PROPOSED METHOD OF MEASURING DISPLAY SYSTEMS FOR TRAINING WITH STIMULATED NIGHT VISION GOGGLES

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ABSTRACT

The accurate and repeatable rendering of images in display systems designed to produce realistic training with stimulated Night Vision Goggles (NVGs) assumes we know what light levels we are trying to achieve and that we have some practical means of measuring the levels produced. In the first part of this paper we provide our best current estimate of the real world levels of lunar luminance and radiance, paying particular attention to the balance between the energy in the visible and the pass band of NVGs.

In the second part of the paper we review four distinct methods of determining the level of class-B NVIS radiance (NR_b) in a training display system. We describe in more detail the spectrometer-based approach we recommend and provide examples of the three basic measurements we assert are the minimum set of measurements needed to characterize the ability of a display system to accurately stimulate NVGs. These measurements are the ratio of NR_b to luminance (NR_b/Lum), the contrast ratio in the NVG pass band (CR_{NRb}), and the level of NR_b for the peak white of the display system (NR_{bW}).

In the final section of the paper we provide a worked example of the proposed measurements and calculations for a simple display system incorporating an LCoS projector.

INTRODUCTION

Night Vision Goggle (NVG) training is an increasingly important element of pilot training syllabi. The training is more effective if the students can use their own goggle sets during flight simulator-based training. Effective training thus creates the need to stimulate the actual goggles using the simulator display imagery. NVG training is further enhanced if the visual system simultaneously provides accurate presentations for both aided (NVG) and un-aided (non-NVG) viewers. Successful training requires that real-world illumination conditions conveyed to the pilot in flight briefings be accurately represented by the simulator display system both for NVG stimulation and for un-aided viewing. Clearly, accuracy implies repeatability, and the display alignment must maintain accuracy on an ongoing basis.

Simulator display systems are undergoing rapid evolution as new technologies emerge and mature. Rapid evolution is accompanied by significant challenges in display system integration, installation, and recurring calibration. The emergence of viable new display types with differing radiometric performance further complicates these issues.

This paper extends our previous work (Lloyd, et al., 2008) where we introduced the use of the NVIS radiance to luminance (NR_b/Lum) ratio as a fundamental metric for analyzing NVG stimulation for a given display system. Our technique has proven useful, and we have successfully applied our NR_b/Lum analysis to CRT display systems, multiple HD projection systems, two QXGA LCoS projection systems, and a laser projection system (Burggraf, 2009).

This paper addresses two fundamental aspects required for accurate high-quality NVG training: 1) characterization of real-world radiometric and photometric illumination/ irradiance requirements, and 2) techniques for measuring and characterizing the radiometric performance of candidate projection systems for NVG stimulation.

LUNAR LEVELS IN THE REAL WORLD

Previous Estimate of Lunar Levels

In our previous paper (Lloyd et al., 2008) we provided estimates of luminance (Lum) and class-B NVIS radiance (NR_b) for real world levels of lunar and other common sources of illumination. These estimates were used to construct a chart that provides guidance relating to the goals of a display system designed for training with stimulated

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NVGs. The diagonal lunar illumination lines on that chart were drawn using estimates of NR_b and Lum for the "full moon" condition drawn from two different sources. Lum for the full moon (0.0345 fL) was drawn from Biberman (2000, p 3-3). The estimate of NR_b for the full moon condition was taken from Table 2 in (Clark et. al., 2005), which derived this level from a theoretical model of sun, moon, planetary motions, and presumably atmospheric effects (citing Jensen, et. al., 2001). Thus, our target line for the lunar source in our 2008 paper indicated an NR_b/Lum ratio of 3.5e-7 W/(cm^2 sr fL).

Excessive Variance

Since our 2008 paper was published we have reviewed additional and more recent papers, and we have made our own measurements of lunar radiation. Upon making comparisons across papers we found substantial variation in these levels with the most significant variance occurring in the reported levels of NR_b. For example, across the documents referenced in this paper we found a 14:1 difference in the estimates of NR_b for the "full moon" condition. After reexamining the literature we found three basic reasons that account for this variance:

- There are substantial differences in the sensors, collection optics, and procedures used across these studies that span a 60 year period of time.
- Large variations in the level of the full moon condition must be expected, even for the same lunar elevation, due to the changing distances between sun, moon, and earth and due to atmospheric effects in particular.
- Due to a phenomenon called the "opposition effect", measurements made near the full moon are highly variable due to the narrow angle retro-reflective like property of the lunar surface that is apparent when the sun is very nearly directly behind the observer. The magnitude of the opposition effect is large enough that one "full" moon may be several times brighter (or dimmer) than another "full" moon measured at the same location and elevation.

A Stable Estimate of NR_b/Lum

In this paper we provide a more stable estimate of NR_b/Lum by employing a strategy that is immune to the measurement challenges described above. With the new strategy we use only ordered pairs of NR_b and Lum measurements that were made using the same instrument, at the same time, at the same location, and under the same atmospheric conditions. This is accomplished by computing the quantities of NR_b and Lum from calibrated spectral data that spans the range of 400 to 950 nm. In the papers we reviewed we found more than a dozen spectral measurements that have been made (or estimated) over the years. The upper portion of Figure 1 shows the spectral power distributions (SPD) of lunar radiation from six of these measurements. The six curves have been normalized to an arbitrary value of 1.5. Below the measurement data are the photopic and NVIS-B response profiles (MIL-STD-3009) for reference.

