

# TOWARDS REPEATABLE, DETERMINISTIC NVG STIMULATION

Dr. Charles J. Lloyd – Principal Staff Engineer  
Steven G. Nigus – Engineering Director  
Brian K. Ford – Lead Engineer

Visual Simulation Systems  
FlightSafety International

## Abstract

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. This creates the need to stimulate the actual goggles using the simulator displays. We have successfully used CRT projector-based display systems for a number of years to stimulate goggles. However, these systems have presented significant challenges during system installation, integration, and recurring calibration. The emergence of viable new non-CRT display types with differing radiometric performance further complicates these issues. This paper presents a range of system improvements leading to improved stimulation repeatability and determinism. We present our methods for quantitatively relating measured NVG device responses to real-world radiance values. These methods are used to compare the capabilities and limitations of several display types. We describe our new illumination model that is traceable to published real-world sky radiance and lunar illumination characteristics. We have developed a set of recommendations for Instructor Operating Station (IOS) illumination controls that relate simulated scene illumination to conditions reported in standard pilot briefings, which provides a familiar, natural training framework.

## Introduction

NVGs are rugged and highly portable light amplification systems that are completely dependent on the available light in the scene or from IR illuminators. By amplifying the available light several thousand times, a user is able to navigate through space and see objects and people at illumination levels that are far lower than what is required for unaided vision.

The NVGs most commonly used by military aviators have one of the three spectral sensitivity profiles as shown in Figure 1. Aviators in rotary wing aircraft most commonly use NVGs with the profile labeled B while fixed wing pilots who may have to use a head up display (HUD) com-

monly use goggles with the profile labeled C that allows the HUD phosphor (at about 540 nm) to be seen through the goggles.

The left-most curves in Figure 1 show the spectral sensitivity of human vision that peaks at 555 nm. Comparison across these curves reveals that the goggles are much more sensitive to near infra-red (NIR) energy than to the wavelengths visible to unaided observers. The primary reason for the high NIR sensitivity of the goggles is illustrated in Figure 2, which shows that under low or no moon conditions the night sky provides significantly more irradiance at wavelengths above 700 nm than over the visible part of the electromagnetic spectrum.

A second reason for the aviator NVGs to be insensitive to the visible band relative to the NIR is to allow cockpit and instrument lighting to remain on while the goggles are in use. The pilot not wearing the goggles can operate the aircraft without washing out the out-the-window scene for the pilot wearing the goggles.

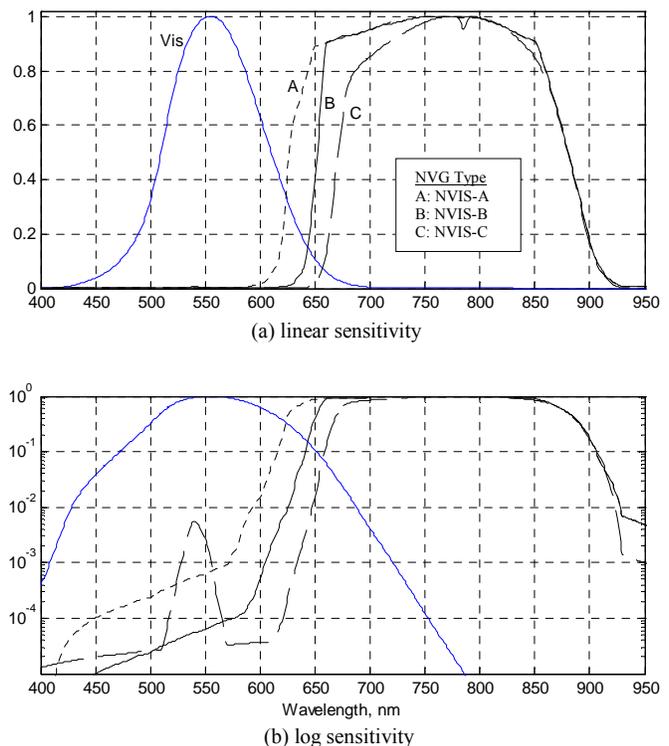


Figure 1 Spectral sensitivity of three goggle types.

## Sources of NIR

Figure 2 provides normalized spectral power distributions (SPDs) for the two primary sources of natural radiance at night (Clark, 2005). The upper curve shows the lunar spectrum, which provides significant radiance spanning the range of 400 to 900 nm. The night sky curve indicates the radiance distribution for the no moon condition where starlight and airglow provide most of the radiance. For the no moon condition, a much higher percentage of the radiance occurs at longer wavelengths.

In the visible range the full moon at zenith produces about 750 times the luminance in the visible range as compared to the night sky. This compares to the NVIS-B goggle passband (Figure 1) where the full moon provides only 35 times the radiance. Given that modern NVGs work well at the lower irradiance levels provided by the night sky (and the assumption that the bad guys are not equipped with NVGs) these curves indicate that the NVG warfighter has a distinct advantage when fighting in low or no moon conditions where the unaided viewer is essentially blind.

For operations occurring within a few miles of modern cities or towns, cultural lighting can provide a significant proportion of the available irradiance, especially for the low or no moon conditions. In high-overcast, hazy, or dusty weather conditions the many sources of outdoor lighting reflected from the clouds, dust, and atmospheric moisture can produce radiance levels exceeding that provided by the night sky. Thus, reflected cultural lighting is often a significant source of irradiance affecting NVG operations.

In the US the two most common types of outdoor lighting in use today are the high-pressure sodium (HPS) and metal halide (MH) lamps. Both of these are high intensity discharge (HID) lamps that are sometimes referred to as “arc lamps.” Figure 3 and Figure 4 show typical spectral power distributions for these sources. For fixed outdoor installations, tung-

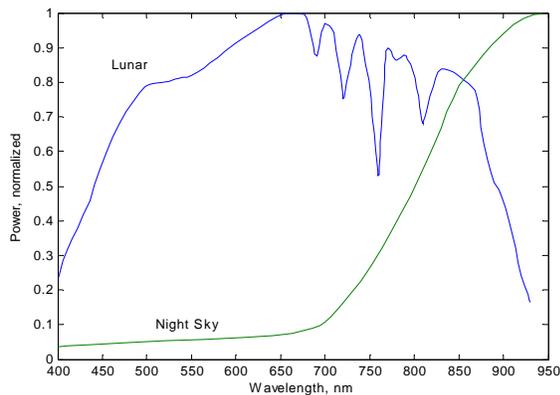


Figure 2 Spectral power distributions for lunar and night sky conditions – no cultural light sources.

sten, halogen, and “mercury” HID lamps are almost extinct today as their luminous efficacy is lower, which makes them more expensive to operate.

