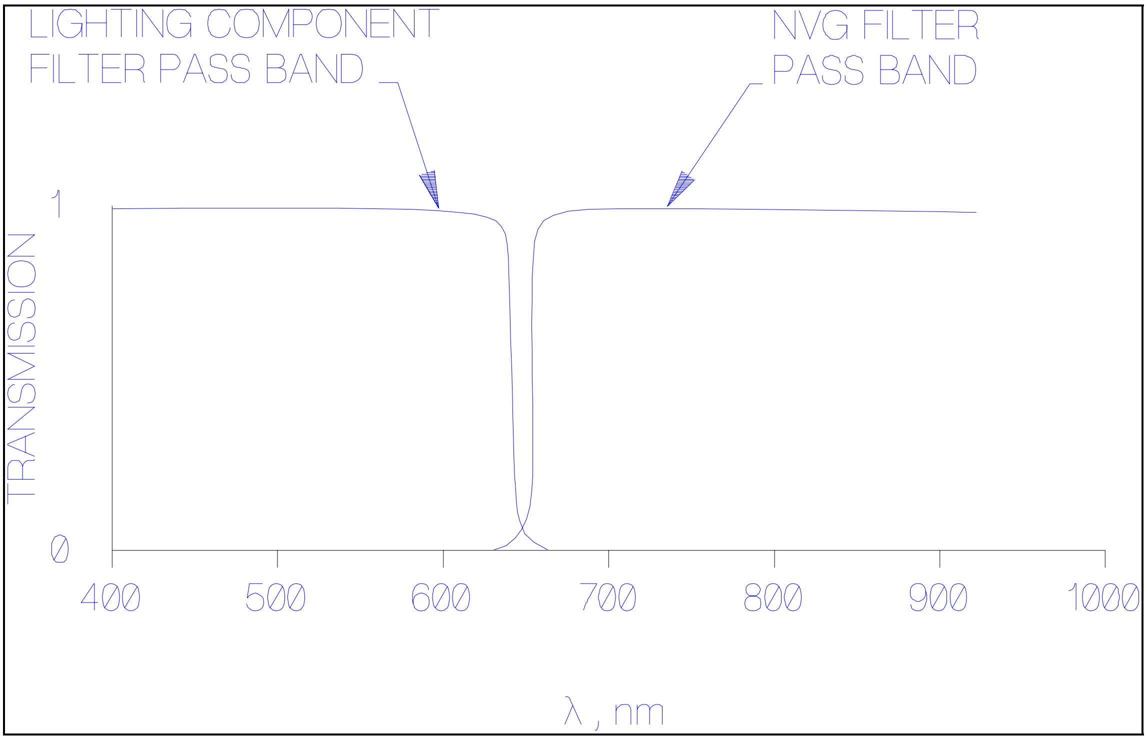


Fig 4a Complementary filters

2.4 Display Properties For Compatibility

In the first instance compatibility requires that the emission in the NVG band is brought below a prescribed limit as defined in a specification such as MIL-L-85762A. At the same time the display will have to meet requirements for direct visual performance in respect of luminance, contrast, colour etc. but often a conflict will be found between these requirements and the compatibility criterion. For example a short-pass filter needed to reduce the IR emission may reduce the luminance by a factor of 2. For night use this is no problem because the drive to the display device can be increased, but for full daylight use the display device is already fully driven so there will be a serious loss of daylight visibility. Any idea of making the filter detachable for daytime use is out of court because the handling and stowage of loose items during flight will be a hazard to the air crew.

There are likely to be several such design compromises just to meet the NVG band emission requirement but, whether or not it features in specifications, the emission properties as a function of angle must be considered very carefully:-

a) Viewing Angle

The cockpit geometry and aircrew anthropometry will dictate a viewing angle envelope over which the display must maintain its visual properties.

b) NVG Compatible at all angles

The emissions in the NVG domain should not increase outside the desired viewing envelope because the radiation paths for NVG degradation can involve all angles of emission.

c) Secure Lighting

In many applications there will be benefits from attenuation of all emissions outside the normal viewing angle envelope both in respect of less radiation bouncing around the cockpit but also reduction of external lighting signature for covert operation.

2.5 Viewing Of Displays Through NVG

As noted in section 2.2 it is not normal for displays to be viewed through NVGs. The NVG objective lens is set for infinity focus so that items within the cockpit will yield an out of focus NVG image. Since the image is also in monochrome it would not be of much use for viewing head-down instruments.

Solutions to the focusing problem have been found but the overriding factor is that it is much easier for the pilot to tip his eyes down to see under the NVG for a glance at the instrument panel than it is to move the whole head to bring the instrument into the NVG field of view.
There are two special cases where viewing through the NVG is needed namely, head up displays and central warning lights which are discussed in sections 2.5.1 and 2.5.2.

2.5.1 Head Up Displays (HUD)

The HUD projects symbology and images into the pilot's central forward view via a combiner glass as depicted in Fig. 5. The image is collimated to appear at near infinity distance so that the information it conveys can be quickly assimilated by the pilot without any re-direction of gaze or any re-accommodation. When using NVG the pilot will need to see the HUD information super imposed on the forward scene just as it would be without NVG. Because the HUD image is collimated there is no focusing problem but there is a brightness problem. If the normal NVG compatibility rules are applied in which the NVG band emission of the HUD is reduced to zero then the HUD will not be seen, but if the rules are not applied its image will invoke the AGC in the NVG and suppress the NVG forward view.

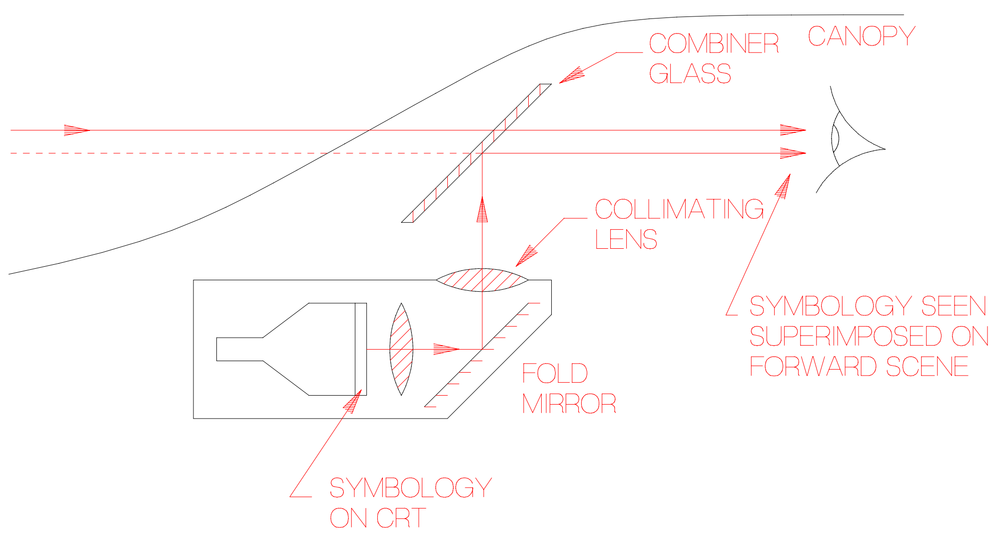


FIG 5 HEAD-UP DISPLAY

Three different solutions to this are being used:

a) Designing the HUD for low NVG band emission but contriving a small controlled amount of emission into the bottom end of the NVG band, such that a readable but not excessively bright image of the HUD appears in the NVG. This could be termed the "red-leak" approach because the NVG is responding to wavelengths in the visible red region. This approach can be made to work but suffers from two drawbacks:-

- The net magnitude of the "red-leak" depends upon proportion of red emission in the normal HUD green phosphor and the magnitude of the actual NVG response in the region of it's band-edge. These are both ill-defined parameters.

- The optics in the HUD are normally optimised for aberrations with green light.

However, the "red-leak" approach enforces operation at red wavelengths also so that compromises in optics performance have to be made.

b) An approach which is sometimes known as "green-leak" was introduced by DRA Farnborough for use in some UK aircraft programs. This uses a direct view optical configuration but with a specially formulated entrance filter chosen to optimise the HUD + NVG operation. This filter has a sharp cut-off below 645nm but has a subsidiary transmission peak around 550nm (the green-leak) yielding the NVG response as indicated in fig. 6. The wavelength and magnitude of the green-leak is chosen to yield a suitable NVG image brightness from the green component of the HUD emission.

This concept yields good compatibility of the HUD and NVG but inevitably makes the NVG more vulnerable to degradation by all other cockpit light sources which have a green component.

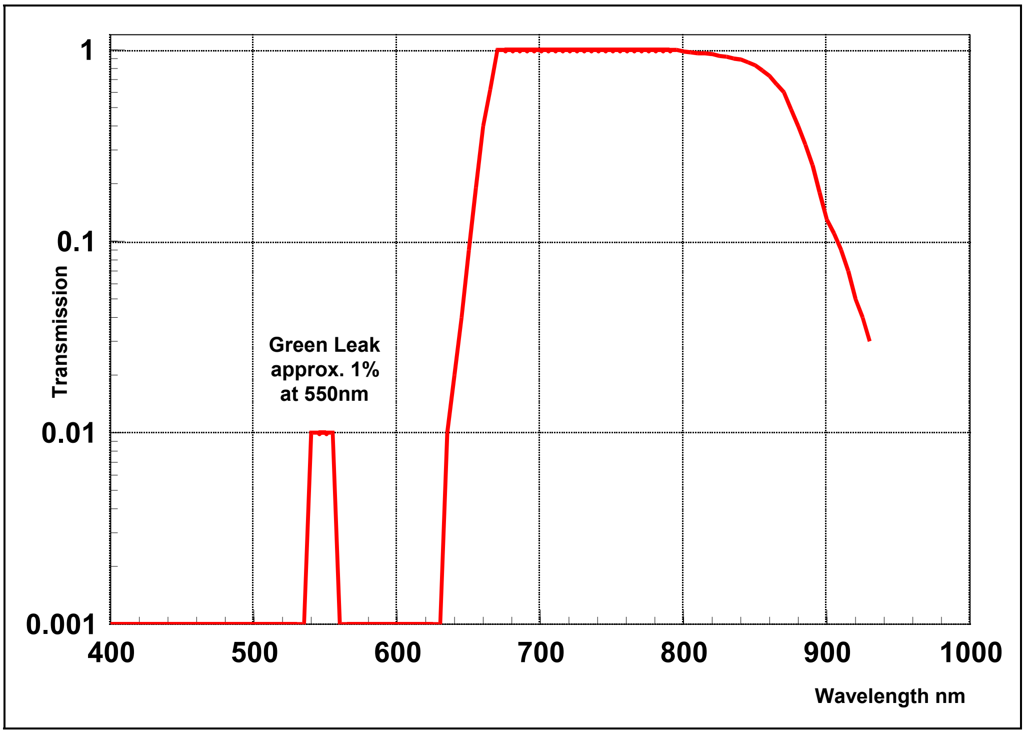


Fig. 6 "Green leak" NVG Response

c) The third concept for accommodating the HUD is the projected image type of NVG illustrated in fig. 3.