Examination of the measurements shows that they all follow the same general curve but with obvious differences in localized shape. Each of these spectral measurements was multiplied by the response profiles and summed, resulting in single numbers for NVIS-B and photopically-weighted integrated radiances. The ratio of these two numbers is provided in Column 2 of Table 1 for each spectral measurement. Recall that the NVIS-B weighted integrated radiance is equivalent to NR_b. Note also that in Table 1 a seventh estimate of the ratios is provided by Clark (2010), however, this paper did not provide an SPD that could be plotted with the other six in Figure 1.

In Column 3 the integrated radiance ratio is converted to NR_b/Lum as these units are more convenient for persons using common luminance meters. To make this conversion the photopically-weighted integrated radiance is converted to fL by dividing by 1.9934e6 which is the conversion from photopically-weighted radiance to fL. This factor is derived from the CIE-defined constant (683) that defines the lumen (CIE, 1926), the conversion from cm^2 to m^2, and the conversion from cd/m^2 to fL.

Eq 1) 1 W / (cm^2 sr) x [683(cd sr) / W] x [10000 cm^2/m^2] / [3.4263 (cd / m^2) / fL] = 1.9934e6 fL

While the measurements in Figure 1 appear to vary considerably, examination of the ratio data in Table 1 shows that the standard deviation of the NR_b/Lum is only 9.5% of the mean value. Based on these data the standard error of the mean (SEM) is 3.6% of our "best current estimate" of the NR_b/Lum ratio which is 1.01 e-6. The 90% confidence interval for NR_b/Lum is (1.01 +/- 0.06)e-6. This new estimate of NR_b/Lum is 2.9 times higher than the estimate we provided in our 2008 paper. Accordingly, a physically correct balance of NR_b and Lum requires a relatively higher amount of NR_b than we previously had estimated.

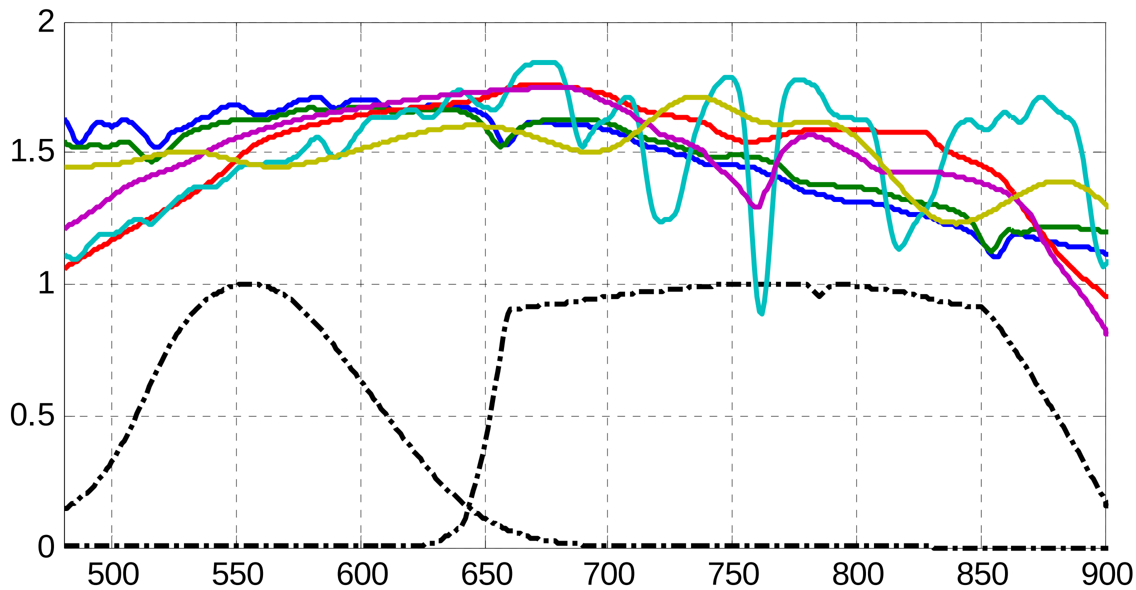

Figure 1 Upper curves: Six measurements of the spectral power distribution of lunar radiation made from the earth. The sources of these data are listed in Table 1. Lower curves: Photopic (left) and NVIS-B (right) response profiles, provided for comparison with the measured data.

Table 1 Shown in Column 2 is the ratio of photopically weighted integrated radiance and NVIS-B weighted integrated radiance for each of the lunar spectral measurements listed in Column 1. Column 3 shows the same data converted to NR_b/Lum. The standard error of the mean of these levels is 9.5 / sqrt(7) = 3.6% of the expected value giving a 90% confidence interval for NR_b/Lum of 0.95e-6 to 1.07e-6. We recommend the nominal value of 1.0e-6 for NR_b/Lum for assessing the ability of a display system to represent lunar illumination.

