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INSIDE THE BLACK BOX: SYSTEM OPTIMIZATION FOR MEASUREMENT OF NVIS COMPATIBLE DISPLAYS

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Inside the Black Box: System Optimization for Measurements of NVIS Compatible Displays

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1. INTRODUCTION.

The design and optimization of any instrument depends on its intended application. However, several alternative and often very different system designs can be envisioned for any specific task. To illustrate this, suppose a system was required which could successfully cross a road. This system might be envisioned as incorporating sensors to detect oncoming traffic, precisely controlled movement and an intelligence to provide for any eventuality. On the other hand, a child's wind-up toy should also succeed most of the time in crossing a road, especially if the road was deserted. To ensure the envisioned system is supplied, and eliminate the child's wind-up toy as a viable alternative, standards for performance under extreme (rather than normal) conditions must be specified. Military specifications ensure that only manufacturers of the highest quality systems are considered.

Displays providing Night Vision Imaging System (NVIS) compatibility must meet exacting standards. Instruments to test these displays must also perform to set minimum requirements, as given in the document MIL-L-85762A[1]. Several companies manufacture sophisticated systems to measure NVIS compatibility of displays (commonly referred to as NVIS systems). Even though systems for MIL-L-85762A applications are all extremely good, individual companies have produced instruments with very different capabilities. These differences arise from the use of different components, conditions and techniques. The performance of instruments with respect to MIL-L-85762A[2] and the basic spectroradiometric principles[3] have been dealt with elsewhere. This article deals primarily with the optimizations possible, the mechanisms of achieving these optimizations, and the impact of any differences on actual measurements.

2. OPTIMIZING THE SYSTEM RESPONSIVITY.

Users often treat spectroradiometers as "black boxes" which generate results for a particular display. Whereas this view is reasonable for users, who would not be expected to know every relevant aspect of instrumentation or spectroradiometry, manufacturers must necessarily demonstrate a high degree of expertise in the design and optimization of their instrument for specific applications. Where different designs are employed by manufacturers, each would be expected to conform to basic performance criteria: suitability for the application; desired measurement accuracy; ability to measure any display normal to the application; and conformance to the standards and expectations of the industry. Sometimes, conformance to these criteria is not obvious, and we must look inside the "black box" in order to assess a system.

Spectroradiometers use components that have different transmission, reflection, efficiency and response as the wavelength of light is varied. Together, they determine the overall spectral responsivity of the system. These components should be matched by the manufacturer to produce the optimum spectral responsivity with wavelength for any particular application. Often, different manufacturers will use the same or similar components when optimizing their system. Even so, significant differences between systems are possible.

Figure 1 (Top) shows the relevant properties of some of the typical components that might be used in the manufacture of an NVIS system. These are: the efficiency of a 750 nm blaze, 600 g/mm grating; the reflectivity of a typical Aluminum mirror; and the spectral response of a GaAs PMT. A GaAs PMT is generally used in modern systems because it offers high sensitivity and response up to 930 nm. For each component, such data is generally readily obtained from the manufacturer. While optimization is at the design stage, these curves provide valuable information since they enable the approximate shape of the responsivity curve to be predicted.

$$\text{Relative Responsivity [\%]} » \overline{(G \cdot A^4 \cdot P)}^{-1} \cdot 100$$

(Equation 1)

Where: G = grating efficiency
A = Aluminum mirror reflectivity raised to the power of the number of mirrors
P = photomultiplier response

The predicted responsivity given by Equation 1 is only approximate since: data is "typical" rather than actual; it does not take the monochromator design into account; antireflection coatings on lenses and protective coatings on mirrors affect their spectral contributions; the grating data is for specific conditions that may not apply in use; and the GaAs PMT data is at a specific temperature which may not be optimum.

The system responsivity calculated using Equation 1 expresses the relative intensity of light required to produce the same signal. Thus, smaller values indicate a better sensitivity of the system to light. The application engineer or scientist would generally start with this approximate relative responsivity curve, shown in Figure 1 (Bottom). Using a knowledge of the behavior and availability of components, changes can be made within practical limits to fine-tune the performance. For instance, the response of the GaAs PMT beyond 880 nm is very sensitive to temperature. Decreasing the temperature by 20°C would make it more than a decade less responsive at 930 nm.

Once the nearest fit to the desired system responsivity shape has been established, the effects of ancillary components such as blocking filter transmissions can be factored in. After this, the contribution of the transmission properties of accessories, such as fiber optics and telescopes, are calculated.