A decade ago the HPS lamp was much more common than the more expensive MH lamp. In recent years the MH lamp has become more popular and many communities have required the use of reflector systems that direct a higher percentage of the light towards the ground rather than letting it go to waste or otherwise pollute the sky. As viewed from aircraft over the past decade, the color of the lights has been trending from the yellowish HPS to the more bluish MH, and we are seeing a lower percentage of lightpoints (direct view of lamps) and a higher percentage of distinct “lighting lobes” on the surfaces illuminated by the lamps.

Another common source of illumination in the urban areas is the automotive headlights. Here, despite the introduction of HID headlamps almost a decade ago, the tungsten-halogen lamp still dominates. The “halogen” lamp is a modern variety of tungsten lamp that has a longer life and higher luminous efficacy, but at a higher lamp cost. Halogen lamps have a spectral distribution that is much different than the common HID lamps used for outdoor lighting as shown in Figure 5. The halogen lamps provide a continuous spectrum and have a much higher fraction of energy in the NIR portion com-

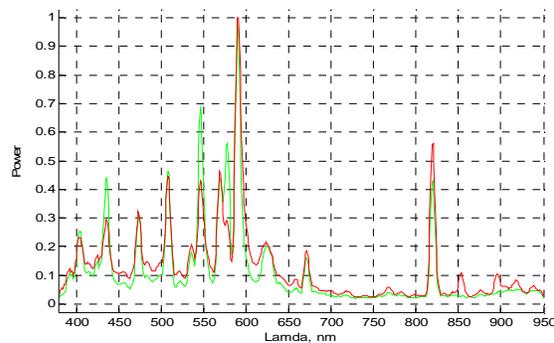


Figure 3 Spectral power distributions for two metal halide lights measured in the St. Louis area

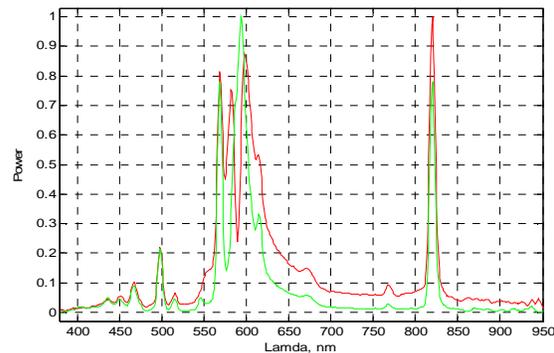


Figure 4 Spectral power distributions for two high pressure sodium lights measured in the St. Louis area.

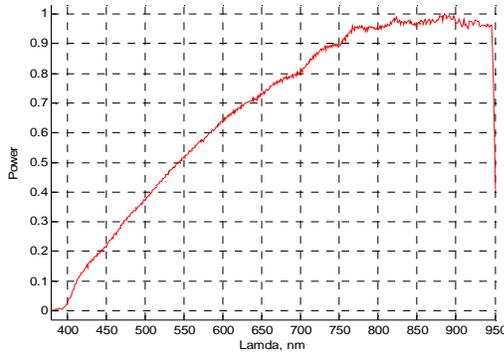


Figure 5 Spectral power distribution for a tungsten-halogen automotive headlamp.

pared to the HID lamps. In the next section, we'll correlate the scenarios described in this section to the display system capabilities.

### The NRb/Vis Ratio Chart

The ability of a display system to produce accurate NVG images is measured by the NRb/Vis ratio. This quantity is defined as the integrated radiance over the NVIS-B ( $W/cm^2 sr$ ) passband divided by luminance in fL. Each of the common illuminants discussed in the last section can be described using this ratio. The light produced by the display system primaries used to stimulate the goggles in a training simulator can also be characterized with this ratio to determine how realistically they can render an NVG image.

It is instructive to plot display system perform-

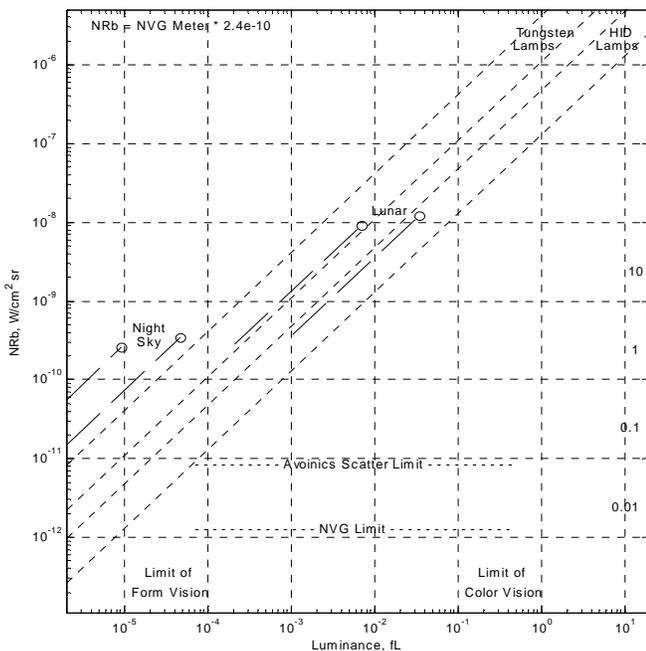


Figure 6 Integrated radiance in the NVIS-B pass band (NRb) as a function of luminance (fL) for a variety of natural and cultural light sources.

ance on a chart showing NRb as a function of luminance (Figure 6). On this chart the lunar illuminant appears near the center of the chart as two lines terminated at their tops with circles. The rightmost lunar line represents the constant NRb/Vis ratio for a white reflectance standard for levels extending from the full moon down to the no-moon condition where the night sky radiance dominates. The left lunar line represents moonlight reflected from foliage which has high reflectance (75%) in the NIR and low reflectance (20%) in the visible.

A pair of similar lines and circles is shown on the left side of this plot for the night sky irradiance. The right line shows the night sky radiance reflected from a white standard and the left line shows the night sky reflected from foliage. The luminance of the night sky is 1/35 of the lunar luminance and the NRb of the night sky is 1/750 of the lunar NRb. Graphically, Figure 6 shows that the night sky produces a much higher proportion of NIR than does the moon.

The two common sources of cultural lighting, HPS and MH are lumped together on this chart as HID lamps as their NRb/Vis ratios are very similar. The right most HID line corresponds to the white standard and the left line corresponds to foliage. The two tungsten lines (white reflectance standard and foliage) appear to the left of the HID lines as they have a significantly higher NRb/Vis ratio.

For the HID and tungsten lamps there is no meaningful upper limit like there is for the natural sources. In the natural world these lamps can be as dim as zero and as bright as  $10^8$  fL.