Source	**Disk Fraction**	**Elevation, deg**	**Cloud cover**	**Radiance: NR_b/Photopic**	**NR_b/Lum, W/(cm^2 SR fL)**
Miller & Turner (2009)	Full	90	Clear	1.77	0.89 e-6
Miller & Turner (2009)	Gibbous	90	Clear	1.86	0.93 e-6
Parry Moon (Biberman, pp 3-10)	?	60	?	2.23	1.12 e-6
Vatsia (1972), Fig 8, curve 1	70%	55	20%	2.11	1.06 e-6
Lloyd (2009)	Full	61	Clear	2.27	1.14 e-6
Clark (2005)	?	?	Clear?	2.02	1.01 e-6
Clark (2010)	?	?	Clear?	1.88	0.94 e-6
Mean				2.02	1.01 e-6
100 * (Range / Mean)				25 %	25 %
100 * (Std. Dev. / Mean)				9.5 %	9.5 %

ANALYZING VISIBLE AND NVG STIMULATION

Figure 2 shows an updated NR_b/Lum ratio chart from our 2008 paper. Changes include: The lunar target line has been raised by a factor of 2.9 to reflect our new estimate of NR_b/Lum. The lunar line is now a curve that transitions from the full moon to the no moon condition which is dominated by the night sky radiance when the contribution of cultural lighting is absent. When cultural lighting is present, the NR_b/Lum ratio moves towards the line representing high intensity discharge (HID) lamps. Typical spectral power distributions for these lamps (high pressure sodium and metal halide) are provided in our 2008 paper.

The brightest portion of the lunar line represents the full moon condition; however, the reader should understand that the absolute levels of both NR_b and luminance co-vary significantly. It is the ratio of NR_b/Lum and thus, the position of the lunar line on this chart that is the stable attribute of lunar illumination. As discussed in our 2008 paper, we believe the ratio of NR_b/Lum is one of the most important attributes of the design of a display system intended for simulation training with stimulated NVGs.

The multiple curves shown as dotted lines in the bottom left portion of the chart are intended to show the effect of variables that significantly change the absolute levels of irradiance. These factors include lunar elevation, percent

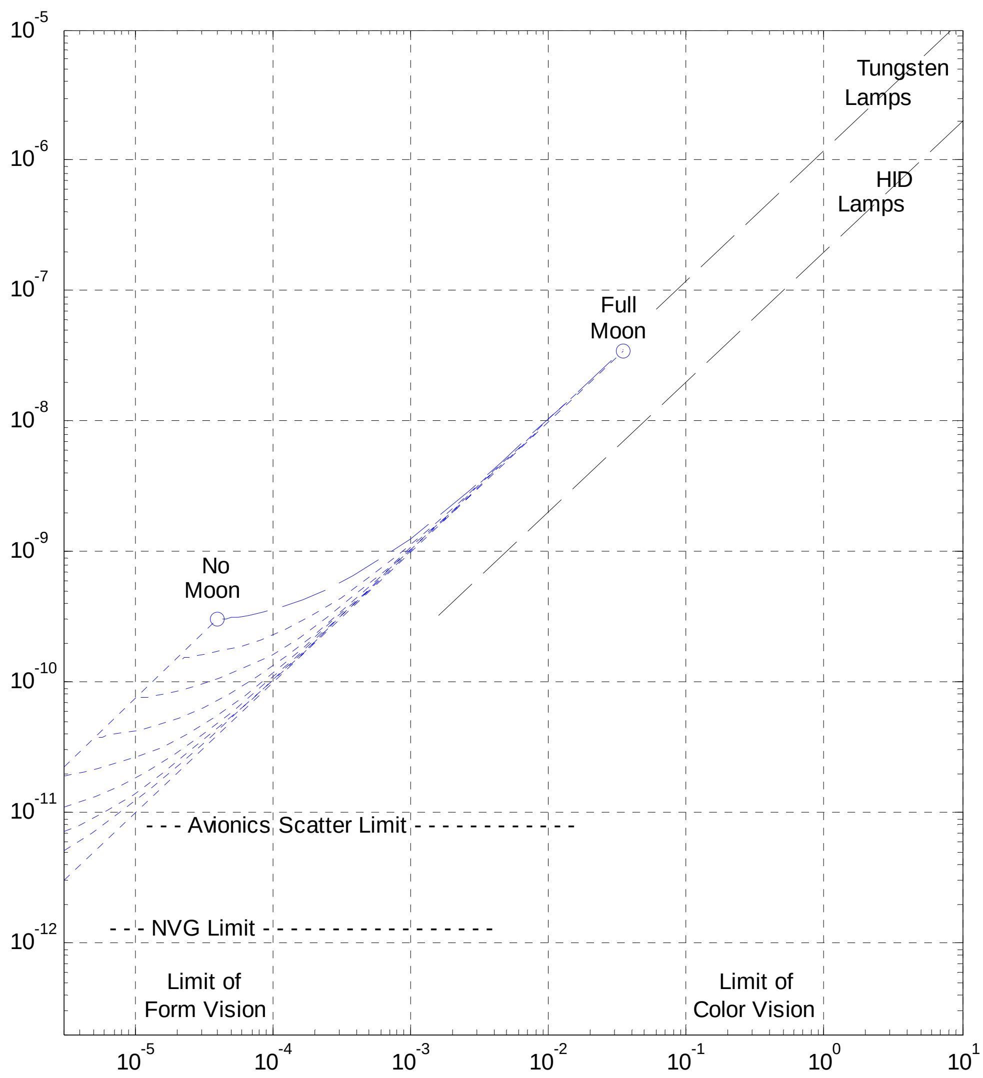

Figure 2 Chart showing NR_b and Luminance for natural and cultural light sources.

disk, and weather effects such as cloud cover. These factors slide the curve up and down the diagonal line without substantially changing the ratio.