Here the symbology of the HUD is viewed directly via the combiner glass of the NVG, the forward scene is captured by the usual intensifier and optics and then the NVG combiner prism superimposes the intensified forward scene and the HUD images. The HUD is designed to emit very low energy in the NVG domain (i.e. the same basic compatibility rules as other displays) but for slightly different reason. If the HUD emission extends into the NVG band there will be two HUD images presented to the aircrew - one direct and one via the intensifier. This double imaging has to be avoided otherwise the inevitable small misregistration of images will cause loss of image resolution.

2.5.2 Central Warning Lights

This is the second type of device which needs some visibility via the NVG. A central warning light, when activated, must immediately get the aircrews' attention even when they are using NVGs and are concentrating on something in the outside world. To this end the NVG band emissions from the warning light are controlled but at a level which would normally be regarded as degrading the NVG performance so that the aircrew are aware of the flashing light even when it is outside the NVG field of view. The temporary degradation of NVG performance does not matter because the aircrew will immediately acknowledge the warning and extinguish the warning light.

Most purchasing specifications for avionics equipment involve one of two specifications to define the NVG Compatibility:-

- US MIL specification MIL-L-85762A
- UK Working Paper 6 from DRA, Farnborough.

For the EFA aircraft program British Aerospace have devised their own specification but occasionally a requirement will be expressed simply as "compatible with Gen III NVG" with no further details, where clearly the customer needs guiding into a closer statement of requirements.

There is a UK document DEF STAN 00-970, chapters 115 and 116, which provides comprehensive discussions about the compatibility issue but introduces no numerical specifications. Instead it refers to the other specifications discussed here but puts responsibility on the aircraft design authority to choose a specification and insert values.

All of the specifications are concerned with defining and policing the wavelength partition concept and all of them invoke the ratio of eye-weighted radiance to NVG-weighted radiance:

$$\text{Eye-weighted radiance } (R_E) = \int P(\lambda)V(\lambda)d\lambda \qquad \text{[Eqn 1]}$$

which is proportional to luminance and represents the brightness producing property of the radiation.

$$\text{NVG-weighted radiance } (R_G) = \int P(\lambda)G(\lambda)d\lambda \qquad \text{[Eqn 2]}$$

which is proportional to NVG output luminance and represents the NVG excitation property of the radiation.

Where $P(\lambda)$ = Power spectral density of the light source.
$V(\lambda)$ = CIE Photopic Eye function.
$G(\lambda)$ = NVG relative spectral response.

The ratio of these two integrals :-

$$\frac{R_G}{R_E} = \frac{\int P(\lambda)\, G(\lambda)\, d\lambda}{\int P(\lambda)\, V(\lambda)\, d\lambda}$$

appears in all the specifications but usually hidden by various constants and procedures.

It is important to remember this implied ratio because it not only guides the interpretation of specifications but has an impact on the way measurements are performed.

3.1 <u>Specification MIL-L-85762A</u>

This US tri-service specification was issued on 26 Aug 1988 to replace the earlier MIL-L-85762 and to embrace further categories of NVGs and displays. It should be noted that the specification also controls issues such as brightness and contrast in full sunlight which are important issues but are not strictly part of NVG Compatibility.

The specification is highly structured and detailed and is regarded, particularly in the US, as the definitive specification such that if an item complies with this specification then it is by definition NVG compatible. This author has found out the hard way that this reputation is not entirely warranted! The important topics covered by the specification are:-

- The scope of the specification
- Colour definitions
- NVG band emission limits
- Test procedures

3.1.1 Scope of MIL-L-85762A

The specification embraces both the direct-view NVG (as sketched in fig. 1) exemplified by the AN/AVS-6 which is termed a type I device and the projected - image NVG (as sketched in fig. 3) exemplified by the GEC "Cats Eyes" which is termed the type II device. In general different emission limits apply to the two types but the most significant impact is in the compatibility with Head-Up displays.

The specification embraces two differing wavelength response functions termed Class A and Class B. The Class A response extends down to 625nm and is essentially the same response as specified in the original MIL-L-85762. Because the Class A response is above 1% down to 600nm it is impossible to have a red lighting component compatible with Class A. The Class B response, which cuts-off at 655nm instead of 625nm, was introduced in MIL-L-85762A so that full-colour electronic displays were no longer ruled-out. The Class A and Class B responses are depicted graphically in Fig. 7.

The definition of two types and two classes logically creates four configurations but in practice only two have been invoked:-

- Type I, Class A for rotary-wing aircraft applications.
- Type II, Class B for fixed-wing aircraft applications.

The specification embraces various categories of lighting components (such as primary instruments, Head-Down displays, Head-Up display etc.) and for each category assigns limits to colour, emission in the NVG band and the luminance at which it is to be measured.

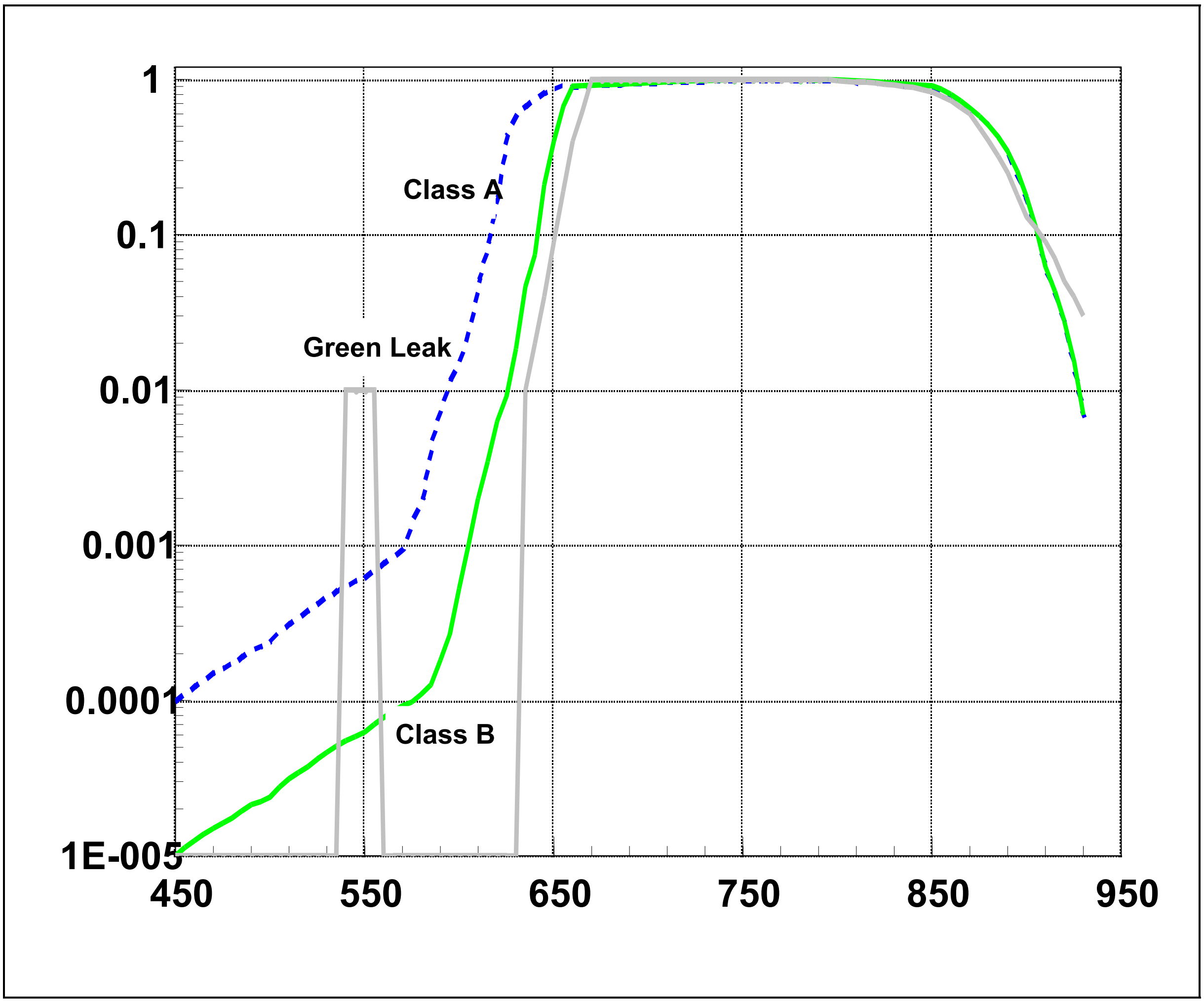


Fig. 7 Comparative NVG responses

3.1.2 Colours

The wavelength partition principle puts constraints on the longest wavelengths than can be utilised by a lighting component so that some colours will not be available and others will be available with difficulty and/or low power utilisation efficiency.

To avoid the situation of a multiplicity of detail colour compromises the specification standardises a few colours that are known to be realisable within the NVG compatibility rules. This set of colours known as NVIS Red, NVIS Green etc. are defined and toleranced in CIE 1976 u', v' chromaticity co-ordinates as depicted in Fig. 8. Note that the circle centres are not to be regarded as nominal values because all the centres (except NIVS Green A) lay beyond the range of physically possible values.

The compliance with NVIS chromaticity co-ordinates is often a necessary condition for NVG compatibility.

However, it may be necessary but it is not sufficient.

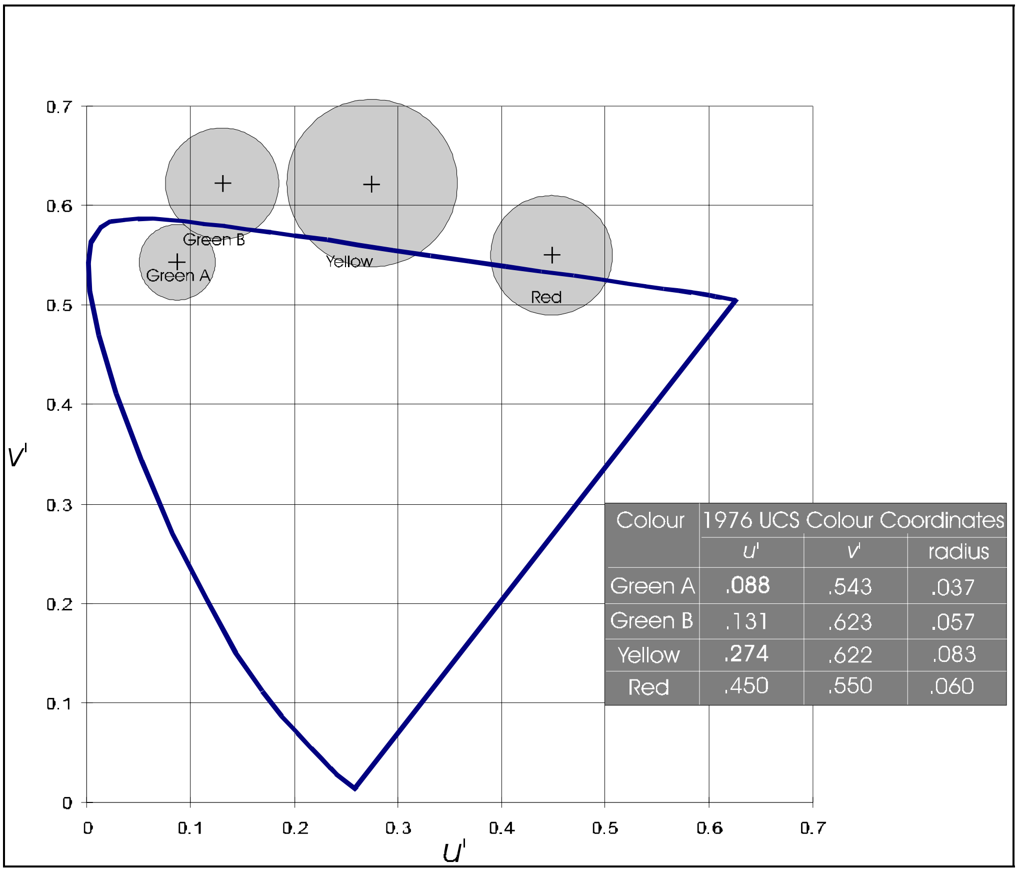


Fig. 8 NVIS Colours in CIE 1976 UCS

3.1.3 NVIS Radiance

This specification puts limits on the "NVIS Radiance" parameter for a lighting component which has been set for a specified luminance.