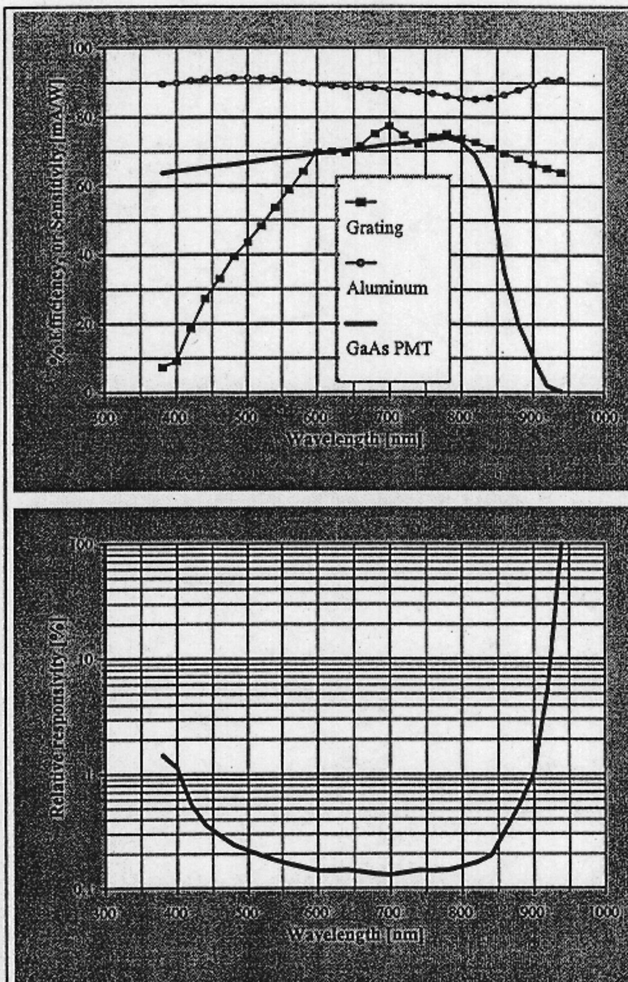

Figure 1. Typical grating efficiency, Aluminum mirror reflectivity and GaAs PMT response that might be used in a NVIS system (Top). The relative responsivity calculated using Equation 1 (Bottom).

Although the approximate shape of the system responsivity spectrum may be calculated, the exact shape and absolute values can only be established by building a system and making measurements. The spectral responsivity of a system is the light output of a source divided by the signal produced at each wavelength. For a source of spectral radiance expressed in W/(cm² nm sr) and a signal measured in Amperes, the spectral radiance responsivity would be in [W/(cm² nm sr)]/A. The determination of the absolute spectral responsivity is known as a calibration.

Once the system is calibrated, the spectral radiance of a test source is determined by multiplying the spectral responsivity by the measured signal for each wavelength. However, spectral responsivity depends on the exact conditions, which must be maintained between a calibration and measurement.

Although the values indicated by equation 1 are not exact, calibrations on many actual systems show very similar overall shapes to this. This curve will therefore be used to illustrate one type of optimization (which will be referred to as System A in the following text). Other optimizations possible might include the use of different gratings (or even the use of more than one grating), PMT temperature optimization and the use of extra components such as filters. In order to compare the effectiveness of different optimizations, the actual calibration curve of a typical OL 750S-NVG system (System B) will be used in following discussions.

A basic assumption in all spectroradiometry is that the signal measured is proportional to light. However, even in complete darkness (zero light) a residual signal is observed. This signal is called the dark current. If this signal were constant it could easily be subtracted, giving a net zero signal with zero light. However, there will always be inherent variations. The best that can be done is to subtract the "average" dark current so that zero light produces an average signal of zero. This leaves the inherent variations (noise) which is present in all systems.

3. OPTIMIZATION OF SYSTEM SPECTRAL SENSITIVITY.

Spectral sensitivity differs from spectral responsivity in that it includes the noise of the system. Essentially, spectral sensitivity is the lowest radiance value that can be measured at each wavelength. Since the system responsivity expresses the relative intensity of light required to produce the same signal, the converse is also true: a given signal value can be expressed in terms of the equivalent light required. In the dark, the electrical noise of the detector and amplifier in any system places a limit on measurements. Any light generating a signal less than this noise is indistinguishable from a dark condition. MIL-L-85762A section B30.2 defines the spectroradiometer radiance sensitivity as the intensity equivalent to ten times the root-mean-square (RMS) noise value, and assigns maximum limits to this quantity at each wavelength between 380 nm and 930 nm. In order to determine the spectral sensitivity of a system to MIL-L-85762A specifications, the RMS noise level is determined, multiplied by ten, then multiplied by the spectral responsivity at each wavelength. Since the spectral responsivity is the only component of spectral sensitivity that varies with wavelength, they must share the same overall spectral shape. The calculated spectral sensitivity is in units of radiance, and can be directly compared to levels mandated in appendix B30.2.

MIL-L-85762A SPECIFICATION

B30.2 Spectroradiometer sensitivity.
The spectroradiometer, when assembled as a complete system, shall have sufficient sensitivity to permit measurement of radiance levels equal to or less than that listed in the table below at a half-power band width of 10 nm and a signal to root-mean-square noise ratio of 10:1.