The data from two of the papers that we reviewed show a tendency for the NR_b/Lum ratio to increase as the percent disk decreases (Vatsia 1972, pp. 31, and Kieffer and Stone, 2005). This increase in the ratio corresponds closely with lunar line on our chart which curves towards higher NR_b/Lum as the lunar iradiance decreases to the night sky condition.

MEASURING NVG STIMULATION IN DISPLAY SYSTEMS

In this section we describe four methods of measuring the capability of display systems to stimulate NVGs.

Photometer and Correlation

With the CRT-based projection systems used for NVG stimulation applications over the past decade, the spectral power distribution of the red phosphor used to stimulate the goggles (and thus the NR_b/Lum) has been relatively constant between projector channels and over the life of a CRT. With these systems the channel-to-channel matching of NR_b has been reasonably successful as long as the systems were matched across channels in luminance. In other words, the high correlation of NR_b with luminance has allowed users to match the level of NVG stimulation across channels using a common luminance meter that does not measure directly the level of NR_b.

With arc lamp based projectors we have found that the NR_b/Lum can change significantly across lamps and projectors of the same model. Additionally, this ratio is known to change significantly over the life of a lamp and we expect it will change over the life of a projector. Because the expected correlation between NR_b and luminance is low, we discourage using this method for projectors with arc lamps.

For projectors that use LED or laser light sources, we do not expect the luminance correlation method to be useful because it is unlikely these projectors will use the visible primaries to stimulate the NVGs. With these sources the spectra is so narrow that not even the red primary can provide sufficient energy in the pass band of the NVGs. Thus a fourth primary must be used for NVG stimulation and the wavelength of this additional primary is typically selected well out of the pass band of the luminance meter (e.g., 800 nm).

NVG-Meter and Photometer

The level of NVG stimulation produced by a display system can be measured directly using a custom "NVG meter" consisting of a standard photometer (e.g., a Minolta LS-100) coupled to an NVG. Credit for this design is given to the Air Force Research Lab (Night Operations Center of Excellence) who demonstrated the method in 2007 as part of our joint work on an AFSOC project (ATARS 2007).

Figure 3 shows a photograph of the NVG meter constructed at FlightSafety. The monocular is described by ITT as a PVS-14 night vision device with a minus blue objective that gives it an NVIS-B sensitivity profile. This meter was calibrated against the AFRL NVIS meter, a Photo Research PR-1530AR radiometer (Serial # AS1655) equipped with a custom filter that produced an NVIS-B response profile. The calibration factor for the FlightSafety NVG meter was as 2.2e-10. The lowest practical level that can be measured with this meter approximately NR_b = 1e-12 (LS-100 reading of 0.004 to 0.005) which is down around the cutoff of NVGs. The highest level that can be measured is around NR_b = 4e-10 (LS-100 reading of 2) which is determined by the level at which the automatic gain control circuit within the goggles begins reducing their gain. Since the gain of the goggles is variable and unknown above this limit, we recommend staying below this level when making measurements of NR_b.

The practical working dynamic range of this meter for NR_b measurements is about 500. Meters of this design can be used to measure projectors with contrast ratios much greater than this with the help of broad band ND filters. We have had good success using a set of 2x2 inch reflective neutral density filters (Catalog number P64-350 from Edmund Optics). Caution should be exercised, however, with the use of these filters as the densities indicated are only nominal. We independently measured the NVIS-B transmittance of the filters in our set to improve the accuracy of our contrast measurements.

An important advantage of the NVG meter, aside from portability and convenience, is the fact that the device is as

Figure 3 Photograph of the NVG meter used at FlightSafety. Device consists of an NVG monocular attached to a Minolta LS-100 photometer with a coupling tube. This meter was calibrated against a PR-1530AR radiometer.

sensitive as the NVGs it is intended to represent. This feature is useful for making direct measurements of levels from the eyepoint of a display system. With the other methods discussed in this paper, the meter must be positioned near the projector in order to collect enough light to make reliable measurements. The measurements must then be scaled to represent the levels expected at the eyepoint.

A notable disadvantage of the NVG meter is that the exact spectral response of the device is unknown. We can only assume the manufacturer produced a device with a spectral response that reasonably approximates of the NVIS standard. And we cannot expect the NVG meter to be stable as NVGs were not designed to be components of measuring instruments. We have little idea how the gain of the NVG meter changes with temperature, battery state, age of the device, or from unit to unit. However, our practical experience with the FlightSafety NVG meter suggests the device is reasonably stable as the measurements made with this device correlate well to the other methods we have used.

Radiometer and Photometer

More direct measurements of NR_b can be made using a radiometer (see Figure 4) that has been equipped with a filter to produce a response profile that matches the NVIS B goggle type. This meter uses a photomultiplier tube as the detector which gives it very high sensitivity, however, at the expense of requiring frequent recalibration. The unit comes with a built in calibration standard that can be regularly calibrated against a NIST traceable standard. While the unit is more sensitive than the photometer or spectrometer described in this paper, it is not sensitive enough to directly measure the radiance of the black from the eyepoint for display systems with very high contrast.