Several additional levels appear on this chart, as they are useful to examine the performance of a display system. For example, the horizontal line labeled "NVG Limit" shows the practical cutoff for Gen III (pre-Pinical) goggles. Below this level, a large target becomes invisible against a black background, even at 100% contrast. The horizontal line labeled "Avionics Scatter Limit" shows the approximate level of the blackest black (projectors turned off) that can be achieved in a collimated flight simulation trainer. This limit is set by the unavoidable inter-reflection and scatter of the "NVG compatible" instrument and panel lighting that is set to levels appropriate for flying NVG missions. Thus, this line establishes the lowest practical black level that the display system will have to achieve for training with NVGs.

At the bottom right, the label "Limit of color vision" shows where human color vision begins to degrade. At luminance levels close to 1 fL the size of a threshold color difference begins to elevate. By 1e-1 fL there is a substantial (e.g., x 5 to 10) increase in color difference thresholds. By about 1e-2 fL, humans are completely blind to color differences and can see only scotopic "luminance" contrast.

While the absolute minimum amount of light a person can see is down around  $1e-6$  fL, it becomes almost impossible to recognize or navigate around people or large objects without collisions at luminance levels on the order of  $1e-4$  and  $1e-5$  fL

### NVG Stimulation with Display Systems

By far the CRT is the most commonly used projector technology for flight simulation display systems used for NVG training. The CRT phosphor technology used in these display systems has remained stable for at least a decade. Thus, we can develop a good estimate of the amount of NVG stimulation that can be provided in a typical flight simulation trainer. Figure 7 provides SPDs for the R, G, and B primaries of the typical CRT projector and compares these with the photopic and NRB response profiles.

### Calibration of NVG Displays

We have developed three ways to measure and verify the NVG stimulation produced by training display systems. For CRT projectors, for which the SPD is stable and known, a photometer can be used to measure luminance and the luminance value can be used to determine NRB. The calibration factors for calibrating NRB against luminance are provided below.

The second and more direct way to measure NRB is with the “NVG Meter” described below. This meter has a spectral sensitivity profile close to that of the NVIS-B goggles. Hence, in addition to CRTs, the NVG Meter can be used to measure other projector technologies for which the SPD of the primaries may not be known. The NVG meter is much more sensitive than a typical photometer and can be used to directly measure the lowest radiance levels that can be seen through the goggles.

A third method for measuring NRB can be applied to non-CRT display systems for which the color of the primaries remains constant over a range of levels. This method uses a spectrometer to capture an SPD extending up to about 950 nm (Figure 7). These data are used together with the spectral sensitivity data

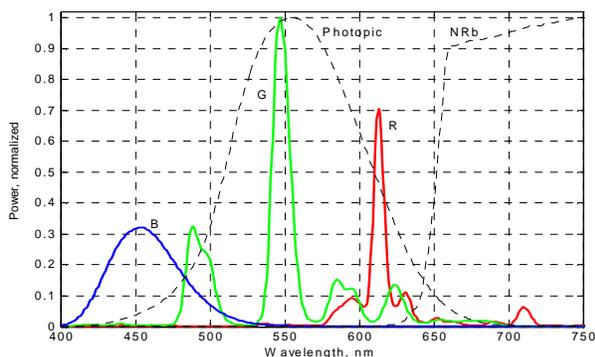


Figure 7 Spectral power distribution of red, green, and blue CRTs and NVIS-B NVG sensitivity

shown in Figure 1 to determine the expected response of the NVGs. This spectrometer-based method is the most accurate of the three methods described here as it uses a version of the NRB response profile that is perfect by definition. However, this method has a significant shortcoming in that it cannot measure small radiance levels. This method is usable down to about the level of full lunar illumination (see Figure 6) that is about 3 orders of magnitude higher than the avionics scatter limit.

For display technologies where the shape of the SPD of the primaries does not change as a function of drive level (e.g., red and green CRTs), spectrometer measurements made off the projection screen are meaningful because the measurements at the highest drive levels can be extrapolated to the low levels. Spectrometer measurements from the screen may not work for most LCoS and LCD projectors as the SPD of the primaries can change significantly with drive level.

The spectrometer-based method to determine the NVG stimulation level is much more practical if the spectrometer is configured to look backward into a diffuser placed very near the projection lens. This configuration works well because the amount of light that is collected is thousands of times greater than can be collected off the much dimmer reflection from the screen.

### NVG Meter

The level of NVG stimulation produced by a display system can be measured directly using a custom “NVG meter” which consists of a standard photometer (Minolta LS-100) that has been coupled to an NVG monocular. Figure 8 shows a photograph of this assembly. 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.

The luminance meter was calibrated against the AFRL NVIS meter, a Photo Research PR-1530AR radiometer equipped with a custom filter that produced an NVIS-B response profile. This NIST-traceable meter (Serial # AS1655) was brought to the training center at Hurlburt Field in Jan 07 and was used to measure the radiance produced by the R, G,



Figure 8 “NVG Meter” assembly used to measure display systems response

and B CRT projector primaries over a range of drive levels. The CRT primaries were also measured using a Minolta LS-100 luminance meter, the NVG meter (gain control set to max), and a similar NVG meter consisting of a Minolta luminance meter coupled to one side of a ANVIS-9 NVG binoculars. The resulting measurement data are provided in Figure 10 for the red CRT.

The calibration factor at the top of the right sub-plot in Figure 10 shows that NRb can be predicted as  $2.2e-10$  \* the reading on the NVG meter. Note that the dashed lines in the center and right sub-plots curve to the right at the top of their ranges. This curvature indicates the highest level that can be measured as this is the point at which the AGC of the goggles begins reducing the gain of the goggles (by an unknown amount). The lowest NRb level that can be measured with the NVG meters is about  $1e-12$  which produces an NVG meter reading of about 0.005. The Minolta LS-100 luminance meter reports readings down to 0.001. The lowest NRb level that can be reliably measured using the AFRL NVIS meter is about  $3e-11$ , thus, the data in Figure 10 do not extend below this level.

The lowest radiance level measured was about  $3e-11$ , which is the practical lower limit of the radiometer. The lowest levels produced by the CRTs are substantially lower than this limit. The CRT projectors were calibrated using an automated alignment system, which employs a sensitive meter that is placed at the projection lenses looking back into the CRTs. With this configuration, the sensor collects more than 1000 times the light than can be collected from a sensor in the cockpit. The practical lower limit of the red and green CRTs is estimated at about  $1e-12$ .

### Adjustable NIR Light Source

Thus far, three means of measuring the NVG stimulation available in the NRb band have been discussed: NVG meter, photometer with calibration factors for the red and green CRTs, and spectrometer.