Wavelength	Radiance level
380 to 600 nm	1.0×10^{-10} W/cm² sr nm
600 to 900 nm	1.7×10^{-11} W/cm² sr nm
900 to 930 nm	1.0×10^{-10} W/cm² sr nm

B30.2.1 Spectroradiometer sensitivity calibration.
Calibration of the spectroradiometer shall be performed within six months (or more frequently if required to insure the spectroradiometer meets the requirements specified herein) prior to taking a measurement. This calibration shall be traceable to NBS standards. The calibrations shall be performed over the wavelength band and at intervals consistent with the measurements to be made. The calibration shall demonstrate that the spectroradiometer meets the sensitivity requirements of B30.2. A separate calibration must be performed for each set of optics used, or when filters are used in front of the spectroradiometer.

To improve sensitivity, a system can be optimized in any or all of three ways: increase the efficiency of components; decrease the electrical noise of the detector and amplifier; or increase the field-of-view of light from the source that enters the system.

For a given design of monochromator, the highest quality state-of-the-art components should be used and improvement is generally limited to technological advances rather than optimization. Providing accessories are matched to the monochromator, improvements in these components is also limited. Increasing the PMT high voltage does increase its gain, and hence the system responsivity. However, the noise from the PMT also increases and overall may produce a decrease in the system sensitivity.

Most systems accommodate several user selectable field-of-view apertures which, when the magnification of the lens is considered, define the area or diameter of the spot on the source which is sampled during measurements. Increasing the spot diameter by a factor of ten should increase the amount of light entering the monochromator by a factor of one hundred. The user may thus select a spot size, within the limits of the apertures available and the constraints of the sample size, appropriate to the sensitivity desired. Increasing the spot size can only increase the light entering the monochromator within limits. Measurements must be made at a certain bandpass, normally 10 nm, which is determined by the monochromator slits. When the spot size exceeds the slit size, the extra light falls on the slit housing rather than entering the monochromator and hence is not seen by the system. If fiber optics are used, the same applies to coupling of light into the end of the fiber bundle.

One popular mechanism for decreasing system noise, and hence increasing sensitivity, is lowering the temperature of the GaAs PMT. Whereas this does reduce the noise, it also changes the shape of the responsivity (and hence sensitivity) spectrum. As the PMT is cooled, the response to wavelengths greater than 880 nm decreases. Conversely, increasing the temperature may improve the responsivity beyond 880 nm, but the increased noise can adversely affect the sensitivity at wavelengths less than 880 nm to the point where the accuracy of measurements is compromised. The best temperature for optimal sensitivity differs slightly for each PMT, and hence should be determined before the system is used.

Another, less popular, mechanism for decreasing system noise to increase sensitivity is to increase the measurement time. This approach is of limited use however, since scans of over 3 hours are required just to achieve a factor of ten decrease in noise relative to a 2 minute scan.

Naturally, if noise from the amplifier is greater than that of the PMT, no amount of PMT optimization will improve the system. Highest quality auto-gaining amplifiers should always be used, together with digital signal processing (DSP) acquisition if possible. DSP technology virtually eliminates sampling and analog filtering errors commonly associated with older designs[4].

Appendix B30.2.1 states that sensitivity values must be determined for all conditions of use. The implication is that these conditions must be met regardless of the brightness of the display being measured. Thus, if a system is desensitized in order to measure bright displays, it must still conform to MIL-L-85762A. Ultimately, there will be a limit where in order to measure a source, the desensitization necessary will not allow conformance.

4. THE IMPACT OF SYSTEM RADIANCE SENSITIVITY SHAPE ON MEASUREMENTS

The primary factor in any optimization must be the intended use of the system. NVIS measurements present a unique challenge, in that real displays must be measured while conforming to applicable individual specifications of MIL-L-85762A. By combining the specifications of appendix B30.2 with the spectral responsivity and dynamic range of a system, the maximum brightness of a display that can be measured while meeting MIL-L-85762A can easily be determined.

Spectral sensitivity is dependent on many factors: most are part of the manufacturer's optimization but some, such as spot size or high voltage are selectable by the user. In general, for a given system, the larger the spot size the smaller the spectral sensitivity values. The overall shape of the sensitivity spectrum is only slightly affected by spot size and high voltage and may be considered a property of a particular optimization. By scaling the sensitivity spectrum, effects of comparative system responsivities can be assessed. As discussed previously, the shape of the radiance sensitivity (as defined in MIL-L-85762A) spectrum and the responsivity spectrum are necessarily identical.

The limits of MIL-L-85762A are idealized and do not reflect the overall shape of spectral responsivities of modern instruments. However, these limits are an integral part of measurement and must be met. Using a combination of spectral radiance sensitivity shape and MIL-L-85762A radiance sensitivity requirements, the <u>maximum</u> measurable luminance of an NVIS display can be established. Figure 2 and Figure 3 show the MIL-L-85762A requirement and the spectral radiance sensitivities of two NVIS systems with different optimizations: System A and System B respectively. Each of these is scaled to the condition where the respective system only just meets MIL-L-85762A specification B30.2.