Figure 4 Photograph of the PR-1530AR NviSpot, Night Vision Radiometer, available from Photo Research. This photomultiplier-based instrument comes with an internal calibration source and a variety of lens options that allow more flexibility in the measurement configurations.

An advantage of the radiometer over the NVG meter is that the spectral sensitivity of the radiometer is known. The most notable disadvantage of the radiometer is that it is significantly more expensive than the other meters described in this paper.

Spectrometer and Photometer

This section describes the use of a spectrometer which provides the most complete characterization of a display system and the most accurate measurement of the NR_b/Lum ratio. The primary advantage afforded by the spectrometer is that both NR_b and luminance are measured simultaneously using a single instrument. Use of a spectrometer for display system measurements avoids the same set of measurement challenges described above relating to the use of separate instruments for measuring lunar NR_b and luminance.

A second significant advantage of using a spectrometer is that it provides the engineer with a more complete picture of what is going on in a display system than do the other three methods. In addition to providing correlated NR_b and luminance measurements, complete spectral plots over the range of wavelengths of interest are available with each measurement. Spectral plots reveal how a display system behaves and serve as good diagnostic tool for understanding and troubleshooting systems and components.

When using spectral data, the measurement of NR_b and luminance can be more exact as the precise definitions of the photopic and NVIS-B sensitivity profiles are used in the computation of these levels. With meters that use physical filters, such as the photometer and radiometer described above, we cannot expect the sensitivity profile to match the standard exactly and we must expect significant variation across devices. A related advantage of the spectrometer over the other approaches is that it requires only a software change to represent classes of NVG other than the NVIS class B.

Spectrometers capable of measuring over wavelengths spanning the visible and near infra-red (400 to 950 nm) have been available for many years. Spectrometers with this capability vary considerably in their sensitivity, speed, portability, ease of use, and price. Historically, laboratory grade spectrometers with built in or external calibration sources have cost tens to many tens of thousands of dollars. While these instruments are generally very capable, we do not recommend a laboratory spectrometer (unless you already own one) if your only need for the device is to check the NR_b/Lum calibration of display systems. Recent years have seen several vendors offer much less expensive "compact" spectrometers well suited for this relatively undemanding spectral measurement.

Compact spectrometers with sufficient accuracy in the range of 400 to 950 nm are now available from multiple sources for prices ranging as low as approximately $3000 including an optical fiber and lens. These devices are expected to work sufficiently well for measuring the NR_b/Lum ratio. The measurement of absolute levels of luminance or radiance is considerably more complex using these devices as an external standard must be used to calibrate the device and the collection optics used to make the measurements. Fortunately, with the recommended procedure described below, we have no requirement to use the spectrometer for measuring absolute levels.

Figure 5 shows an example of a common type of compact spectrometer that has been used in display calibration applications. Similar devices (e.g., the USB-2000 and USB-4000) have performed well in embedded display calibration systems such as the Display Management System (DMS) by FlightSafety (Lloyd et. al., 2008) and the ACURAS by BARCO (Lloyd et. al., 2003). The device to the right of the computer is the spectrometer which connects to and is powered from the computer via a USB connection. Light is directed into the spectrometer via the fiber optic cable which is coiled up in the lower right portion of the figure. Typically, a lens is attached to the input end of the fiber to increase the efficiency with which the system collects light.

When purchasing a compact spectrometer we recommend

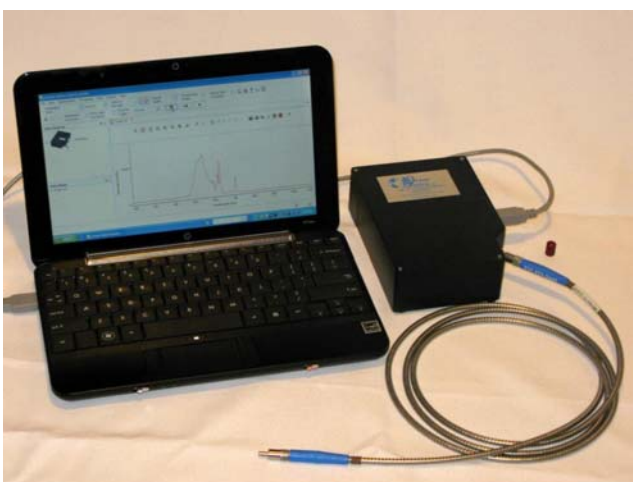

Figure 5 Photograph of an OceanOptics HR2000+ spectrometer operated (and powered) from an HP Mini 1000 netbook computer. Light is directed into the spectrometer using the fiber optic cable (silver coil with blue ends) that would be fitted with a lens/diffuser assembly (not shown) selected for each type of measurement. Computer is running the SpectraSuite software purchased with the spectrometer.

you work with a vendor engineer to make appropriate decisions regarding the internal setup of the spectrometer. With the goal of maximizing optical throughput (sensitivity) of the device you are advised to consider the following points:

- Select a detector technology that provides suitable sensitivity, range of integration times, and signal/noise ratio for these measurements. Today several suitable technology options available, thus we make no specific recommendation. Devices available ten years ago (e.g, an un-cooled Ocean Optics USB 2000) had sufficient sensitivity and stability they could provide useful colorimetric measurements of display systems and components. In general the compact spectrometers of today are more capable than those of 10 years ago.
- Select a grating and configuration that produces an acceptable signal/noise ratio covering the 400 to 950 nm range of wavelengths. We chose the HC1 composite grating with gives our device a nominal working range of 200 to 1100 nm.
- Consider using a wider optical entrance aperture than may come standard. Any data collected using this spectrometer will be multiplied by and integrated with sensitivity functions (e.g., photopic or NVIS-B) that are a hundred or more nm in width. Fine discrimination of wavelength is of little value relative to our goals, thus, use of an aperture that produces an optical bandwidth as wide as 10 to 15 nm is appropriate. We selected the 25 μm slit option for our spectrometer.
- Consider using the largest diameter fiber available that will work with the system. We chose the 600 rather than the more common 400 μm fiber core diameter.
- Ask about other options (e.g., an internal field lens) that may improve the sensitivity of the system.

An important limitation of the compact spectrometer relative to the radiometer described above is that it has a more limited dynamic range. At any single integration time the spectrometer has reasonable accuracy over a dynamic range of no more than approximately 10:1. Integration times suitable for making display measurements range from a single frame time up to several seconds for a dynamic range of no more than about 200:1. Thus, the highest contrast ratio that can be measured directly with this type of spectrometer is approximately 2000:1. As with the NVG meter described above, a calibrated neutral density filter can be used with the spectrometer to measure display systems with higher contrast. Alternatively, the compact spectrometer can be used in conjunction with a high dynamic range photometer to make high dynamic range measurements of NR_b contrast (see the last section in this paper).

Table 2 Summary of the advantages and disadvantages of the four measurement approaches for characterizing the ability of a display system to stimulate NVGs.

Method	Advantages	Disadvantages
Photometer and Correlation	Meter is affordable and most customers and suppliers already own one. Meter is typically calibrated against NIST traceable luminance standard. Response of meter is stable between calibration intervals	Unacceptable accuracy for arc-lamp based projectors for which the NR_b/Lum varies significantly between projectors and lamps and even over the life of a single projector/lamp. For CRT projectors, the method is vulnerable to changes in the formulation of the red phosphor.
NVG Meter and Photometer	The sensitivity is similar to the NVGs used in training. Measurements down to the cutoff of the NVGs can be made from the eyepoint. The instrument is readily portable and convenient for making spot-checks in simulation trainers. Cost is much lower than radiometer but higher than the other two approaches.	The spectral response of a monocular is unknown and only an approximation of the NVIS standard. The NR_b/Lum response of the monocular varies from device to device, thus, the meter must be calibrated against a known source. The dynamic range is no greater than about 500:1. Neutral density filters must be used with the meter to measure projectors with higher contrast. Government regulations may restrict some from obtaining NVGs. Cost of an NVG monocular is about twice the cost of the most common luminance meter.
Radiometer and Photometer	Method provides the most "direct" measurement of NR_b. Meter can have a built in calibration source that is typically calibrated against NIST traceable standards The spectral sensitivity of the meter is known.	Sensitivity is insufficient to allow measurement down to the cutoff of the NVGs from the eyepoint. Equipment cost is many times higher than the luminance meter or spectrometer used in the other three methods. Meter uses a photomultiplier tube which requires frequent re-calibration. Accuracy appears to be poor for narrow-band sources such as red LEDs and lasers.
Spectrometer and Photometer	Measures both NR_b and luminance with same device, thus provides the most precise measurement of NR_b/Lum Response matches the NVIS class B standard with the greatest precision and can be readily adapted to represent other classes of NVG. Can be embedded in display systems as part of an auto-calibration system.	Not sensitive enough to make measurements from the eyepoint. Calibration for absolute levels requires the use of an external source.

Collection Optics and Materials

This section provides several practical suggestions relating to spectral measurements of projectors and display systems.

- Homogenize the exit pupil. With most digital projectors you will find that the exit pupil of the projector is not at all uniform in luminance or color. An obvious way to measure the spectra of the black state of the projector is to aim the spectrometer back into the exit pupil. If you choose to measure the black state this way we recommend you use a ground glass diffuser between the projector lens and the spectrometer fiber. Avoid the use of plastic diffusers unless you are confident they are spectrally flat over the range of 400 to 950 nm. We have found that a diffuse white reflector positioned near the projection lens homogenizes the light sufficiently.
- Beware of absorptive filters. We recommend great caution with the use of absorptive ND filters unless you are confident they are spectrally flat over the range of 400 to 950 nm. An unfortunate choice of filter would be the Roscolux ND filter designed for use in the theater industry. These filters work well in their intended application but are a poor choice for our use as their transmittance is high in the near infrared. We have found several glass absorptive ND filters to exhibit the same spectral characteristics.
- Beware of "black" aluminum. More than once we have been caught by surprise in the laboratory by suspiciously high NR_b measurements that were traced back to the "black" treatments on aluminum components. Some of the common black treatments can have a reflectance in the near infrared that is nearly as high as white.
- Beware of black velvet. Black velvet is often recommended as a good material for absorbing stray light in the laboratory environment. Upon measuring our sample of black velvet we were surprised to learn that it was a very good reflector in the NR_b pass band. We suspect the material may have contained nylon which is known to be a good IR reflector.