NVIS Radiance is the NVG-Weighted Radiance parameter defined by Eqn 2 at the start of section 3. The specification does not explicitly assign units to NVIS Radiance but the implied units are W $cm^{-2}sr^{-1}$. The luminance is defined in ft L units so a limit would be expressed, for example, as

$$NRB \leq 1.7 \times 10^{-10} \text{ at } 0.1 \text{ ft L}$$

where NRB means NVIS Radiance in W $cm^{-2}sr^{-1}$ when assessed against the Class B response function.

The formulation specifically allows the measurement to be performed at other than the specified luminance provided that the NVIS Radiance is pro-rata scaled.

Scaling in this way effectively expresses the limit as an NVG Weighted Radiance: Eye Weighted Radiance ratio, albeit in the clumsy units of W $cm^{-2}sr^{-1}$ ft L^{-1}. This ratio

property assists in comparison between specifications (see section 3.4) and offers useful measurement conveniences. (see section 5.2 and 6.3)
It must be remembered, however, that significant scaling is valid only if there is no change of spectral distribution between the specified luminance and the test luminance. The emission from CRT phosphors for example mostly have spectral distributions which are independent of drive level but the common incandescent lamp shows a higher infra-red to visible energy ratio as it is dimmed.

3.1.4 Test Method

The specification recognises only spectroradiometric methods of showing conformance with chromaticity and NVIS Radiance requirements and moreover specifies the spectroradiometer performance in much detail.

Despite the detail, it has omitted some important factors such as:

- The all important noise level and sensitivity requirements of a spectroradiometer are not accompanied by any statement about the size of the emitting area being measured.

- Nothing is said about the viewing angle for measurement.

There are test methods and measuring equipment which are entirely valid but which are outside this specification, some of which are described in section 5.

It is this author's experience that avionics customers will accept other test methods provided that the validity and rationale can be demonstrated.

3.2 FS(F) Working Paper No. 6

This document, usefully read in conjunction with FS(F) Working Paper 160/87, is not a specification but more a set of guidelines which does include some numerical recommendations.

3.2.1 Green/Red Ratio

It introduces a parameter termed the "green/red ratio" which is exactly the ratio of Eye-Weighted radiance to NVG Weighted radiance discussed at the start of section 3, with no other constants. It is a true dimensionless parameter so is independent of the units in which spectral radiance is measured. It is unfortunate that unnecessary confusion has arisen from:-

- The name "green/red ratio" misleads into ideas that it is something to do with colour or chromaticity.

- A high value is associated with low excitation of the NVGs which is the converse of the two other common metrics: NVIS Radiance and NVG Gain.

It would have been preferable to have inverted the ratio.

3.2.2 Limits

The central part of the document's recommendations are in the form of some Green/Red ratio limits which are a function of two variables:-

- Where the lighting component is installed in the cockpit.
- The type of component in relation to it's operational function.

The limits are advisory and show a range for each configuration to make room for optimisation in each application. The emerging practice is for the aircraft constructor, with the advice of DRA Farnborough, to define a specific limit for Green/Red ratio for each lighting component of an aircraft program.

3.2.3 NVG Response Function

Working Paper 6 defines a response function with a long-pass cut-off at 645nm (i.e. somewhere between the Class A and Class B responses of MIL-L-85762A).

However, the "green-leak" concept to solve the HUD compatibility problem which is introduced in Working Paper 160 appears to have become a de-facto UK standard. Just as each aircraft program has Green/Red ratio limits assigned each program is also defining the NVG response function so that there is no single agreed version of the "green-leak" function. The illustration in Fig.7 uses the function defined for the Tornado Mid-Life-Update program.

3.2.4 Test Methods

Working Paper 6 does not dictate any test methods or instruments but it does describe a simple and effective method of quantifying emission in the NVG band.

A silicon-diode photo sensor, whose response naturally extends up to 1100nm, is provided with two filters which are used in turn:-

a) A filter which in conjunction with the photo sensor response will yield the $V(\lambda)$ photopic eye response. Such a filter is of green appearance.

b) A filter which in conjunction with the photo sensor response will yield the NVG response function. Such a filter is of red appearance.

The method is to take readings of photo diode output using the green and red filters in turn and the ratio of the two readings is the Green/Red ratio. Some correction factors have to be established and applied to account for filter insertion loses and other systematic errors from non-ideal filter characteristics.

3.2.5 Colours

No lighting colours are explicitly defined but there are recommendations. The NVIS colours of MIL-L-85762A are acknowledged and found to be acceptable but there are strong warnings to avoid highly saturated blue and green colours.

3.3 EFA Lighting Standard

British Aerospace have done much in-house work on the modelling of various lighting and visibility issues in the military aircraft cockpit. One result of this work is a Lighting Standard specification which is invoked in purchasing specifications for the EFA aircraft program, one small part of which addresses NVG compatibility. Only two aspects are covered:-

a) A numerical definition of the NVG response function that is deemed to apply. The response function is of the "green-leak" type.

b) A value is assigned to the overall sensitivity of the NVG so that the ratio NVG-Weighted radiance: Eye-weighted radiance can be converted to NVG Gain. As defined in para 2.1 (c) NVG Gain refers to the ratio of NVG output luminance to light source luminance.

The NVG Gain is a physically comprehensible parameter compared to the numerical abstractions such as NVIS Radiance and Green/Red ratio.

It is unfortunate however, that the NVG sensitivity value is assigned in the Lighting Standard is low compared to operational NVG

The Lighting Standard does not itself put limits on NVG Gain. These limits are imposed separately for each individual equipment in the equipment purchasing specification.

3.4 Specification Equivalences

We have seen that there are three compatibility metrics in use:

- NVIS Radiance at a specified luminance
- Green/Red ratio
- NVG Gain

The defining equations for these are:

$$\text{NR} = \int P(\lambda)G(\lambda)d\lambda \quad)$$

$$\quad)$$

$$\text{Luminance} = 1.99 \times 10^6 \int P(\lambda)\, V(\lambda)\, d\lambda \quad)\ P(\lambda) \text{ in } W.cm^{-2}sr^{-1}\, nm^{-1}$$

$$\text{Green/Red Ratio} = \frac{\int P(\lambda)V(\lambda)d(\lambda)}{}$$

$$\int P(\lambda)G(\lambda)d(\lambda)$$

$$\text{NVG Gain} = \frac{Kg}{683} \cdot \frac{\int P(\lambda)G(\lambda)d(\lambda)}{\int P(\lambda)V(\lambda)d(\lambda)} \quad P(\lambda) \text{ in } W.m^{-2}sr^{-1}nm^{-1}$$

Kg = Sensitivity in Lumen/Watt
= 1.36×10^5 for EFA Lighting Standard

From these definitions it is straightforward to derive equivalencies between the metrics. The equivalencies are valid only if the same NVG response function invoked for each parameter.

Between NVIS Radiance and Green/Red ratio

$$\text{Green/Red ratio} = 5.01 \times 10^{-7} \frac{(\text{Luminance, ft L})}{(\text{NVIS Radiance})}$$

Between NVG Gain and Green/Red ratio

$$\text{NVG Gain} = \frac{199}{(\text{Green/Red ratio})}$$

for NVG sensitivity = 1.36×10^5 lum/Watt

Between NVG Gain and NVIS Radiance

$$\text{NVG Gain} = 3.97 \times 10^{8} \frac{(\text{NVIS Radiance})}{(\text{Luminance, ft L})}$$

There are no foolproof recipes or ready made solutions to designing for compatibility - it is more a convergent process of informed trial and error. These days much of the early trial and error can be assessed by numerical modelling on a computer perhaps accompanied by measurements of the properties of candidate materials. This section provides some pointers to the techniques and materials available.

4.1 Establishing Feasibility Boundary

When a new performance criteria appears it is a good idea to locate the boundary between the possible and the impossible, to avoid expending effort on a lot of trials which all fail.

The ideal, but hypothetical, lighting component emits light at just one wavelength which we can choose to be anywhere in the visual range. Such a source is readily analysed against any of the compatibility metrics in sect. 3 to see where the ideal source stands in relation to the performance target we have been set.

If the ideal monochromatic source cannot meet the target then neither will any real source so we stop looking. If the ideal source can meet the target with some margin then a solution is worth pursuing (but not guaranteed to exist!)

As an example suppose the requirement is in NVIS Radiance terms using the Class A response function. The basic NVIS Radiance formulation is

$$NR = \int P(\lambda)G(\lambda)d(\lambda)$$
$$L = 1.99 \times 10^6 \int P(\lambda)\, V(\lambda)\, d\lambda$$

Let P(λ) be a monochromatic source of power P so that the integration is trivial yielding:

$$NR = PG(\lambda)$$
$$L = 1.99 \times 10^6\, PV(\lambda)$$

If we normalise to NVIS Radiance per ft L we get $\frac{NR}{L} = 5.02 \times 10^{-7} \frac{G(\lambda)}{V(\lambda)}$

This function is plotted in Fig. 9 together with some target NVIS Radiance numbers from MIL-L-85762A which shows that:-

a) Primary Lighting requiring NRa< $1.7\ 10^{-10}$ at 0.1 ft L (i.e $\frac{NR}{L}$. = $1.7\ 10^{-9}$) can be met us using wavelengths between 445 and 585nm. Thus blue and green colours should be obtainable, some sort of yellow may be obtainable but red is definitely not possible.

b) A monochrome electro-optics display requiring NR a <1.7^{-10} at 0.5 ft L (i.e. $\frac{NR}{}$ = $3.4\ 10^{-10}$) can only just be met and would have to be green with strict

L
suppression of other wavelengths.