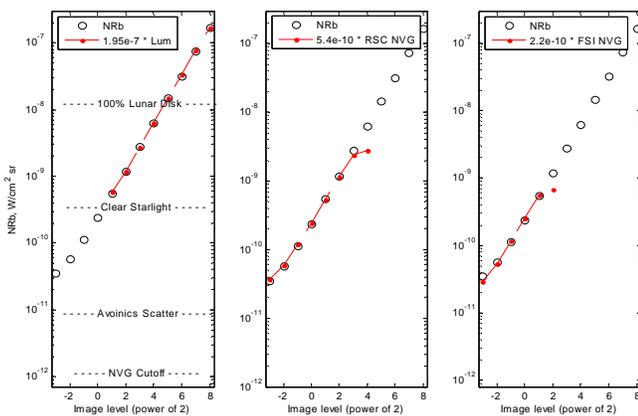


Figure 10 Red CRT Measurements using four meters over 12 levels (projector black level  $\leq 1e-12$ )

Each of these measurement techniques can be periodically checked using an adjustable radiance standard, shown in Figure 9, developed to support NVG measurements.

This NVG standard was designed with three level controls that allow it to be adjusted over a large range of radiance, while holding the shape of the SPD as constant as practical. The standard was designed with two “integrating chambers” ( $TiO_2$  coated) with two adjustable apertures. Each aperture had five positions that allowed light to pass through. The diameters of the apertures were 1,  $\frac{1}{2}$ ,  $\frac{1}{4}$ ,  $\frac{1}{8}$ , and  $\frac{1}{16}$  inches. Thus, the areas of the apertures in each control varied over a range of 256:1. The lamp was mounted to an adjustable slide in a black chamber that moved it towards and away from the first aperture which let the light into the first integrating chamber. This slide could vary the intensity of the light over a range of 32:1. Using the combination of the slide and the two apertures, the radiance at the output diffuser of the box could be adjusted over a  $256 * 32 > 2$  million : 1 range.

The lamp power, integrating chamber sizes, and aperture diameters were selected such that the bottom end of the radiance range was below the cutoff of the NVGs. Given that there exist no meters that are more sensitive to the NRb range than are the NVGs themselves, it becomes a challenge to accurately measure the lowest level within the capability of NVGs. Note that the relatively sensitive (and expensive) radiometer used by AFRL can only measure reliably down to a level of about  $3e-11$ , which turns out to be about 20 times the goggle cutoff level.

The primary reason for us to use multiple integrating chambers was to allow the standard to be calibrated to levels much lower than the capability of any meter. This was possible because placing integrating chambers between each control made the controls independent of one another, that is, the throughput of one control does not depend on the settings of other controls. Given this independence, the throughput of the system is equal to the product of the throughput of each control. The expected inde-



Figure 9 Adjustable radiance standard used to measure goggle cutoff and check NVG meter calibration

pendence of the three controls was validated by measuring many control combinations using a laboratory radiometer. The controls were found to be multiplicative to within a few percent.

We calibrated the standard by setting the lamp current to 0.23 A, setting the controls to 1, 1, and 1, and measuring the output using the radiometer. At these control settings the NRb was  $4.1 \times 10^{-9} \text{ W/cm}^2 \cdot \text{SR}$  which sets the calibration factor for the device. To use the standard for checking the other meters, we set the lamp current to the level used for calibration and the controls to produce the desired NRb. The standard is used occasionally so that the lamp receives few hours of use, thus, maximizing the repeatability of the device.

### NVG Training: Display System Challenges

NVGs are used in flight training simulators to conduct two types of training: familiarization with NVGs, and mission rehearsal.

**Familiarization** – Students flying with NVGs may start training with relatively well-lit nights with a near full moon, and transition to low or no moon conditions. Training is often conducted using models of terrain near US military bases.

**Mission Rehearsal** -- Mission rehearsal training objectives typically include practicing reconnaissance, rescue, or attack missions with specific military objectives and resources, and at specific locations. Achieving accurate levels of visible and NVG stimulation is generally more important for the mission rehearsal tasks than it is for the initial familiarization training.

### Existing NVG Training Systems Challenges

All known operational flight simulation training display systems in use today (excluding a few “research simulators”) use only three primary colors, R, G, and B. Most of these systems use CRT projectors. With these systems, the red color channel produces enough energy in the NIR to be useful for stimulating the NVGs. This section describes several common challenges associated with the use of 3-primary display systems for NVG training.

**Unaided Scene Too Bright** -- The most common complaint registered by users of existing NVG training systems is that the unaided (Vis) scene is too visible when the NVG image has been adjusted to a suitable visibility level for the condition of interest. Stated differently, it is too often reported that when the brightness of the unaided scene is set to be appropriate for some desired illumination level (e.g., no-moon), the image as seen through the NVGs is too dim and too noisy, or not at all visible. These reports suggest that the intensity of images produced by CRT projectors in the visible range is too high relative to the intensity of images produced in the NVG range.

In other words, the NVG/Vis ratio is too low. This finding is illustrated in Figure 11 by plotting the response of the CRT projector on the chart that was first presented in Figure 6.

The white line (labeled “W”) in this figure shows the relative amount of NRb and luminance produced by a balanced white of a typical CRT projector. This white line occurs about a factor of 6 to the right of the line indicating the reflectance of moonlight from white objects. In other words, the balanced white of a typical CRT projector produces only about 1/6<sup>th</sup> of the NRb/Vis that would be produced by white paper in moonlight. For luminance levels greater than about 0.1 fL, where human color vision begins to work, it is not possible to produce a white that looks white and simultaneously produces an appropriate NRb level using a standard CRT projector.

**Unaided Scene Too Red** -- Perhaps the second most common complaint with existing NVG training systems is that the unaided OTW scene looks too red. With standard CRT projectors, one way to improve the ratio of NRb/Vis ratio is to increase the relative proportion of red in the image. This adjustment has the effect of moving from the W towards the R lines in Figure 11 which certainly moves the NRb/Vis in the right direction (by a factor of about 3). This solution works pretty well as long as luminance remains below about 0.1 fL where observers have poor color vision. When this strategy is employed, the brightest objects in the scene such as the lunar disk, light lobes, lightpoints, and other bright objects can look distinctly red. A fundamental solution to this problem, using an optical filter to increase the NRb/Vis, is

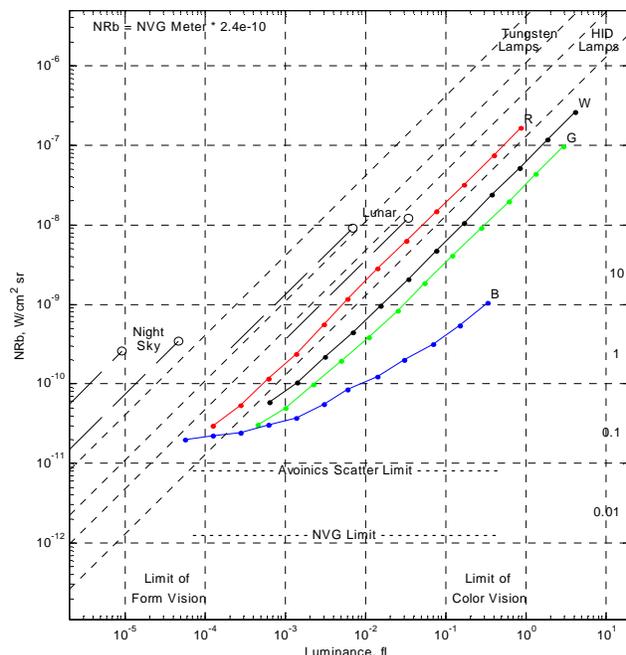


Figure 11 Luminance and NRb produced by the R, G, B, and white of a typical CRT projector used for flight simulation training with NVGs.

described below.