By scaling the system responsivities in this way, the <u>least</u> sensitive condition while still maintaining conformance to specification B30.2 is revealed. Since the sensitivity defined in MIL-L-85762A section B30.2 is a radiance level at 10:1 RMS noise, the actual system noise level must be a factor of 10 below this system sensitivity curve. From this, the <u>highest</u> measurable radiance level can also be found using the dynamic range, which is defined as *the ratio of the maximum measurable signal to the RMS noise.*

Most NVIS systems are limited by the inherent dynamic range of the GaAs PMT which, according suppliers specifications and advice, should not be used above 10^{-7}A current. Since most conditions of the GaAs PMT lead to RMS noise values of 10^{-13} to 10^{-12}A at best, the dynamic range of these devices is 5 to 6 decades.

Suppose System A has a 5 decade dynamic range (which is a value published by some manufacturers), an envelope (shown as Noise to Max. signal in Figure 2), spanning the region between the noise and maximum signal may be constructed. Any spectral radiance level below the envelope is too small to be measured, and any level above the top is too bright be measured (and may saturate or damage the PMT). Also shown on Figure 2 are spectra of a sample NVIS source scaled to values from 0.1 fL to 10,000 fL. It can be seen that only the source at 0.1 fL lies below the saturation (Max. signal) levels of the

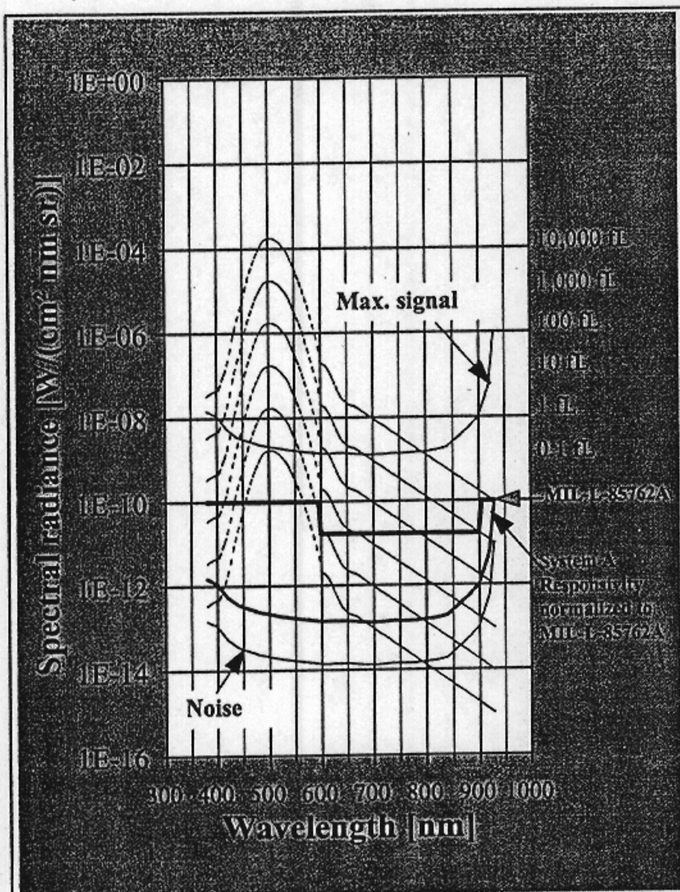

Figure 2. System responsivity envelope (Noise to Max. signal) for system A exactly matched to MIL-L-85762A limits, showing a source (dashed lines) of 0.1 fL is the brightest measurable.

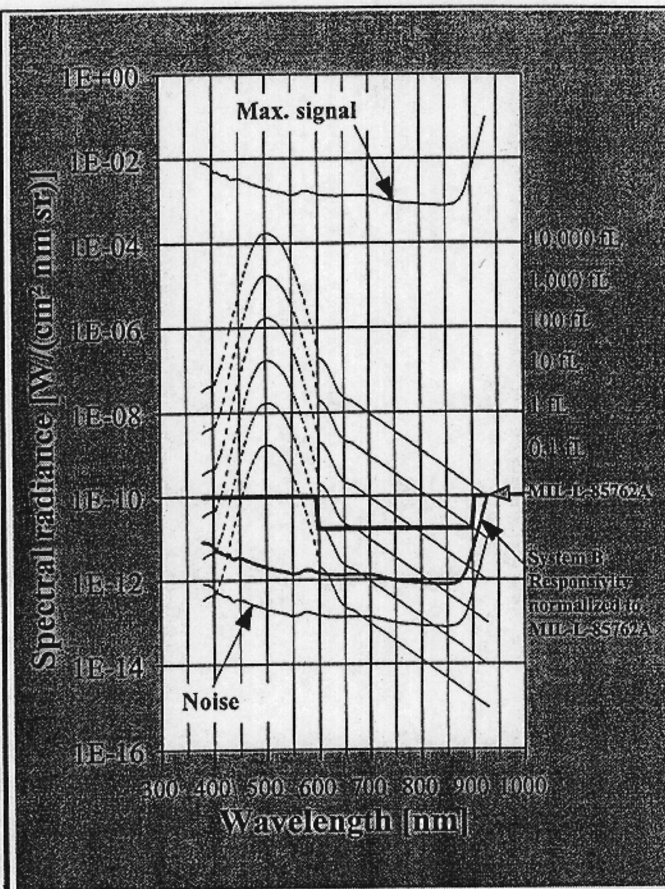

Figure 3. System responsivity envelope (Noise to Max. signal) for system B exactly matched to MIL-L-85762A limits, showing all sources (dashed lines) up to more than 10,000 fL are measurable.