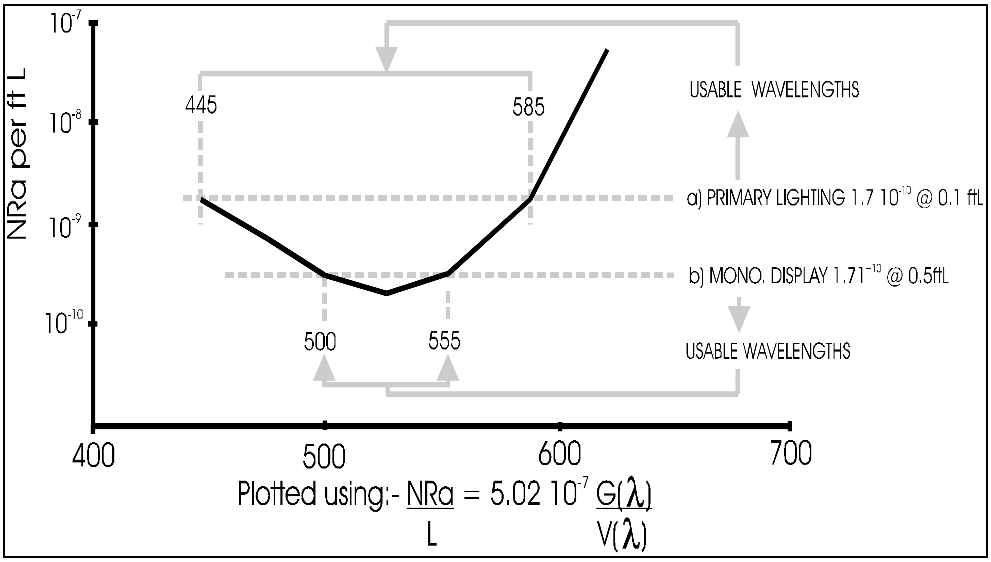


Fig. 9 Limiting Monochromatic NVIS Radiance Example

The principle demonstrated by Fig. 9 can be usefully applied to the commonly encountered NVG response functions and compatibility metrics as shown in Figs 10, 11 & 12.

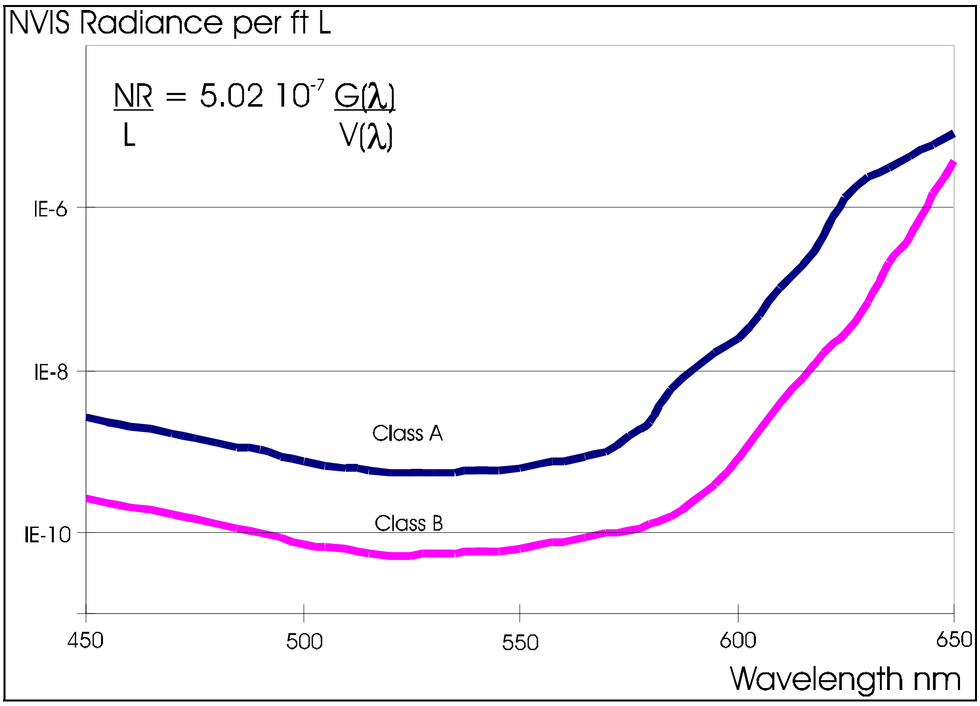


Fig. 10 Minimum NVIS Radiance for hypothetical monochromatic source used with MIL-L-85762A NVG responses

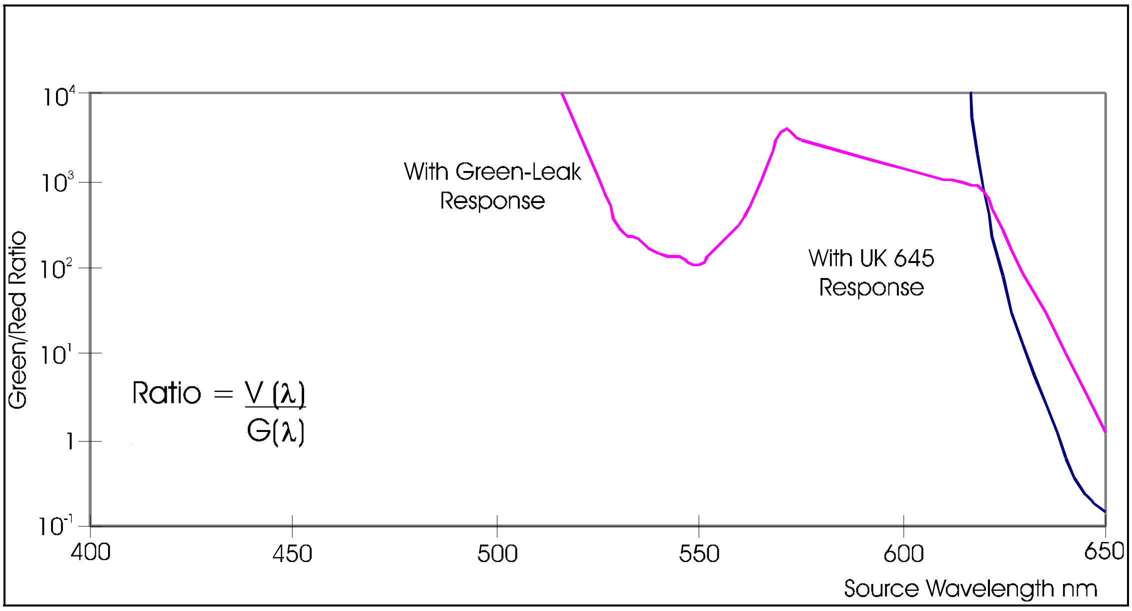


Fig. 11 Maximum GREEN/RED RATIO for hypothetical monochromatic source used with UK NVG response.

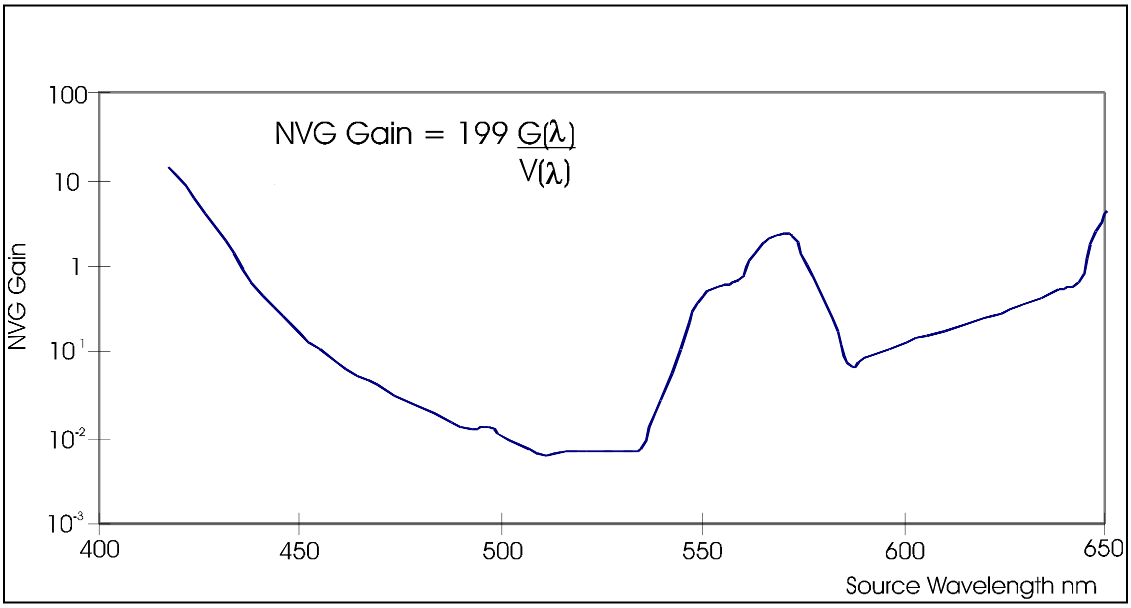


Fig. 12 Minimum NVG GAIN for hypothetical monochromatic source used with UK NVG response (scaling and response details as per EFA programme).

4.2 Light Sources

Obviously it is desirable to choose a light source which has its energy output concentrated in the visible region with a minimum of energy in the NVG band. However, the lighting designer rarely has a free choice but is constrained by a host of more pressing functional requirements. The light sources encountered will include:

a) Incandescent Lamps

The ubiquitous incandescent lamp has a history of widespread use in avionics for instrument lighting, floodlighting, legend back lighting etc. but it is at the same time the worst possible starting point for NVG compatibility!

Most of its radiant energy is in the infra-red which contributes nothing to the visual brightness but is powerful at corrupting NVG performance. Furthermore the ratio of NVG band emission to visual emission gets worse as the lamp is dimmed below it's rated voltage.

However, the widespread use of such lamps, coupled with the existence of many retro-fit programs which look for NVG compatibility with minimum re-design, has provided the incentive for a number of specialist suppliers to develop filters which can render incandescent lamps compatible.

Because such filters introduce a high degree of attenuation to the infra-red emission it is all important that the design and manufacture of the lamp/filter assembly does not compromise the filter action by allowing infra-red to sneak-out around the filter.

b) Electro-luminescent (EL) Panels

EL panels find applications such as backlighting for illuminated legends and area floodlighting. Their radiant energy is mostly in the visible so that only modest filtering is needed for compatibility.

c) Light Emitting Diodes (LED)

This technology finds application to warning lights, panel backlighting and in matrix-addressed arrays. Again, only modest filtering is needed for compatibility but in a matrix display, which must also be sunlight-readable, the filter component will also need to perform a contrast - enhancement function.

d) CRT Phosphors

When overriding considerations such as efficiency, colour and life are decided there are not a lot of phosphors from which to choose.

Monochrome CRTs will be green using one of the P43 or P53 line spectrum phosphors. These have their major emission at 545nm but also have some minor spectral lines in the deep red which need to be filtered out. The earlier P1 phosphor is a better green colour and a continuum spectrum peaking at 530nm. However, it has a long tail on the spectral distribution which extends into the NVG band.