**Misadjusted NVG Black Levels** -- Until very recently there has been no alternative to the CRT for flight simulation trainers designed for night operations. This was primarily because no alternate technology was able to produce the very high contrast ratios, and thus the very dark blacks that are required for reasonable rendering of night scenes. When three-primary display systems are to be used to produce NVG images in addition to visible, the dynamic range requirement has far exceeded the capability of any practical non-CRT projector. That is until the very recent introduction of the sequential panel projector that can reliably produce contrast ratios in excess of 200,000.

With an appropriate setup of the image generator and gamma correction tables, most CRT projectors used in trainers over the past decade are capable of producing suitable black levels. However, significant problems related to the appropriate and reliable adjustment of the black levels are too often encountered. Two distinct reasons for these problems are:

- Display system designers have not had practical equipment or procedures to regularly measure and adjust the levels of NVG stimulation.
- The flight training community has not had clear understanding, requirements, or guidelines to make these adjustments.

**Grayscale Sampling Errors** -- Numerous authors have pointed out the need for high-bit depth image encoding when very high contrast images are processed and displayed. (Reinhard, 2006) (Clark, 2005) (Schreiber, 1986) If suitably fine grayscale encoding is not performed, then undesirable “grayscale banding” or “false contours” can be introduced into the images. While some within the flight simulation training industry may have encountered the problems associated with limited grayscale bit depth, we have successfully employed dithering techniques for many years to eliminate this problem. Recent tests have demonstrated that these artifacts are not visible at any level ranging from the darkest NVG levels to the brightest whites producible by the display.

**Underwhelming Halos** -- One reason the calligraphic CRT projector has enjoyed success within NVG training systems is that calligraphic lightpoints can achieve peak luminance (and NRb) levels that are 5 to 10 times higher than the maximum raster white produced by the display system. This attribute of the calligraphic lightpoints has been used to stimulate visible halos around the lightpoints when observed through the NVGs.

As the industry transitions away from calligraphic CRT projectors and towards the more affordable and maintainable light valve projectors, the ability to pro-

duce lightpoints many times brighter than the raster white will go away. Many have cited this relatively weak ability of light valve projectors to stimulate halos in NVGs as a shortcoming of the new technology. It appears that the most practical solution to the production of halos for the NVG wearer is to use the image generator to simulate the halos around the brightest lightpoints and objects.

### Optical Filters for CRT Projectors

A significant improvement to the performance of the installed base of CRT projectors can be expected with the use of optical filters. Figure 12 shows such a filter installed over the red lens of a Skylight 1500 raster/calligraphic projector. While this concept was evaluated using a manually placed filter, we envision a computer controlled filter changer for simulation trainers so that rapid transitions can be made to and from NVG mode. The performance of this filter is illustrated graphically in Figure 13. Comparison of Figure 13 and Figure 11 shows that the addition of this filter increases the NRb/Vis ratio of the red CRT by a factor of 8, which has the effect of increasing the NRb/Vis ratio of the white by a factor of 6. This has the net effect of making the white produced by the projector comparable with that of white objects under lunar illumination. This change to the optical performance of the projector is expected to significantly reduce or eliminate the two most common complaints associated with current NVG training implementations, “unaided scene too bright and too red”.

### Alternatives to CRT Projectors

Current trends in display design are pushing contrast ratios for non-CRT projectors to much higher levels than were achievable just a few years ago. Circa 2002, the best LCD and DLP projectors produced contrast ratios no larger than about 1200 to 1500. When standard LCoS projectors were first introduced in the 2003-2004 time frame, their contrast ratio was not substantially higher than LCD and

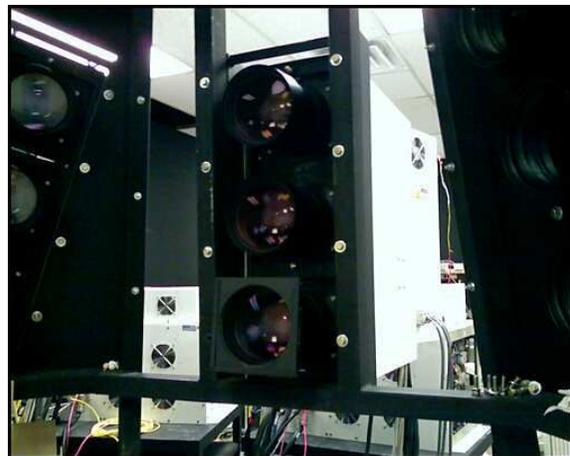


Figure 12 CRT projector fitted with optical filter on red channel.

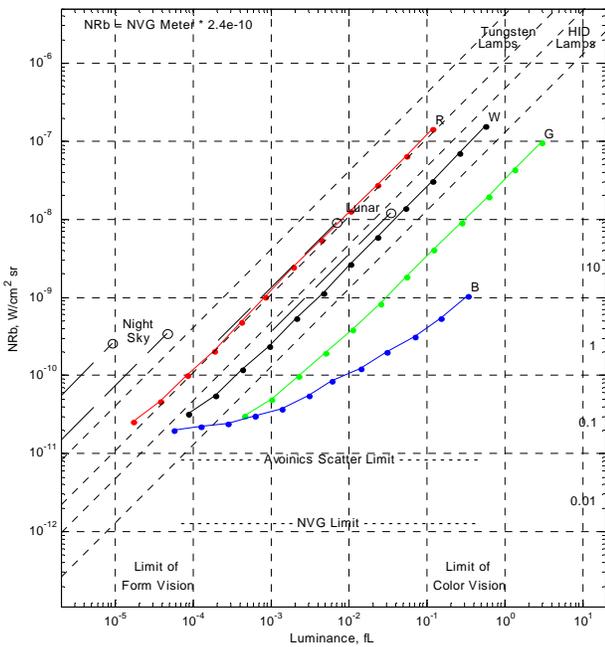


Figure 13 Luminance and NRb produced by the R, G, B, and white of a typical CRT projector equipped with an optical filter on the red channel

DLP projectors. The past two years have seen several companies push the CR of commercially available “home theater” projectors up over 10,000. Today there are several commercial offerings that have a CR as high as 15,000.