System A envelope, and measurement of any source significantly brighter than this is impossible. If, for instance, System A is de-sensitized to allow measurements of brighter sources, the system radiance sensitivity would then exceed the required specification B30.2 levels. This restriction would make this instrument generally unacceptable since many NVIS compatible displays are brighter than 0.1 fL. Indeed, some displays such as warning lights are very much brighter.

In contrast, System B exhibits a radiance sensitivity spectrum that is much closer in shape to the levels defined in specification B30.2 and, more importantly, has a much larger dynamic range of 10 decades. Figure 3 shows that a NVIS sample of well over 10,000 fL may be measured while maintaining MIL-L-85762A compatibility.

5. THE IMPACT OF SYSTEM RADIANCE SENSITIVITY SHAPE ON CALIBRATIONS.

In order to make any measurement, the system must first be calibrated. An integrating sphere source, calibrated for spectral radiance, is generally most convenient for this. In the previous section, the limiting spectral radiance sensitivity corresponding to just meeting MIL-L-85762A specifications was established for System A and System B. Applying the same analysis, but this time to a calibration source at a blackbody temperature of 2856K, reveals the maximum luminance level that may be used. Figure 4 shows System A with a 2856K blackbody source scaled to the maximum measurable spectral radiance. This source corresponds to a luminance of just 0.12 fL. Working with sources of such low luminance can present many problems.

In setting a calibration source to low levels, the accuracy of the display reporting the luminance level is a limiting factor. If the last digit represents, for example, 0.01 fL then the source could never be set to better than 0.1 ± 0.01 fL, which is an error of ±10%. A display giving values to 0.0001fL is necessary to make this error insignificant. Even if the display is to this quality, zero offsets, drift and linearity problems may limit accuracy to a few percent.

In addition to display errors, it is essential to the calibration that the spectral radiance values at these luminance levels are correct. Adjusting sphere sources to this level may introduce spectral changes relative to the original calibration condition, and stray light may seriously affect the spectral radiance values. Stray light comes from external sources such as room lights, computer screens, LEDs and neon indicators. This light enters the sphere and contributes to the overall luminance and spectral radiance. For example, room lights entering the sphere may typically give an increase in luminance of 1 to 5 fL. Obviously, this is unacceptable if a level of 0.1 fL is required. In fact, virtually any light within the room may cause serious errors in spectral radiances at 0.1 fL.

A similar treatment of System B reveals that this problem does not apply. The 10 decade dynamic range of System B allows calibration sources at high levels to be used. If, for instance, a calibration source is at 100 fL then the errors discussed above are reduced by a factor of 1000. This not only makes calibration more accurate, but also makes the system easier to use.

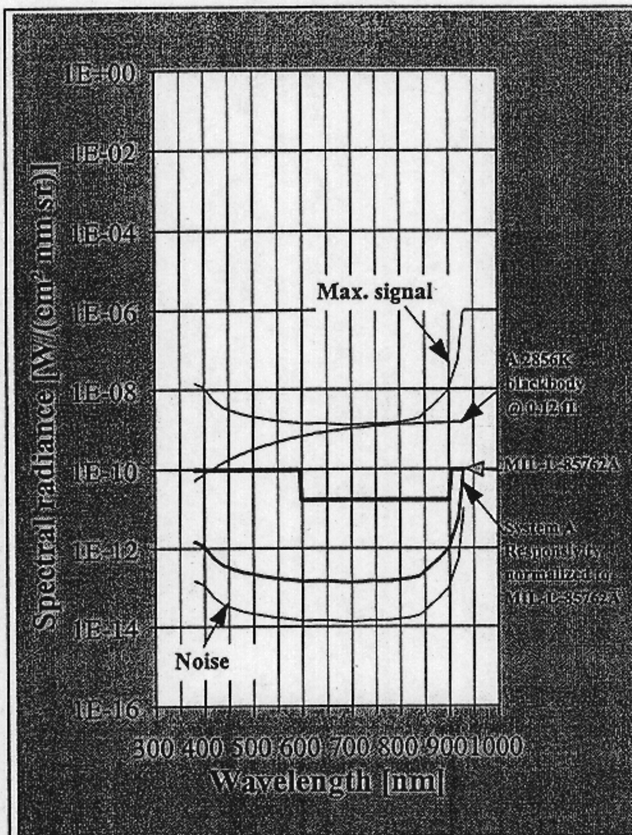

Figure 4. System responsivity envelope (Noise to Max. signal) for system A exactly matched to MIL-L-85762A limits, showing a blackbody sphere source at 2856K of 0.12 fL is the brightest usable in calibration.