Full colour displays need red, green and blue primary colour phosphors. The major choice here is two alternative red phosphors, with a compromise between a good colour which is difficult to make compatible and a more orange red which can be brought within the limits of MIL-L-85762A Class B.

e) Fluorescent Lamps

The fluorescent lamp is now appearing as a backlighting component for active-matrix liquid crystal displays (AMLCD). Lamps for this application use the tri-band phosphor (effectively a mix of the same phosphors as those used in a colour CRT) to generate the light so it could be likened to the colour CRT as a compatibility problem. However, two factors make it considerably more onerous:-

- The tri-band phosphor is excited by the UV emission from a discharge in mercury vapour with an inert buffer gas. Unfortunately there is direct radiant energy from the discharge at a range of wavelengths across the NVG band.

- The AMLCD panel transmission is much higher in the NVG band than it is in the visual band due to failure of polarisers at long wavelengths.

4.3 Filters

For all applications we are in need of filters which :-

- Have high transmission in the visible band.
- Exhibit a sharp cut-off somewhere in the deep red.
- Maintain high attenuation at wavelengths up to 1000nm.
- Have all the above characteristics at all angles of incidence and under all environment conditions including UV irradiation.

Needless to say these ideal components do not exist but there is quite a range of materials which can be considered:-

a) Coloured Glass

Glass filters from the catalogues of suppliers such as Schott and Hoya can often provide a solution. The characteristics can be tailored to some extent by choosing the glass thickness but apart from that the desired characteristics are obtained more by serendipity than by design.
These materials all work by absorption of light which is not transmitted and their transmission characteristics are only weakly dependant upon incidence angle.

b) Dielectric Filters

Multiple thin-film dielectric layers can be designed and manufactured to match any required cut-off wavelength, cut-off sharpness and pass-band behaviour. Against this designability must be considered the following:-

- A tight specification and/or large area results in a very expensive component.

- Energy at wavelengths that are not transmitted through are reflected back to source, not absorbed. Thus a short-pass dielectric filter with a 600 nm cut-off will also be a bright red mirror - not the best thing to put in front of a display.

- The cut-off wavelength and pass band shape will change significantly when subject to angle of incidence change.

- At some long wavelength the short-pass filter will become transmissive again particularly at non-normal incidence. For this reason the dielectric filter is likely to be put on an IR absorbing substrate.

c) Dyed Plastics and Compound Filters

A number of specialist suppliers have emerged who target the NVG compatibility applications. They use combinations of proprietary dyed plastics, coloured glass and dielectric filters to serve perceived specific needs and will undertake custom formulations.

4.4 Material Characterisation

Ideally the suppliers of CRTs, EL panels, fluorescent lamps, filters, mirrors etc. can furnish data on spectral properties preferably as computer files. However, in practice, if data is available at all it will not extend into the infra-red and it will be presented in graphical form with linear ordinates so that the minor components are all lost in graphical resolution. The specialist suppliers understand this problem and are usually prepared to provide logarithmic plots or tabulated numerical values or even machine readable files.

However, the lighting designer will need to be able to do the measurements in his own laboratory under conditions appropriate to the application.

For this type of work there is no alternative to a good quality flexible spectroradiometer system such as the Bentham Instruments system outlined in Fig. 13. With this equipment it will be possible to:-

- Generate data on spectral distribution of light sources and discover how the properties change with drive level, temperature, viewing angle etc. The spectral distribution data is essential for compatibility design but it also provides the best colorimetric data.

- Generate data on spectral transmission and spectral reflectance by the substitution method.

- The operating software for the spectroradiometer will probably include facility for arithmetic operations on spectral files (such as wavelength by wavelength multiplication of two files) so that the compatibility metrics can be calculated for hypothetical combinations of light sources and filters.

4.5 Materials Pitfalls

We are very accustomed to seeing directly "with our own eyes" how components and materials behave and will have established in our minds some correlation of what we see with physical measurable properties.

It is very easy to fall into the trap therefore of extrapolating the visual properties into the infra-red. Some examples of unexpected material behaviour are:-

a) Filters which remove red components to yield a blue or blue green colour can become transmissive again in the infra-red.

b) A pair of crossed polariser films appear to be black (i.e. low transmission at visual wavelengths) but are highly transmissive in the infra-red.

c) Some materials are fluorescent to a small degree, not enough for normal visual applications, but serious for NVGs.

Fluorescence is usually manifested as emission at visible wavelengths as a result of UV excitations but the concern here is with emission in the infra-red as a result of blue or green excitation.

It can be exhibited by paints, plastics, and coloured glasses and should always be suspected when anomalous results arise.

d) Adhesives of black appearance which appear suitable for light-proofing of joints can be IR transparent.

e) As was noted in the introduction NVGs work with natural illumination not by thermal radiation. However, they do have some response to thermal radiation as testified by the fact that a Gen. III based NVG can yield a bright image of a regular hot soldering-iron (in complete dark conditions). This is not a warning about including hot soldering-irons in a design but it is to make the point that hardware not designed to emit light can have an ability to degrade NVG performance.

Another example of this pitfall is the touch-screen device which uses an array of infra-red LEDs and silicon photodiodes to sense the position of a finger. The LED emission is inside the NVG band but there is nothing in any of the controlling specifications for NVG compatibility which defines methods of assessing such a device.

Verification that compatibility has been achieved can be performed in various ways but the method chosen will depend on resources available and the context of the verification.

For engineering purposes to prove that a design is valid the testing needs to be extensive and to provide data on the margin between actual and desired performance.

For production purposes the testing needs to be fast and can be formulated on the basis that the design is known to be valid so the test purpose is to reveal manufacturing defects.

5.1 Aircraft Mock-Up

The top level of verification addresses the basic concern of NVG compatibility which is avoiding degradation of NVG performance by the ensemble effects of all cockpit displays and lighting components.

The aircraft, with its cockpit fully equipped with all lighting components, is put in a completely darkened hangar. A resolution target illuminated with simulated starlight is configured to simulate the most demanding NVG imaging task. Then air crew in the cockpit assess the resolution of the NVG both will all cockpit lighting fully off and with cockpit lighting at normal level. If the lighting significantly degrades the NVG resolution the cockpit is deemed non-compatible and a process of elimination is used to identify the offending lighting components.

Such testing requires the resources of the aircraft constructor but the lighting components supplier does need to be aware that his equipment may be subject to this type of verification.

5.2 Filtered Radiometer

The most economical way of assessing conformance with numerical specifications is the use of a single radiometer with alternative filters as introduced in Working Paper 6 as a method of measuring Green/Red ratio.

The method is applicable to all the compatibility metrics and comprises the elements shown in Fig. 13.

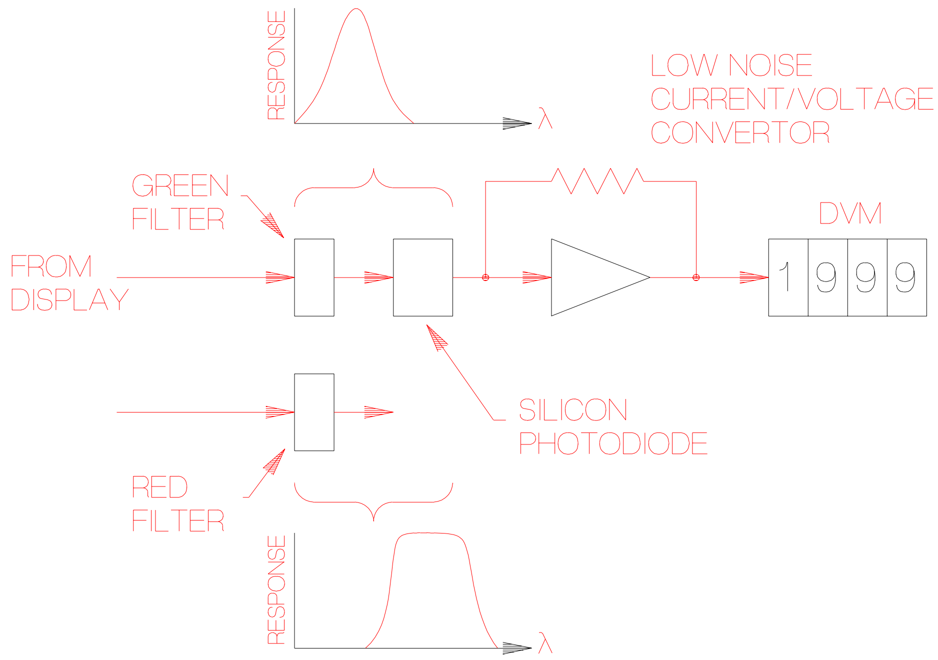


Fig. 13 Filtered Radiometer

A large area silicon photodiode (typically 10mm dia active area) is used with one of two filters. The first filter is contrived to give the photodiode a photopic response and the second to give a response matching the desired NVG response. The photodiode is run under zero bias conditions and the output current measured using a low-noise amplifier.

A pair of readings on the source under test using the two filters will yield the Green/Red ratio which can be arithmetically converted to other metrics using the equations in paragraph 3.4. Such simple equipment is usable because the compatibility metrics are all ratios of energy contained in two spectral regions and absolute values of luminance or radiance are not required. The light collecting optics can therefore be chosen for maximum light collection without concern for well defined geometry except that the change of filter should not change geometry.

There will of course be some subjects where there is insufficient signal in relation to the radiometer noise level such as small-area back lit legends at low luminance but an experienced improviser will be able to adapt the technique to a surprising number of applications.