The SEOS Zorro 2015 projector, which is expected to be available in 2008, was designed specifically for the simulation training market. This projector has a unique “sequential panel” design that can produce a CR that is at least 250,000 in the visible range and 30,000 in the NVG range. Thus, in a 3 year period we have seen more than a 100 X increase in CR which has been translated into a large reduction in black levels of non-CRT projectors. This greatly reduced black level makes the Zorro an interesting option for training with NVGs.

The performance of a prototype Zorro 2015 projector, measured in mid 2007, is plotted in Figure 14. It shows the variation of NRb and luminance as a function of drive level. Comparison with Figure 11 indicates that the performance is quite similar to the unfiltered CRT projector. The position of the white line for the Zorro is to the right of the lunar white line by a factor of about 4 indicating the need to increase the NRb/Vis ratio somewhat. This ratio can be increased by using an optical filter similar to that used on the CRT projector. The design of this filter would be more complex, however, since the filter affects all three primary colors on the Zorro (a single lens system) whereas the filter has no effect on the green and blue primaries for the 3-lens CRT projectors. The

initial approach taken with the Zorro projector has been to ask the vendor to alter the design of the color separation and recombination filters within the projector to raise the NRb/Vis ratio. Thus, it may be possible to accurately match the lunar-white line with no alterations to the production projector.

Note that the lowest NRb level produced by the Zorro is about a factor of 10 lower than the lowest level produced by the CRT. This result is simply an artifact of the limit of the radiometer used to measure the CRT. Independent measurements of the CRT projectors show that the lowest controllable NRb level extends down to about 1e-12. Since both projectors extend below the avionics scatter limit, there is no practical difference in their black level performance.

While providing a huge contrast ratio, the peak brightness of lightpoints produced on the Zorro will not be as high as can be produced by the Skylight projector. Recall that the peak brightness of calligraphic lightpoints can be 5 to 10 times that of the raster white. While the raster white of the Zorro will be up to twice that of a CRT projector, the peak lightpoint brightness will be only 20 to 50% of the calligraphic projectors.

Over the next few years, we expect to see a steady increase in peak luminance of simulation training display systems; however, this improvement is expected to be much slower than the recent rapid increase in CR. Current requirements for simulation trainers typically state that the peak raster white for collimated systems must be at least 4 fL. We expect that this level will increase to 10 to 15 fL over the

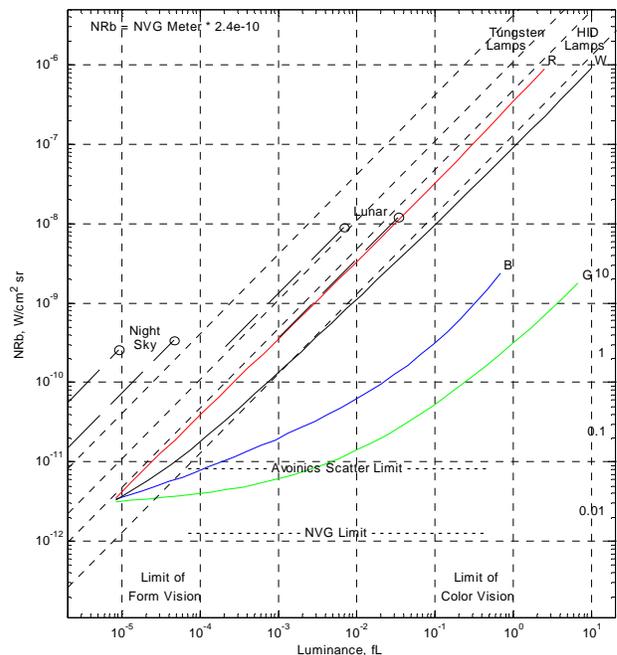


Figure 14 Luminance and NRb produced by the R, G, B, and white for the Zorro 2015 projector.

next few years as modern projectors are capable of producing more lumens than the CRTs used over the past few decades. Even if we increased the peak luminance of the display system to 20 or 30 fL, the displays would be no where near bright enough to stimulate the overdrive behavior of NVGs to realistic levels.

### NVG Rendering

To support deterministic NVG stimulation, we have implemented a comprehensive lunar illumination model that is traceable to published real-world sky radiance and lunar illumination characteristics. With this model, specified lunar elevation and phase conditions will result in a scene illumination that matches real-world illumination for those same conditions. The associated NVG stimulation will also match real-world stimulation to the extent possible given the limitations of the display at hand. The sections below describe the rendering model.

### VITAL Rendering Baseline

The evolutionary step here is to convert our standard rendering pipeline to one based on physically correct illumination parameters and with a dynamic range appropriate for NVG stimulation. Fortunately, the rendering pipeline already has many of the requisite characteristics for proper physics-based rendering as described below:

**Wide Dynamic Range** – Our older visual systems used a 16-bit pipeline dithered into a 10-bit floating point frame buffer. The newer PC-IG systems have a 24-bit or 32-bit pipeline (depending on GPU type), which is dithered into an 8-bit frame buffer. Early on, a rendering model was considered that used special illuminance and irradiance normalizations to increase instantaneous dynamic range. However, it was determined that the intrinsic dynamic range of our rendering systems was adequate and that the added complexity of such normalizations provided little benefit.

**Effective Dither** – The dither algorithms used in our older and newer image generators were demonstrated to be effective throughout the full dynamic range covering NVG stimulation. In particular, the floating point dither used in GPU-based systems was shown to be artifact-free when operating through an 8-bit frame buffer over DVI-D video links.

**Effective Display Compensation** – For years, we have used an automated compensation technique to linearize display operation by taking a set of photometric measurements over a wide range of display levels. These measurements are then used to construct a display compensation table that assures deterministic display operation. Deterministic display compensation is fundamental in achieving repeatable, deterministic physics-based rendering.

The combination of the above basic features provides a good foundation for the implementation of the upgraded NVG stimulation.

### New Real-World Illumination Model

A primary result of this project is the implementation of a physics-based illumination model traceable to real-world illumination characteristics. The model has the following fundamental relationships:

**Lunar Illuminance Versus Lunar Phase** – The curve in Figure 15 relates the photometric intensity of light incident on surfaces to lunar phases. The illuminance is configured in units of foot-candles. One foot-candle incident on a lambertian reflector results in a surface luminance of one foot-Lambert. The equivalent international SI illuminance unit is the lux (1 foot-candle = 10.76 lux). As we will see, SLAP (Solar/Lunar Almanac Program) uses lux to report illuminance.

**Lunar NRb Irradiance Versus Lunar Phase** -- Figure 15 also plots lunar scaled NRb irradiance as a function of moon phase as a curve fit of the data recommended by AFRL/RSC. The lunar illuminance and scaled lunar NRb irradiance curves are virtually identical.