MEASUREMENT EXAMPLE:LCOS PROJECTOR

In this section we provide a worked example of what we expect is the minimal set of measurements needed to characterize a display system for training with stimulated NVGs. These measurements include the NR_b/Lum ratio, the NR_b contrast, and the peak NR_b. For this example we assume our display system incorporates a single LCoS projector typical of those currently sold into the home theater market.

Equipment:

- Projector and some means of displaying full white and black test patterns
- Compact spectrometer equivalent to the device described above
- Calibrated luminance meter such as the Minolta LS-100 or CS-100
- Diffuse white reflector. Note that a high or even a known reflectance is not required for these measurements. Flat white wall paint (titanium dioxide) will work as well as a calibrated reflectance standard for this measurement

Procedure:

- Turn on projector and let the lamp warm up as per vendor recommendations
- Set the test pattern to full white
- Measure display luminance from the eyepoint, record this level as Lum_W
- Position the diffuse reflector in the light path several meters from the projector
  - Place diffuser far enough away that you do not saturate the spectrometer
  - The actual distance is unimportant since the calculations do not require the absolute level of the spectrometer response.
- Aim the photometer at the diffuser and measure luminance, record the level as Lum_{Hi}
- Aim the spectrometer at the diffuser and measure the spectrum, save and label the file SPD_W
- Set the test pattern to black
- Position the diffuse reflector in the light path up close to the projector
  - Place diffuser close enough to the projector to obtain an acceptable signal/noise ratio
  - The actual distance is unimportant since the calculations do not require the absolute level of the spectrometer response.
- Aim the photometer at the diffuser and measure luminance, record the level as Lum_{Lo}
- Aim the spectrometer at the diffuser and measure the spectrum, save and label the file SPD_B

Results and Calculations:

The spectral power distributions collected as part of this example are shown in Figure 6 and Figure 7 along with the photopic and NVIS-B sensitivity profiles. The caption of each figure provides the NR_b/Lum ratio that was computed from each data set. Comparison across these figures reveals the relative amount of energy under the NVIS-B curve is higher for the black than it is for the white state. This finding is typical of LCoS projectors that were designed to have optimal contrast in the visible range of wavelengths.

The numerator is calculated by multiplying, wavelength-by wavelength, the measured SPD and the NVIS-B response profile and summing across wavelength (e.g., 400 to 900 nm). Similarly, the denominator is calculated by multiplying the measured SPD and the photopic luminosity function and summing across wavelength. The units of the denominator are converted to fL by dividing by 1.9934e6 as discussed above. The ratio of these two numbers produces NR_b/Lum which is shown in the caption of each figure.

For our example we assume the technician measured the following luminance levels with the photometer:

- Lum_{Hi} = 1500 fL (recall the diffuser was placed close to the projection lens)
- Lum_{Lo} = 0.1 fL
- Lum_W = 8 fL

Using these luminance levels and the computed levels of NR_b/Lum from the captions of Figures 6 and 7 we can determine the remaining quantities of interest.

- The luminance contrast of the display: CR_{Lum} = Lum_{Hi} / Lum_{Lo} = CR_{Lum}
  - For our example CR_{Lum} = 1500 / 0.01 = 15000
- The NR_b contrast of the display: CR_{NRb} = ((NR_b/Lum_W) / (NR_b/Lum_B)) * CR_{Lum}
  - For our example CR_{NRb} = (0.28e-6 / 0.65e-6) * 15000 = 6460
- Using the 8 fL white measured from the eyepoint, we can scale the other measurements to be representative of the eyepoint:
  - NR_b of the white: NR_{bW} = Lum_W * NR_b/Lum_W 8 * 0.28e-6 = 2.24e-6
  - Luminance of the black: Lum_B = Lum_W / CR_{Lum} = 8 / 15000 = 5.3e-4
  - NR_b of the black: = NR_{bB} = NR_{bW} / CR_{NRb} = 2.24e-6 / 6460 = 3.5e-10

We have found it useful to record the various measured and calculated quantities describing the performance of the display system in table form as this helps convey the relationships among the values as shown in Table 3.

Table 3 . Performance summary for the display system in this example. The five bolded quantities were measured using the photometer or spectrometer. The remaining six quantities were derived from the five bolded measurements.