5.3 Spectroradiometric Methods

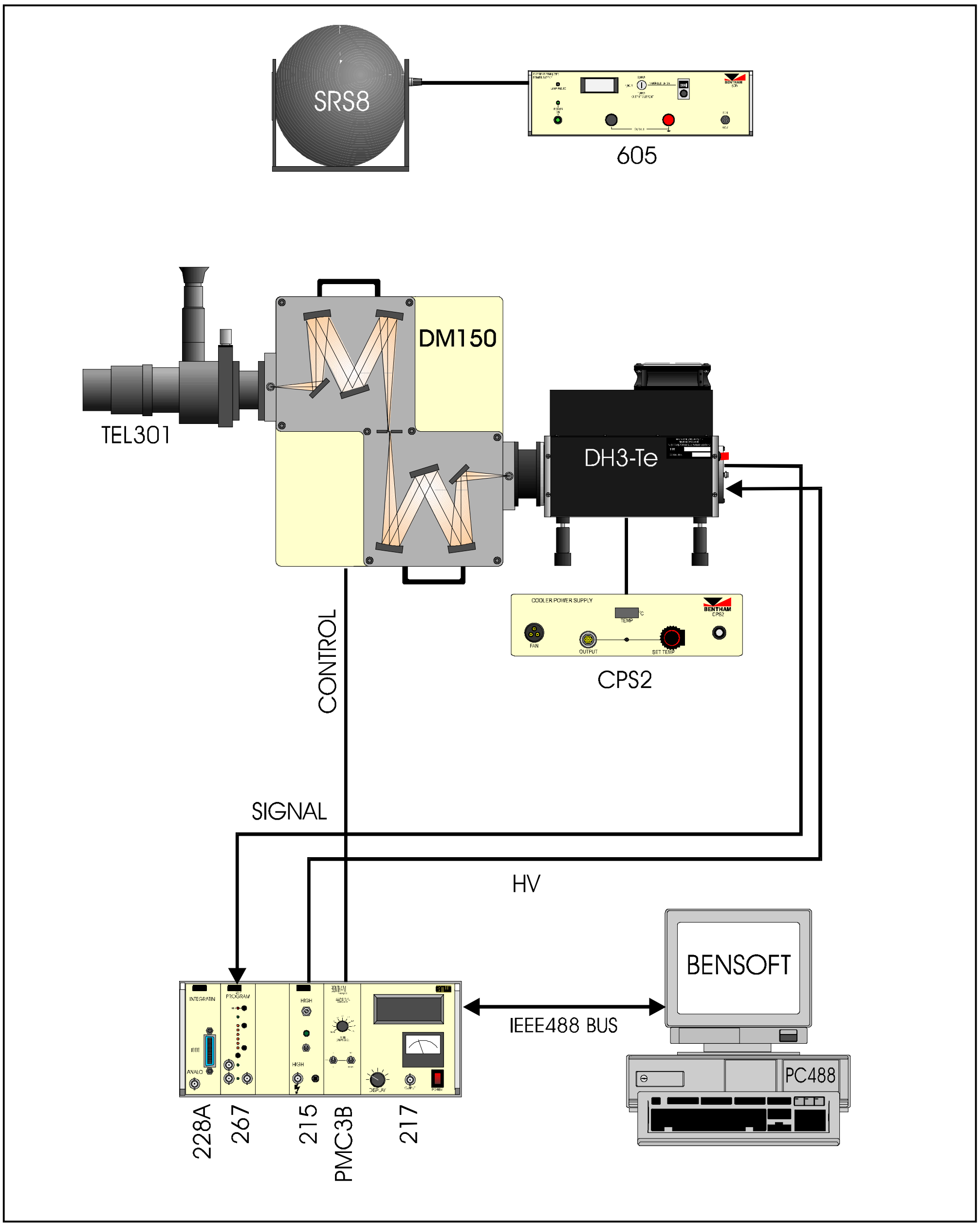


Fig. 14 Schematic diagram of Bentham NVG Spectroradiometer system

The definitive method of measurement to show conformance to numerical specification is to use a spectroradiometer to measure the spectral radiance over the whole range from 380nm to 930nm. From this data the required compatibility parameters can be computed using routines included in the spectroradiometer software, including:-

- Luminance (Using CIE
- Chromaticity standard definitions.)
- NVIS Radiance (Using any or all
- NVG Gain of the various NVG
- Green/Red ratio response functions.)

A spectroradiometer suitable for this work is a sophisticated system and is bulky enough to be a fixed installation in the laboratory but it does more than provide a pass-fail criteria against a numerical specification. It also gives valuable data to explain the causes of the result that has been obtained. For example a linear plot, not of the measured spectrum P(λ), but of the product P(λ)G(λ) shows which wavelengths will give rise to NVG excitation. Ideally the P(λ)G(λ) is near zero at all wavelengths but the illustrative plots in Fig. 15 depicts various situations:-

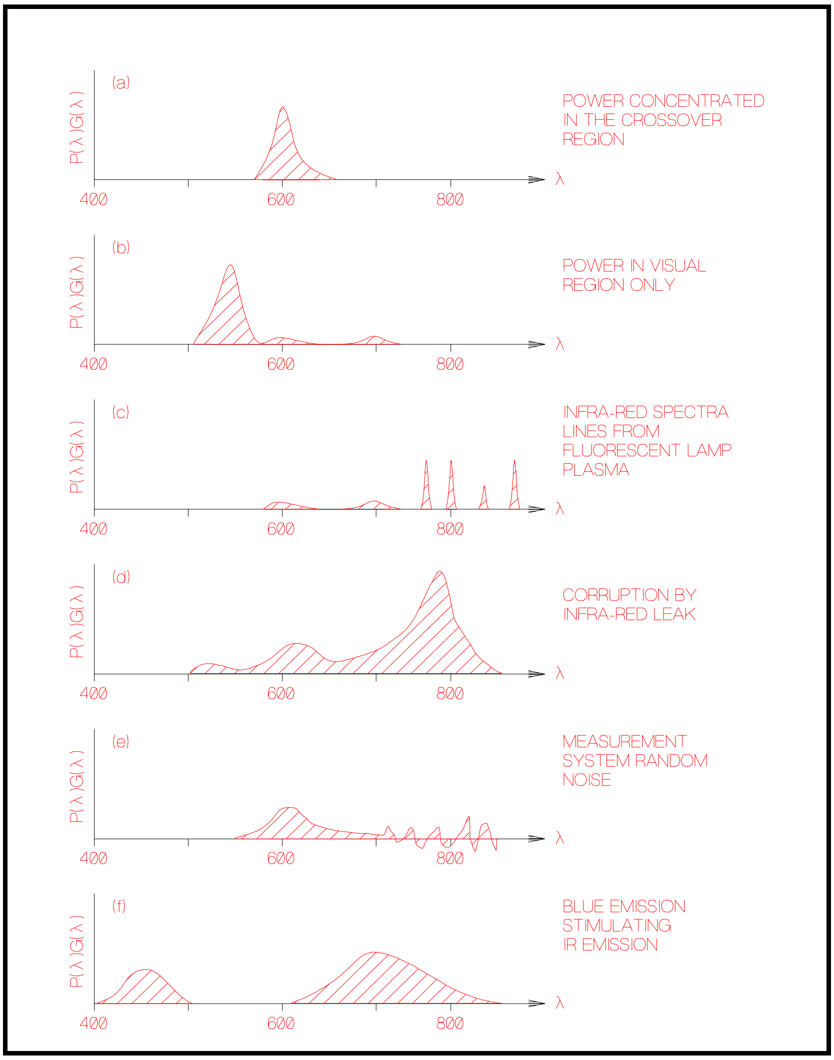


Fig. 15 Typical P(λ)G(λ) Plots

a) This result with a concentration of energy in the 600 to 620nm region is very common and is due to some overlap between the falling P(λ) emission and the rising G(λ) response. If the NVIS radiance (which is proportional to the area under the plot) is marginal or excessive in relation to the specification then a sharper rate of cut-off must be contrived somehow.

b) This represents a green display which has been successfully filtered to eliminate any red or infra-red components but whose NVIS Radiance is, nevertheless marginal. This result is a consequence of a non-zero NVG response function (e.g. MIL-L-85762A Class A) in the visual domain and there is nothing that the display designer can do to reduce the NVIS Radiance. However, an actual NVG response may well be more favourable than the standardised, but notional, functions in MIL-L-85762A.

c) This represents a filtered fluorescent lamp which shows some energy in the crossover region due to phosphor emissions but insufficient suppression of the argon-line emissions from the lamp plasma.

d) This depicts an incandescent lamp fitted with a green filter advertised as suitable for this purpose. A separate measurement of filter spectral transmission with a spectroradiometer showed that the filter behaved as advertised and the source of the problem was an opaque sealing material being IR transparent and allowing the filter to be bypassed!

e) This represents a measurement made at the limit of the spectroradiometer's capability as evidenced by the random positive and negative excursions near the wavelength extreme. The positive and negative excursions largely self-cancel and have not in this instance invalidated the conclusions, but it is a good idea to be alert for this situation which could be more extreme.

f) The last example depicts a blue CRT phosphor emission via a filter which is fluorescent. The minor peak at 450nm is due to non-zero $G(\lambda)$ at the phosphor emission wavelength but the IR component is due to fluorescent emission.

5.4 NVG Survey

Measurements to verify conformance to NVIS Radiance (or other equivalent metrics) do not on their own, guarantee compatibility.

There are plenty of opportunities for deficiencies in design or in manufacture of some part of the lighting component surface at some angle of view to emit too highly in the NVG band due to causes such as:-

- Dielectric filter band-edges shifting at extreme angle of view.
- Light leakage paths which bypass filters.
- Imperfectly mated joints which spill light at some specific angle.
- Cracked filters.
- Unexpected infra-red sources such as CRT cathodes and LED opto-sensors.
- IR transparent sealing materials.
- Incorrect assembly such as missing gaskets.
- Plus all the other causes which this author has yet to experience!

The air crew will eventually discover all such deficiencies but it is less embarrassing and less costly all round if the manufacturer discovers it first.

This can be accomplished in a matter of minutes by surveying the item with NVGs (in a completely dark room) looking at all parts over a range of angles to detect bright spots which are brighter than the region that has been checked for numerical conformance.

Regular air crew NVGs are unnecessarily expensive for this purpose because they include precision mounting and adjustment, are binocular and use IITs selected for low noise, low defect incidence etc.

A basic hand held monocular NVG using a Gen. III intensifier is a fraction of the cost and serves the purpose well.

The short wave cut-off filter is arranged as alternative clip-on filters over the objective lens to simulate the operational NVGs. This monocular NVG also has adjustable objective lens focusing down to a couple of feet to help pin-point the source of any high-spots.

Such a survey with NVGs is highly desirable for the reasons already described but in addition the same NVG can be used for semi-quantitative assessment in a production context. Once the design has been validated one production item is set aside as a reference unit. Having passed an NVG survey and numerical assessment (maybe by an external test-house) the reference unit is put side by side with the production unit under test and the survey criteria is extended to require that no part of the unit under test shall appear to be brighter (through the NVG) than the equivalent part of the reference unit. There is obviously a large subjective element in such a test but it is adequate to pick out faulty assembly if the basic design is known to be sound.

A spectroradiometer is an essential tool for serious NVG compatible design work but for this application the spectroradiometer needs some specific performance attributes, especially:-

- Wavelength range extending over the whole visual range into the near infra-red.
- High sensitivity.
- Ability to measure very low power levels in the presence of high power levels at other wavelengths, i.e. good stray-light performance.

There is some choice of spectroradiometers on the market and the diode-array concept has led to some compact and easy to use instruments. However, the diode-array type is not suitable for this application because it cannot measure up to the stringent stray-light performance required.

The conventional scanning instrument (with a single detector) can meet the requirements given suitable detail design and the Bentham Instruments system that would be appropriate here is illustrated in Fig. 14. The essential components are the Light Collection Optics, the monochromator, the detector, interface electronics, computer and calibration sources. The attributes and usage of these component parts are discussed next.

6.1 The Monochromator

The monochromator, which extracts one narrow band of wavelengths from the incoming radiation, is a key component.

The basic Czerny-Turner monochromator configuration is shown in Fig. 16. Light entering via the entrance slit is collimated, by the first concave mirror, reflected off the diffraction grating and reconverged by the second concave mirror to form an image of the entrance slit in the plane of the exit slit. At any one wavelength there is an angle at which constructive interference occurs in the reflected wavefronts from the grating lines so that the entrance slit image may be brought into coincidence with the exit slit by grating-angle adjustment. The wavelength for coincidence is a sine function of grating angle so a sine-bar linkage can create a linear movement to wavelength scale. The mechanical function is completed by a precision lead-screw and computer controlled stepper-motor so that the monochromator acceptance wavelength can be set to anywhere in the range. To the basic monochromator described above there are options needed to cope with specific performance issues.

a) <u>Higher Order Response</u>

There are higher order modes of the diffraction grating operation which result in additional (and unwanted) response when the tuned wavelength is a multiple of the input wavelength. For example there will be a spurious response at the 800nm setting if there is input energy at 400nm. This spurious response is readily suppressed by inserting a minus-blue filter when the tuned wavelength is beyond the blue region. A multiple-position filter turret will serve this and other purposes.