**Relative Lunar Illuminance Versus Lunar Elevation** – The illuminance shown in Figure 15 applies only at 90° moon elevations. The curve shown in Figure 17 (shown in both linear and log forms) is used to scale the values in Figure 15 to arrive at the illuminance at reduced lunar elevations. This curve is also used to scale lunar NRb irradiance (watts/meter<sup>2</sup>) as a function of the lunar elevation for NVG stimulation.

We now have a basic model that supplies lunar photometric scene illuminance for the naked eye and radiometric NRb scene irradiance for the NVGs. This incident lighting is then applied to surface prop-

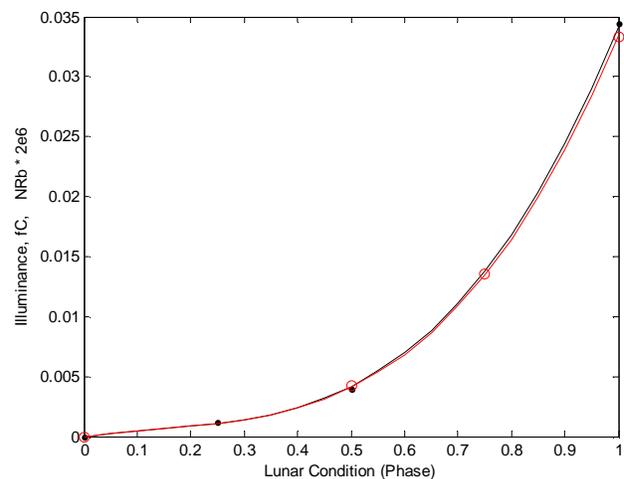


Figure 15 Lunar Phase Illuminance (fC) and Irradiance (NRb) At 90° Lunar Elevation

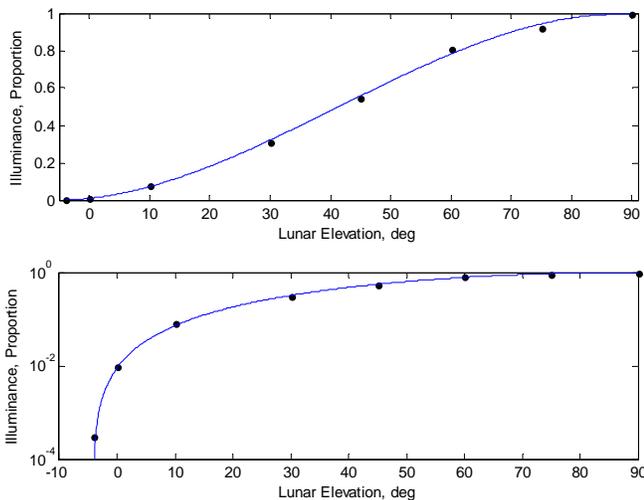


Figure 17 Relative Illuminance Versus Lunar Elevation

erties to determine surface luminance and NRb radiance. The illumination model is configured via ambient and diffuse reflectance runtime parameters for lambertian surfaces, measured in units of foot-candles. The ambient and diffuse reflectance terms are typically set to .0035 and .031 foot-candles, respectively. Thus, a fully reflective lambertian surface viewed perpendicularly and illuminated by less than 100% moon phase will have a luminance of .034 foot-lamberts, which tracks the peak in Figure 15.

### IOS Approach

Over the years, the baseline lunar controls provided in our standard image generator host interface have been exposed to instructors on the IOS in a variety of ways depending on specific IPT decisions for the associated systems.

This paper recommends standardization of associated IOS controls based on the widely-used SLAP mission planning tool. The Solar/Lunar Almanac Program (SLAP) module of the Geophysics Fleet Mission Program Library (GF MPL) is a widely used mission planning and briefing tool. SLAP generates daily or monthly summaries of ephemeral data for sun and moon locations worldwide. These summaries are custom tailored to meet the specific needs of the user, but generally include times for sunrise/sunset, moonrise/moonset, beginning/ending times of nautical and civil twilight, phases of the moon and percent illumination, total daylight, time and altitude of sun/moon meridional passage, and 24 hour solar/lunar positions. The SLAP module also generates NVG performance predictions based on cloud cover and user defined lux thresholds. The SLAP paradigm extension to the IOS requires three fundamental parameters:

**Percent Illumination** – Figure 16 shows the basic SLAP lunar illumination display. The SLAP notion of percent illumination correlates well to the lunar phase parameter in our illumination model described earlier. Basically, percent illumination gives an indication of the illumination potential for a given moon condition. Note that Figure 16 displays illuminance in lux, which corresponds to the foot-candle illuminance model defined above. (SLAP reported illuminance appears to be inconsistent over some ephemeral conditions. These anomalies are still under investigation.)

**Lunar Elevation** – Clearly, for a given percent illumination, terrain illumination will be higher when the moon is higher in elevation. SLAP reports lunar elevation per the ephemeris given the specified date, time, and geographic location. In the simulator, we provide both ephemeris and manually controlled illumination.

**Weather Condition** -- Figure 16 also shows the degradation of illumination due to weather conditions. The baseline visual system attenuates illumination only as a function of solid cloud thickness. SLAP and standard USAF aircrew briefings differ in how they characterize weather conditions. The exact presentation of weather conditions for a given IOS becomes an IPT decision.

### IOS Recommendation

Figure 18 is a stylized generalization of the basic recommended standardized IOS controls that support improved NVG stimulation. The controls are described below.

**NVG Mode** -- This control activates and deactivates NVG processing. NVG processing attempts to maximize NVG stimulation by boosting and otherwise transforming scene content in the red display

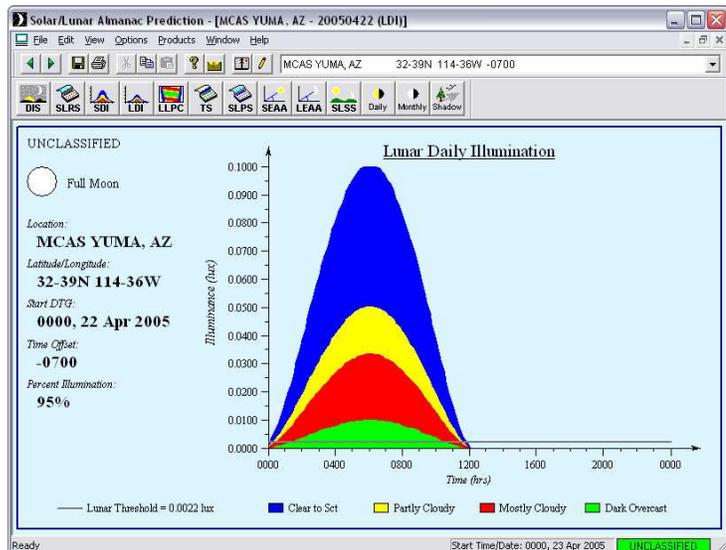


Figure 16 SLAP Illumination Display

channel. Given the spectral characteristics of the display at hand, NVG processing seeks a compromise between good NVG stimulation and minimal artifacts in the unaided out-the-window view. Accordingly, night-mode out-the-window quality is maximized by deactivating NVG processing, which would be recommended when NVGs are not being used.