6. INCREMENTAL OR TOTAL SCAN OPTIMIZATION

Although a large dynamic range is obviously desirable, for some systems it is not an option. The components available have their own inherent dynamic range and will always limit the system unless changes can be introduced at each point <u>during</u> the scan. These changes must be signal dependent and reversible to maintain full sensitivity to low light levels. The essential requirement for the very high dynamic ranges in previous sections is that scans are incremental. This means a wavelength is selected, data is gathered and then the next wavelength is selected. Data is always obtained with the wavelength stationary, so there are no time constraints in optimizing conditions: which can be determined and implemented prior to the next wavelength selection. On the other hand, if the wavelength is not constant during acquisition as in continuous scans, any decision to make changes to improve optimization would be useless since the wavelength to which it applies is already passed.

Normal NVIS sources can vary in spectral radiance at different wavelengths by up to 7 decades, and more than this is required for sources of different brightness. The required dynamic range of a system is therefore much greater than the inherent dynamic range of a GaAs PMT. If conditions are optimized for the entire scan, measurements would necessarily be limited to the PMT dynamic range. Extending the dynamic range necessarily involves incremental scan optimization, using a method that preserves the critical conditions of measurement. The OL 750-NVG uses incremental scanning as standard and provides full optimizations at each wavelength to give the best possible results.

Most manufacturers of NVIS systems provide total scan optimization only. In this technique, any neutral density filters, high voltage changes etc. to match the system response to the intensity of the source are placed in position before the start of data acquisition. The dynamic range under these conditions is therefore limited to that of the PMT, but in practice only part of that range may be used. In order to make use of the PMTs full dynamic range the system response must be matched so as to reach the maximum possible signal during the scan. This means that the PMT must operate perilously close to damage thresholds and, unfortunately, one must acquire data (and risk damaging the PMT) in order to determine the optimum conditions. This may lead to a long process of trial and error before the full potential of the system is realized. Without such user optimizations, even the limited dynamic range of the PMT can never be realized.

In the incremental scan optimization of the OL 750-NVG, the wavelength movement is halted at each data interval until the best conditions for acquisition is achieved. Neutral density filters may be placed in the beam path or removed as needed to achieve the optimum signal level for greatest accuracy. These neutral density filters therefore act in a similar way to, and in conjunction with, gain ranging. As such, the entire process is totally automatic and user-friendly. Since the transmission of neutral density filters varies with the beam profile, care must be taken to characterize them *in-situ*. Measurements must be made over the entire wavelength region of interest, since the transmission is not precisely neutral. Ideally, this should be done by the manufacturer, but users can perform these measurements if a suitable variable intensity sphere source[5] is available. Using these neutral density filters in incremental scan optimization, intense sources can be measured without compromising the sensitivity at low levels of radiance. Ten or more decades of dynamic range is easily achievable using this technique.

The use of automatic neutral density filters also provides added safety mechanisms to a system. If at the start of scans, grating or blocking filter changes, an ND4 (0.01% transmission) is selected while the light levels are checked, the PMT will be protected from overexposure and damage. Users can make measurements without having to worry about the intensity of the source because during a scan, as the signal varies, filters of appropriate densities are selected to keep light levels on the PMT optimum and well below damage thresholds.

An additional benefit of incremental scanning, is that the data integration time can be varied. At high spectral radiance levels, noise is not significant and short integrations provide good data. At low spectral radiance levels, longer integrations provide more accurate results. Using point-by-point optimization, the data integration time may be varied according to the signal, giving short integrations at high levels and longer integrations at lower levels, providing the best results in the shortest possible scan time.

7. OPTIMIZATION OF SYSTEM LINEARITY.

MIL-L-85762A SPECIFICATION

B30.6 Linearity.

Within any given measurement scale, the linearity shall be ±1% of the full scale value. The linearity between any two measurement scales shall be ±2%.

B30.6.1 Linearity verification

The linearity of the spectroradiometer shall be verified within 6 months prior to taking a measurement. A linearity check shall be performed on each detector used during the test procedures. The spectroradiometer operational parameters shall not be varied during the linearity test. The linearity check shall be performed at a specific wavelength (to be determined by the contractor) which shall not be varied during the linearity test. A light source which can be precisely, mechanically or optically varied in intensity shall be used for the linearity check. Acceptable methods that may be used to vary the intensity of the light source include the use of neutral density filters (with known transmission), precision apertures, superposition, or the inverse square law (provided the distance between the lamp and spectroradiometer can be precisely controlled using a photometric type bench). Dimming of the lamp through electronic means is unacceptable. The intensity of the lamp shall be adjusted to give a full scale reading on the lowest level of dynamic range of the spectroradiometer. Call the lamp output N and the reading on the spectroradiometer R. The intensity of the lamp shall be varied in accordance with the table below, and, in order to pass the linearity check the output of the spectroradiometer, over its entire dynamic range (as applicable) shall be within the limits shown below.