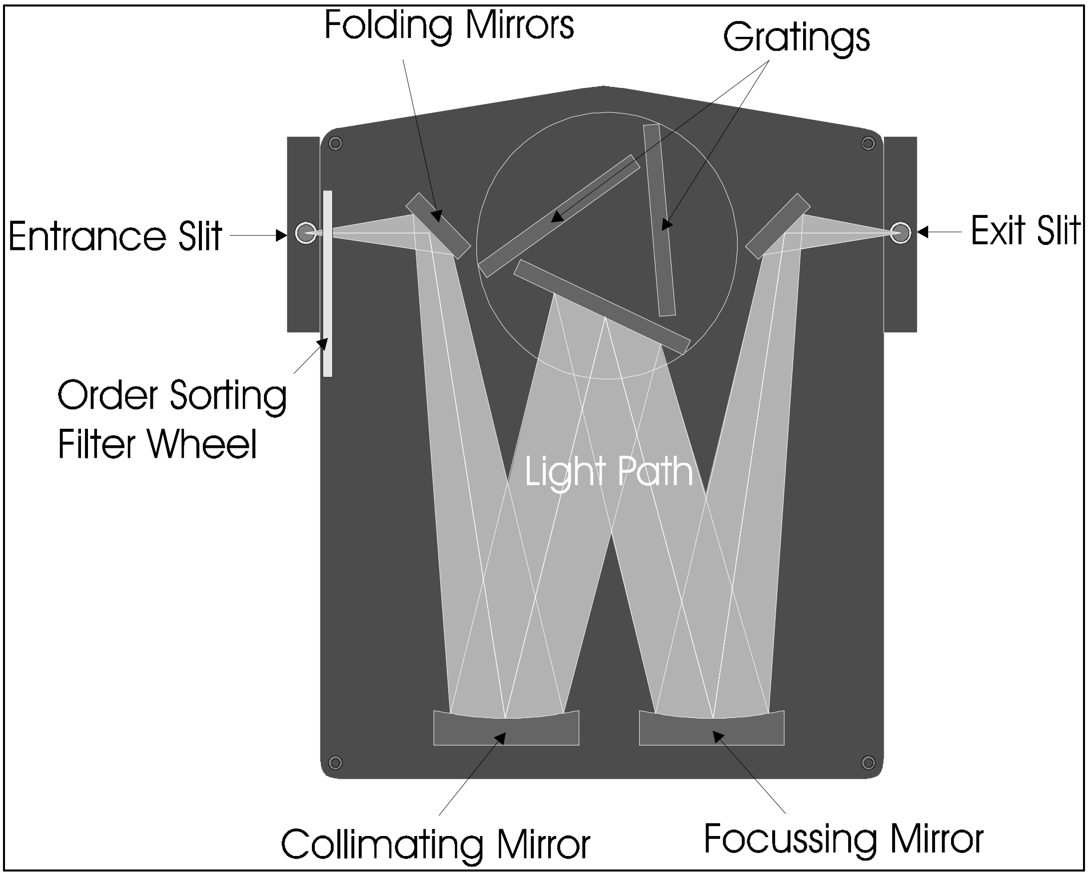


Fig. 16 Optical configuration and light path of monochromator.

b) <u>Wavelength Band-Pass</u>

If the entrance and exit slits are the same width the band-pass shape will be triangular, which is the preferred shape.

The bandpass width, measured as total width between the 50% levels, it proportional to the slit-width and most designs have some arrangement to alter the slit width because there will be compromises to make:-

- Narrow slits mean good wavelength resolution, say 1nm, which may help to trace the origin of spectral lines and which yield impressive plots but is mostly not justified.

- Wider slits yield more radiant power into the detector for better signal/noise ratio. In general a doubling of slit width will improve the power by a factor of four. Because signal/noise ratio is so often the limiting factor always use the widest possible bandwidth of at least 5nm extending it 10 to 20nm in especially difficult cases.

- It is usual to cover the wavelength range in equi-spaced wavelength intervals. Obviously the interval size should not exceed the band pass width but if line-spectrum emissions are expected then it is also necessary to ensure that the bandpass width is an integer multiple of the interval.

c) <u>Stray Light</u>

Stray light is the term applied to the internal mechanisms which give rise to non-zero response of the monochromator at wavelengths other than the wavelength to which it is tuned.

When testing an NVG Compatible lighting component we shall present to the spectroradiometer a spectrum with substantial power at say 550nm but expect the instrument to make a valid measurement of the power in the NVG band which is one thousand times lower so stray light performance is a major issue.

Stray light arises from internal light paths from entrance slit to exit slit which do not follow the intended route, including reflection from mirror and grating edges and frames, scattering from baffles and scattering from dust and/or defects on the grating.

Good baffle design and matt black interior surfaces can limit stray light to perhaps 1 part in 2000. This sounds like good performance but consider input from a monochromatic light source at say 550nm. We record 2000 units when tuned to 550nm and record 1 unit at all other wavelengths (in say 5nm steps) including the 50 readings in the NVG band giving a total of 50 units in the NVG band corresponding to only 1 part in 40 of the visual band. The numerical specifications in all the lighting components require something in the range 1 in 100 to 1 in 1000 so the measuring equipment needs much better stray light performance than the above example. There are two candidate methods:-

- Use the filter turret to introduce a filter(s) which cut-out the visible band when measuring the NVG band. This implies some knowledge of where the important bands are before doing the measurement which gets procedurally cumbersome.

- Use a second monochromator to clean up the signal extracted by the first one, i.e. use a double monochromator. This can take either the form of two single units coupled together or a unit designed as double monochromator which will be more compact.

The double monochromator is the preferred method of getting acceptable stray-light performance.

d) Wavelength Accuracy

For this application wavelength accuracy to ±1nm is adequate and readily met by the configurations described here.

It is usual to arrange (within the control software) that the desired wavelength is always attained from a consistent direction of motion to eliminate the effect of any mechanical backlash. This should be borne in mind if manual wavelength adjustment is ever used.

6.2 The Detector

The detector performance is crucial to the instrument performance in respect of wavelength range and signal/noise ratio. The usual choice for this application is a photomultiplier tube because of its remarkable low-noise amplification of the photocathode signal. The choice of the most appropriate type is a complex issue best left in the hands of the instruments supplier but there are some factors which the spectroradiometer user should be aware of:-

a) Delicate : The photomultiplier is a somewhat delicate item sensitive to disturbance due to temperature, mechanical shock, magnetic fields and excessive light exposure. It may recover from mild abuse but will take hours or even days to so do.

b) Cooling : For this application the photomultiplier can usefully be cooled (to say -20°c) to reduce dark-current (and therefore to reduce noise). It is necessary therefore to ensure that the cooling system has had time to reach an equilibrium situation before use commences, or preferably to arrange continuous operation of the cooling system.

c) Noise reduction : The detector / computer interface will incorporate a signal averaging process in which the user can choose to average over shorter or longer periods. Longer periods can be used to improve the signal/noise ratio if one is prepared to wait longer for the results. However, it is not just a question of patience - the longer the time to make a scan the more any systematic dark-current drift will corrupt the results so that too long averaging period can be counter productive. Before this point is reached consider introducing dark-current subtraction at each wavelength or multiple-scan averaging.

d) Dark Current Subtraction : It is the fluctuation of dark-current, not the dark-current itself that established the lower limit of detectable radiation so a dark-current subtraction routine is included in the control software. This routine will move the filter wheel to a completely opaque position (i.e. exclude all light), measure the detector output and store it in memory and then restore the filter to its previous position. This routine is invoked before a scan commences and then the stored dark-current reading is subtracted from each of the subsequent readings.

6.3 Input Optics

Again we remind ourselves that compatibility metrics are essentially ratios of power in two parts of the spectrum. Chromaticity is also a ratio function so the important data is the shape of the spectral distribution not the absolute magnitude.

This means that the input optics can be biased towards maximising light collection at the expense of uncertainty about the absolute value.

a) Fibre-optic bundle

The simplest but most useful configuration is a straightforward fibre-optic flexible bundle perhaps 1/2 metre long. The exit end is preferably shaped into a rectangular ferrule to maximise coupling into the monochromator entrance slit.

The input end of the bundle is simply held against or near the lighting component luminous surface to gather as much light as possible. A useful addition to the bundle is a simple nose-piece as indicated in Fig. 17 which serves the following purposes:-

- It defines the distance of the fibre input from the source so that a measurement is readily repeated.
- The entrance hole defines the area of a luminous surface that is being measured.
- It helps to shield the entrance of the fibre from ambient light.

b) Telescope

The Bentham spectroradiometer is offered with telescope input optics as an option. Whilst suitable for NVG compatibility work it may also be used to cover other work such as display colorimetry and can be used where it is necessary to accurately define the light emitting area to be measured. The Bentham telescope implements a spot-meter with aperture-mirror viewing to ensure that there is no uncertainty about placement of the measuring area.

Further, the telescope input optics allow measurement of absolute values of spectral radiance provided that the measuring area is fully filled in both measurement and calibration.

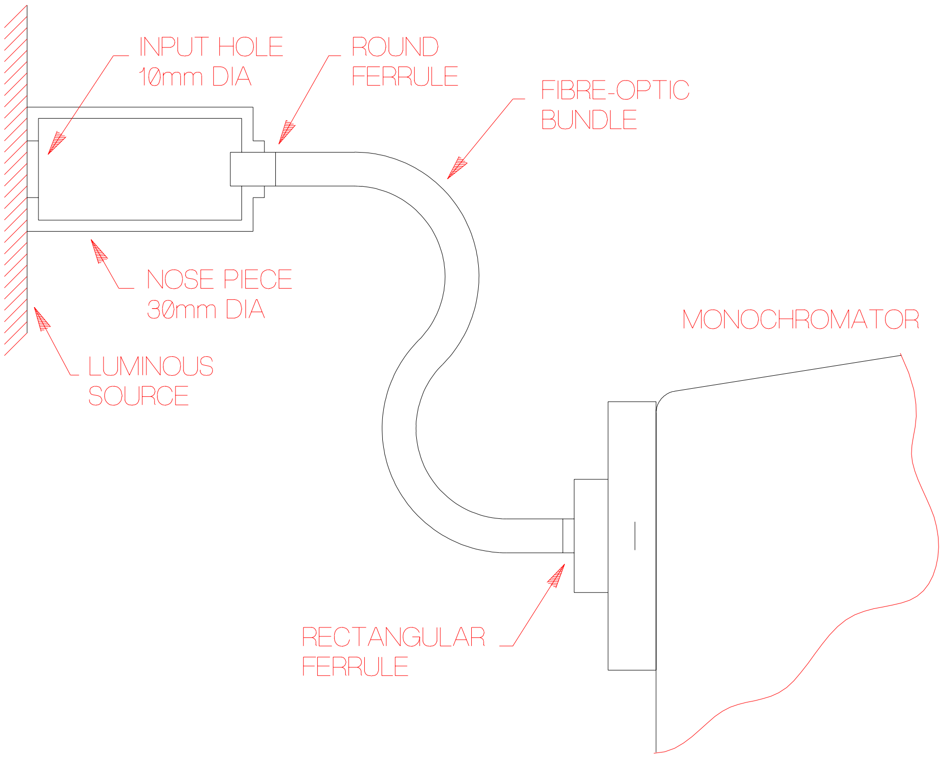


Fig. 17 Fibre-Optic Bundle with Nose Piece

6.4 Spectroradiometer Calibration

The calibration of a spectroradiometer is performed in the spectral radiance domain and does not invoke CIE parameters.