	White	Black	Contrast
Lum, close to projector, fL	**1500**	**0.10**	15000
Lum, from eye point, fL	**8.0**	5.3e-4	15000
NR_b, eye point, W/(cm^2 SR).	2.24e-6	3.5e-10	6460
NR_b/Lum, W/(cm^2 SR fL).	**0.28e-6**	**0.65e-6**	

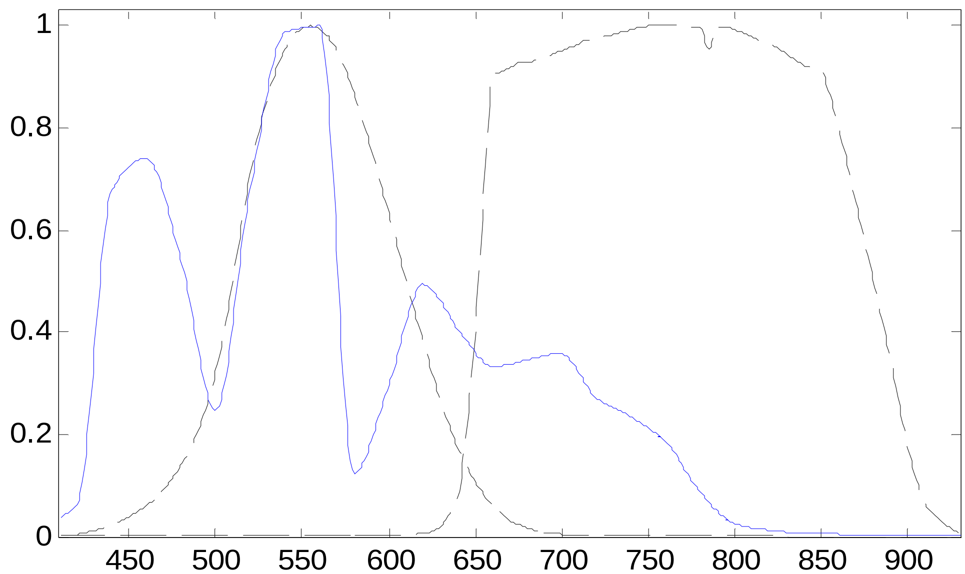

Figure 6 Spectral power distribution of the projector with the test pattern set to full WHITE. The NR_b/Lum ratio computed from this spectra is 0.28e-6 W/(cm^2 SR fL).

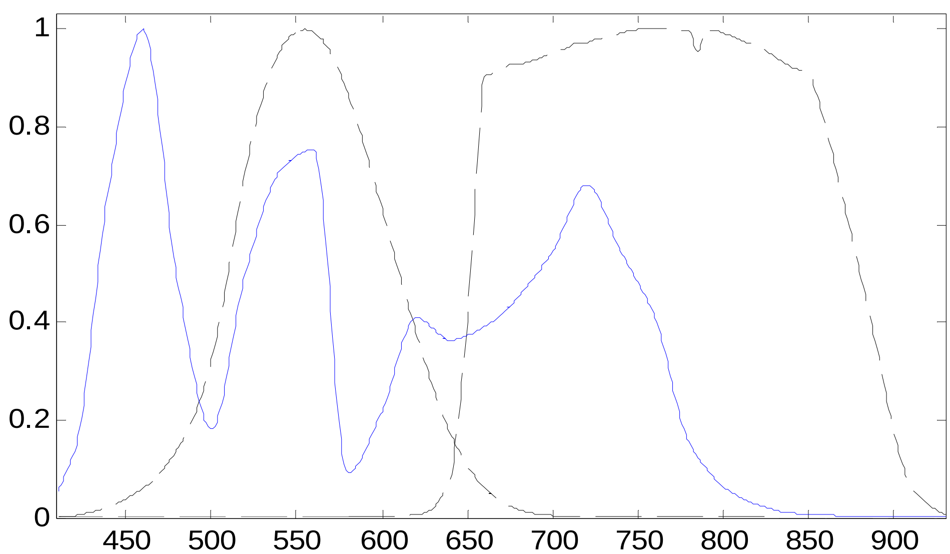

Figure 7 Spectral power distribution of the projector with the test pattern set to BLACK. The NR_b/Lum ratio computed from this spectra is 0.65e-6 W/(cm^2 SR fL).

CONCLUSIONS

We have refined our definition of real-world illumination and irradiance requirements. Our refined estimate is more accurate than the estimate provided in our 2008 paper.

For lunar levels ranging from full moon down to a few percent of full moon it is important to achieve a reasonably accurate NR_b/Lum ratio. For levels below this the maintenance of this ratio becomes less important as unaided vision is so poor that significant errors in the ratio are not visible. For levels below a few percent of full moon achieving an accurate NRb level becomes the primary goal and the luminance level can be allowed to vary significantly.

The five measurements described in the last section of this paper allow technicians to concisely describe the performance of a display system designed for simulation training with stimulated NVGs. The benefits of using this particular combination of measurements include:

- This procedure allows the three essential NVG-related quantities (NR_b/Lum, and CR_{NRb} and NR_{bW}) to be measured without expensive or uncommon equipment.
- The procedure relies on the luminance meter for the large dynamic range required to measure the high contrast of modern projectors. This allows a low dynamic range spectrometer to be used for a significant cost reduction .
- Most parties in the simulation training business already own a suitable photometer and have procedures in place for calibrating their meter against NIST traceable standards. Reliance on the luminance meter to measure absolute levels eliminates the complexity and expense of calibrating the spectrometer and collection optics to report radiance levels accurately.
- Use of a diffusing reflector placed close to the projector allows a spectral power distribution to be measured with an acceptable signal/noise ratio. We are unaware of any means by which a black spectrum can be measured from the eyepoint for very high contrast projectors.
- The NRb and luminance of the black as seen from the eyepoint can be estimated with confidence. For display systems with a contrast of greater than a few thousand, these quantities cannot be measured directly from the eyepoint using common and affordable meters.

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