Lamp Output	Spectroradiometer Output
0.1N	0.1R ± .01R
0.5 N	0.5 R ± .01 R
5 N	5.0 R ± 0.2 R
10 N	10 R ± 0.2 R
50 N	50 R ± 2.0 R
100 N	100 R ± 2.0 R
500 N	500 R ± 20 R
1000 N	1000 R ± 20 R
5000 N	5000 R ± 200 R
10000 N	10000 R ± 200 R

A basic assumption of all spectroradiometry is that the measured signal is proportional to light at any given wavelength. If the spectral radiance of a source increases by a factor of 100, but the measured signal using an instrument increases by 99, the instrument is said to have a 1% linearity error over these two decades. In normal use, any NVIS system needs to measure spectral radiances over an extremely large range. Also, the highest spectral radiance from calibration sources normally occurs at 930 nm. Typical NVIS compatible displays may have compatible spectral radiances to the calibration source in the visible, but the infrared emission is extremely low. A large dynamic range is certainly necessary to accommodate these very different spectral radiances, but accurate results can only be obtained if the system is also linear.

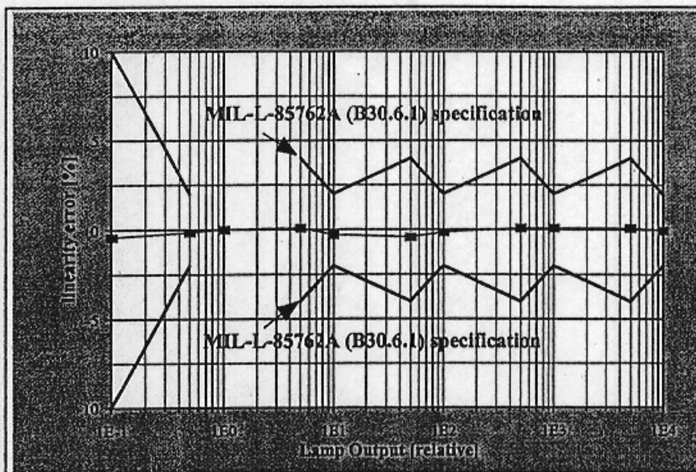

Figure 5. The linearity of a typical OL 750-NVG determined according to MIL-L-85762A section B30.6.1.

MIL-L-85762A sections B30.6 and B30.6.1 specify the maximum limits to linearity error for any NVIS system. These sections cover mandatory measurements that ideally should be made over 5 decades with the fourth decade being full scale on a gain range. In order to comply, a system needs well over 6 decades of dynamic range. Regardless of performance therefore, these measurements cannot by made with a system providing a 5 decade dynamic range since this means (by definition) the lowest values will be pure noise.

With its high dynamic range, the OL 750-NVG can easily accommodate the tests of section B30.6.1. The linearity of the OL 750-NVG will depend on: the linearity of the PMT over the desired range of light intensities; the high voltage applied to the PMT; the accuracy of neutral density filter transmission calibrations; the accuracy of calibrating individual amplifier gain ranges; the quality of the amplifier components; and the linearity of the analog-to-digital converter. All of these are selected, characterized and calibrated precisely to achieve the desired specifications. Also, exact matching of detector and amplifier characteristics and operational ranges give the best possible linearity. The result of this attention to detail is, with a maximum linearity error of less than ±0.5%, the OL 750-NVG easily exceeds the MIL-L-85762A specifications, as shown in Figure 5.

Traditionally, testing linearity has involved complex and time consuming measurements to ensure that the source intensity is set and accurately known at a all the required levels specified in B30.6.1. However, new types of sphere sources such as the OL 455-6 are now available, and greatly simplify these tests. The OL 455-6 allows continuous adjustment of spectral radiance over more than 5 decades, reducing linearity testing to a rapid and easy procedure.

8. OPTIMIZATION OF SYSTEM POLARIZATION.

Polarization is a property of light[6] not normally perceived by humans. The polarization of light may change when passing through or reflecting from materials, and the intensity may be reduced in this process. For instance, polarizing sunglasses reduce glare from swimming pool surface reflections by attenuating light at certain polarizations, allowing the wearer to see into the water underneath. In a similar way, a person wearing these glasses can make a polarized source, such as an LCD display or computer screen, appear brighter or dimmer by tilting his head. An unpolarized source would always appear equally bright, regardless of the orientation. An instrument that is sensitive to polarization may attenuate or transmit polarized light, making it appear more or less intense, depending on the direction of polarization.

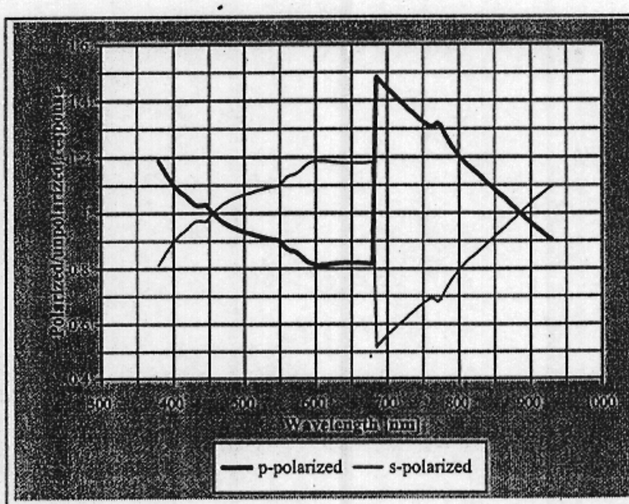

Figure 6. System response of a typical uncorrected two-grating NVIS system to polarized light relative to that with unpolarized light. Note the grating change at 680 nm.