The detail procedure will be different for each instrument design but there will always be the two aspects of establishing the wavelength scale and establishing the radiance scale at each wavelength.

The calibration process will be incorporated into software routines which generate correction files in computer memory and these files are invoked in all subsequent measurements.

a) Wavelength Scale

In a conventional monochromator the sine-bar mechanism will yield a linear relation between lead-screw rotation and tuned wavelength. However, the relation may not be exactly linear and will exhibit some wavelength offset errors.

The wavelength scale is established by scanning a source which exhibits strong line-spectrum emissions at a few suitable wavelengths. Analysis of the wavelength errors at each spectral line provides the coefficients of an error polynomial which are stored and invoked for all subsequent measurements.

Small capillary-tube discharge lamps with appropriate filling provide line spectrum emission by mechanisms which are sufficiently fundamental to be wavelength standards in their own right without resort to a higher level of calibration.

Both mercury filling and cadmium filling provide spectral lines suitable for spectroradiometer wavelength calibration. It is worth noting that the most common displays include spectral lines of known wavelength so that each measurement provides a check that there have been no major shifts in wavelength scale. Colour CRT phosphors usually incorporate a line spectrum red at 625nm and AMLCDs are usually backlit with fluorescent lamps having a mercury line at 546nm.

b) Spectral Radiance Scale

All the elements in a spectroradiometer exhibit variations in performance with wavelength:-

- The transmission of lenses, fibre-optic bundles etc. is wavelength dependant.
- The throughput of the monochromator is wavelength dependant.
- The detector responsivity is wavelength dependent.

The net result is an instrument whose uncorrected response varies widely with wavelength. The basic approach to this is to establish the detail of the instruments response by using the instrument to measure the apparent spectral radiance of a Standard Source. This process can be formalised as follows:-

A calibration measurement will yield a spectral file

$$Mc(\lambda) = S(\lambda) \times R(\lambda) \qquad \text{[Eqn 7]}$$

Where $S(\lambda)$ = Standard Source spectral radiance
$R(\lambda)$ = Instrument response function

With calibration measurement $Mc(\lambda)$ and the known $S(\lambda)$ compute and store a calibration file $C(\lambda)$ using

$$C(\lambda) = S(\lambda)/Mc(\lambda) \qquad \text{[Eqn 8]}$$

Subsequent measurement on an unknown source P(λ) yields a measurement M(λ) where

$$M(\lambda) = P(\lambda) \times R(\lambda) \qquad \text{[Eqn 9]}$$

Use Equa. 7 and 8 to replace R(λ) and obtain

$$P(\lambda) = M(\lambda) \times C(\lambda) \qquad \text{[Eqn 10]}$$

Thus the stored calibration file can be used, with one arithmetic operation, to convert all subsequent raw measurements M(λ) to valid P(λ) data. For colorimetric data the measured spectral radiance P(λ) is plugged into the CIE formulations.

Clearly the validity of the radiance scale thus generated depends very much on maintaining the same instrument configuration during measurements as was used to generate the calibration data.

The following should be considered when applying general procedure describe above:-

- In the interests of flexibility of application it allows many configuration options from a choice of lenses, of field stops, of spectral bandwidth, of measurement wavelength interval, of wavelength range and of filters inserted in the optical path. Each configuration option will require differing C(λ) calibration files which virtually dictates that the user should perform an in-site calibration whenever the configuration is changed.

- In the interests of sensitivity the photomultiplier tube (PMT) is the preferred detector. However, the excellent sensitivity of a PMT is effected by many parameters of its local environment such as temperature, magnetic fields, mechanical shock and recent history of light exposure. For this reason it is recommended that a spectral radiance calibration is performed at the start of each day’s measurement session. Allow about half an hour after application of power to the PMT before proceeding with calibration, and also allow the standard source about 10 minutes to reach a temperature equilibrium.

For the best confidence in equipment stability perform another calibration at the end of the measurement session and compare the new C(λ) file with the old C(λ) file.

6.5 Data Presentation

The basic measurement data is spectral radiance held as a numerical array in computer memory and stored on disc. This is also the form needed to compute compatibility metrics but there will also be a need to explain results to colleagues, customers and clients and for those purposes plots of spectral data are more comprehensible. The plots can use either linear or logarithmic ordinates:-

- Linear ordinates allow easier visualisation of the area under a function so is preferred for emission spectral density when the interest is in colour and is also preferred for the P(λ)G(λ) plotting discussed in paragraph. 5.3 and the plots of Fig. 15.

- Logarithmic plots allow depiction of a wider range of parameter value. Data on spectra emission, spectral transmission and spectral responsivity for compatibility studies are most useful as a 6 decade logarithmic ordinate plot. However, it is worth finding out what the log plotting routine does with the negative values that can occur with noise-limited data. The use of an "absolute value" function avoids computer error messages but it can make random noise look like a real signal so it is better to arrange that negative values are plotted "beyond the bottom of the page".

For both logarithmic and linear plots there can be confusion about the treatment of line-spectrum emissions in comparison with continuum emissions. It should be remembered that the ordinates in a spectral emission plot is power per unit wavelength (because on a continuum source the power at one exactly defined wavelength must be zero).

Thus, for example with data reported every 5nm, a data point showing power density = 1W/nm at 545nm really means that the total power in the range 542.5 to 547.5 nm is equivalent to 1W/nm spread uniformly over the 5nm range, irrespective of how it is actually distributed. The actual distribution may be near to uniform (as in a continuum distribution) or it may be very non-uniform such as one very narrow spectral line somewhere in the 5nm band.

The proper way to plot the data without hiding the above meaning is the histogram type plot as in the example of Fig. 18(b).

However, it appears to be common practice to plot in the "joining the dots" style of Fig. 18(a) on the grounds that it looks more pleasing because it makes the continuum more smooth and the line emission more spiky.

The problem with the "joining the dots" style is that it hides fact that the data is in 5nm chunks and that it may be misrepresenting the wavelength of the line-emission. A line emission at 543nm or at 546nm would be depicted by the same 545nm spike on the plot because 545 is the centre of the data chunk.

A further cause of confusion is the effect of monochromator bandwidth on sources such as Fig. 18. The true bandwidth of line emissions is very narrow so what we record is the bandwidth of the monochromator so if we re-measured the subject of Fig. 18 using 1nm bandwidth and 1nm data interval we would get the same curve for the continuum components but the line emission spike will more narrow but have five times higher power spectral density.

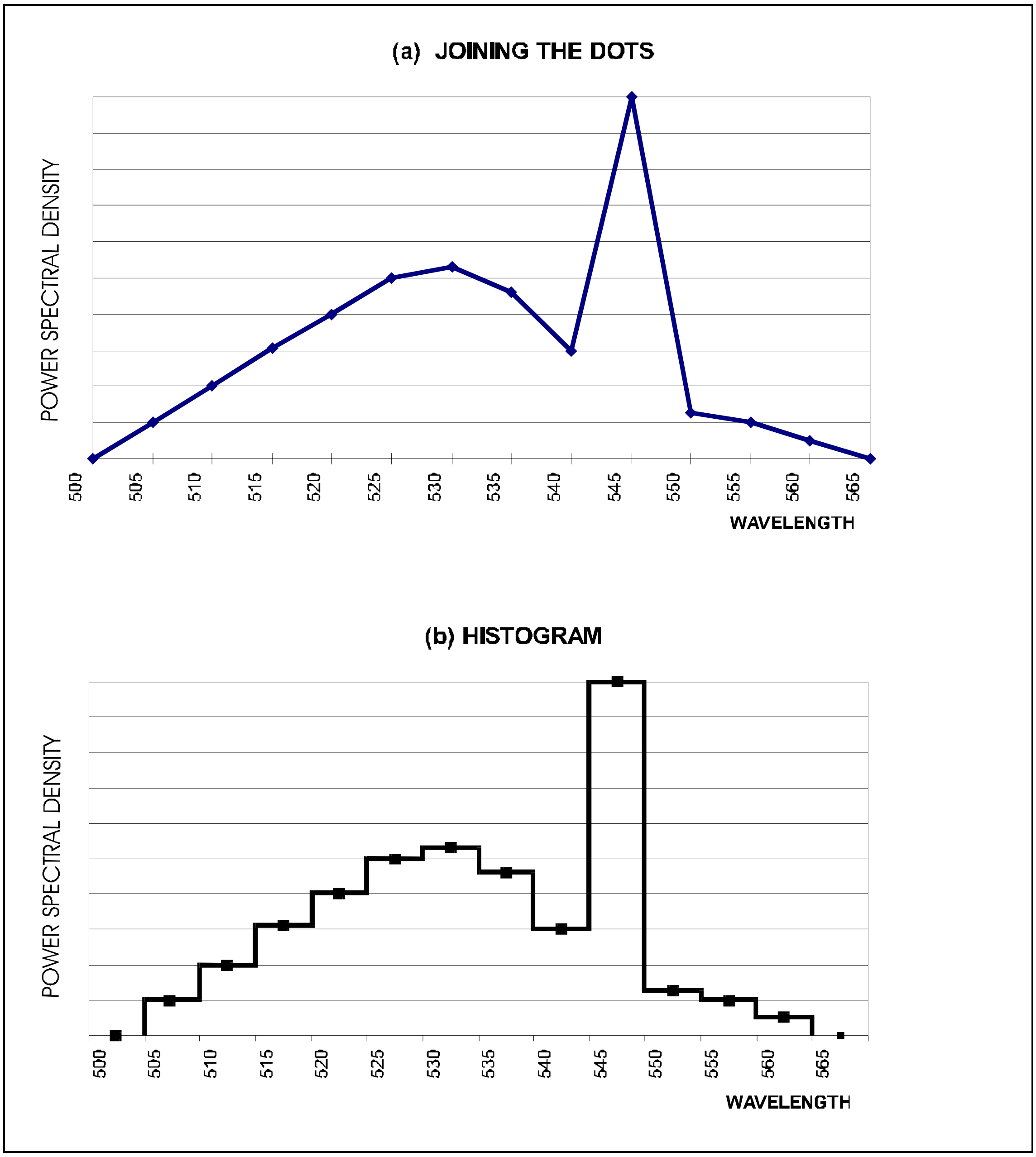


Fig. 18 Alternative Power Spectral Density Presentations
(a), (b) are identical data at 5nm interval

Such a change in spectral plot, where the height of the spike changes in relation to the height of the continuum, is counter-intuitive but is a necessary result of the power spectral density convention.

References 7

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