Surprisingly, MIL-L-85762A mentions polarization only in section B40, which applies to photometers. In fact, polarization is not normally a problem for broad-band photometers, but can affect spectroradiometer results dramatically. This is due to the efficiency of gratings, which are an integral part of modern spectroradiometers, being very sensitive to the polarization of light. The polarization sensitivity of the spectroradiometer also changes substantially with wavelength. In section 2, on the optimization of system responsivity, the grating efficiency data used was for unpolarized light. This condition is appropriate for integrating sphere calibration sources, which are inherently unpolarized. However, many displays will emit partially or completely polarized light. Depending on the polarization direction of the source, the spectroradiometer may be more sensitive at lower wavelengths and less sensitive at higher wavelengths than if the source was unpolarized, as illustrated in Figure 6. In this scenario, if light is s-polarized, measurements of luminance values would be higher and NVISa and NVISb values would be lower than is really the case. Errors of up a factor of 2 too low might be expected in NVISa and NVISb values for such a system. On the other hand, if the light was p-polarized, NVISa and NVISb values might be a factor of 2 too high. Thus, it is possible with this system (however unlikely) for two measurements to disagree by a factor of 4 and still conform to MIL-L-85762A standards of testing.

The effects of polarization on spectral radiance measurements are well known[7] and are difficult to correct. Rather than correct them using complex procedures, it is better to eliminate them using depolarization optics. The effectiveness of the depolarization optic is indicated by the residual polarization sensitivity. Practical depolarization optics may be divided into three types: integrating spheres, fiber optics and scramblers.

Integrating spheres are efficient depolarizers, but their throughput is very low. For an application such as NVIS compatibility testing, the reduction in sensitivity caused by the use of integrating spheres is unacceptable.

Fiber optics depolarize light, but their efficiency in this respect depends on the type and length of the fiber. The attenuation of light in a fiber optic also varies with the length. Making the fiber long enough to reduce the residual polarization to acceptable limits (MIL-L-85762A section B40.6 places a 1% limit on this) may also degrade the sensitivity of the system to unacceptable levels.

Polarization scramblers provide efficient depolarization in appropriate circumstances, yet transmit over 90% of light in the 380 nm to 930 nm region. These devices are obviously the components of choice in fully optimized systems. They are included in the OL 750-NVG as standard, and reduce the residual polarization to less than 0.5%. This is well within the 1% level specified in section B40.6 for photometers and, more importantly, eliminates concerns or checks as to whether or not the source is polarized.

9. CONCLUSION.

MIL-L-85762A specifications provide a basis for measurements, but do not cover parameters such as dynamic range or spectroradiometer residual polarization. Ignoring these parameters in the optimization can reduce the usefulness of instruments substantially, and place a responsibility on the user to ensure that the correct results are obtained. Effective optimization of all parameters is necessary in achieving the best spectral responsivity, sensitivity, linearity and residual polarization performance for NVIS display compatibility testing. The consequences of slight changes in the optimization process are dramatic, and may place unacceptable restrictions on the accuracy and range of measurements that can be performed.

Manufacturers providing instruments for NVIS compatibility measurements differ in some respects to their approach to optimization. All optimizations clearly work in terms of generating the same result on common sources, since such discrepancies would be obvious to the user. Differences between systems would be expected when less common sources, such as polarized LCD displays, are considered. Full optimization needs to account for these less common sources, so that users obtain correct results at all times. Within the constraints of measuring real NVIS compatible displays while conforming to all relevant MIL-L-85762A specifications, the OL 750-NVG performs extremely well whereas some other possible optimizations are clearly very limited.

References

[1] Military Specification MIL-L-85762A, "Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible", project number 6220-0335.

[2] R. Young, "Fast NVIS Measurements", *Advanced Seminar Proceedings*, **section 14,** published by the Aerospace Lighting Institute, Clearwater, Florida (1997).

[3] William E. Schneider and Richard Young, "Spectroradiometry Methods", *Handbook of Applied Photometry*, Casimer DeCusatis (Ed.), 239-287, AIP Press (1997).

[4] Emmett Bradford, "The Benefits of DSP Lock-in Amplifiers", *Lasers & Optronics*, Cahners Publishing Company (November 1996).

[5] William E. Schneider and Phillip Austin, "Automated Integrating Sphere Calibration Standard", *publication pending*.

[6] Eugene Hecht and Alfred Zajac, *Optics*, 219-274, Addison-Wesley Publishing Company (1974).

[7] Henry J. Kostkowski, *Reliable Spectroradiometry*, 121-153, published by Spectroradiometry Consulting, Maryland (1997).