**Lunar Mode** – The Lunar Mode control selects between manual and ephemeris-driven lunar configurations. In the Manual mode, Lunar Illumination, Lunar Elevation, and Lunar Azimuth can be independently set. In the Auto mode, the lunar parameters, including Lunar Illumination, are derived from the ephemeris given the current simulation date, time, and geographic position. In the Auto mode, it is recommended that the Lunar Illumination, Elevation, and Azimuth control indications be set to the current ephemeris conditions as reported by the visual.

The instructor should be given a lunar illumination override capability so that current NVG conditions can be tweaked given some ad hoc circumstance. Clearly, in the Manual mode, a continuous Lunar Illumination slider can be arbitrarily positioned. However, if the IPT elects to use discrete Lunar Illumination buttons, such as 25%, 50%, 75%, then an IOS Lunar Illumination override function becomes problematic. In the Auto mode, the Lunar Illumination override function also becomes problematic because toggling into the Manual Mode for tweaks defeats the Continuous Time-Of-Day function of the Auto Mode. (It should be noted that tweaking is to be discouraged because we've worked diligently to achieve a real-world simulation.)

**Lunar Illumination** – Lunar Illumination is equivalent to the SLAP *percent illumination* quantity and is basically a percent moon-disc value. The phase of the visible moon model in the sky also

tracks this value.

**Lunar Elevation** – This is the elevation of the moon above the horizon, in degrees. The Lunar Elevation setting influences current scene illuminance and also sets the sky position of the moon model.

**Lunar Azimuth** – Lunar Azimuth does not affect scene illumination. It is only positions the moon model in the sky.

**Weather Condition** – The visual system currently scales scene illumination as a function of solid-cloud thickness. AFRL recommends generalizing the IOS presentation to include standard SLAP or USAF weather briefing states. This is most-generally accomplished with a slider; however, the use of discrete states is probably friendlier to the instructor.

### NVG Tuning

Comprehensive, deterministic NVG techniques notwithstanding, NVG stimulation quality is still limited by the intrinsic spectral content of the display at-hand in achieving high-quality NVG stimulation. Also, if specific NIR reflectance textures are not available, run-time color transforms are used to boost the red content of texture areas representing features that have higher NIR reflectance. Clearly, red content is boosted at the risk of making the unaided out-the-window appearance too bright or too reddish. As a result, the system must undergo a tuning process where Subject Matter Expert tuning is solicited to establish a compromise balance between goggle stimulation and unaided out-the-window appearance at all illumination levels. In order to increase productivity of SME tuning sessions, we developed an NVG Calibration operator interface (See Figure 19) that interactively configures the red boost as a function of illumination level.

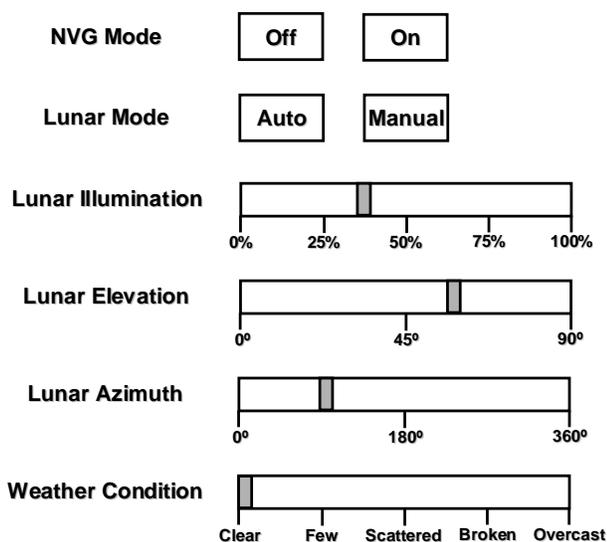


Figure 18 Recommended IOS NVG Controls

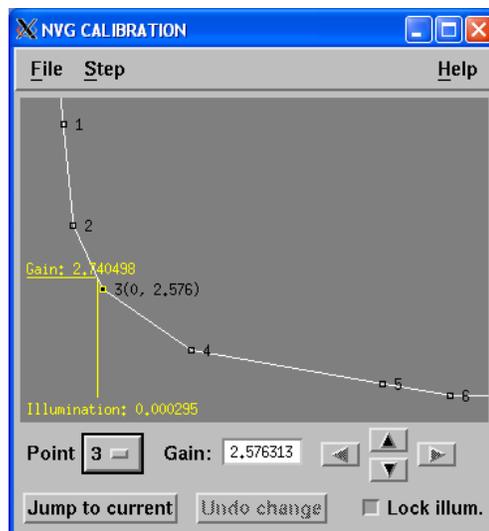


Figure 19 NVG Calibration Interface

## NVG Stimulation Repeatability

The maintenance of display system photometric and colorimetric alignment directly affects NVG stimulation quality. We have been fielding NVG stimulation in CRT-based systems for many years using automated alignment technique where photometric measurements are taken down to 1 part in 32000. The measurements, in turn, are used to linearize the display photometric response. The result supports the deterministic stimulation provided by our rendering system. As display systems move to fixed-matrix displays, our Display Management System (Lloyd, et. al. 2008) extends the range of photometric measurements and includes a spectral radiometer that directly measures NVG passband response over a million to one range.

## Conclusions

Through this activity, we have significantly improved our understanding of what is needed to effectively stimulate modern NVGs. We have adopted quantitative techniques using a traceable real-world illumination model and physics-based rendering. We base our instructor controls on illumination parameters commonly provided to pilots during flight briefings. Thus, for a given flight briefing, the pilot will see the same NVG responses and unaided illumination in the simulator as he sees in the real world – to maximum extent allowed by the simulator's particular display system.

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## About The Authors

**Dr. Charles J. Lloyd** has 22 years of experience in the area of display systems and applied vision research at such organizations as the Displays and Controls Lab at Virginia Tech, the Advanced Displays Group at Honeywell, Lighting Research Center at Rensselaer Polytech, Visual Performance Inc., and BARCO Projection Systems. Charles now works at FlightSafety International where he manages the development of next-generation display and alignment systems. Charles has published/presented 50+ papers in the field and has taught the graduate course in vision at Rensselaer.

**Steven G. Nigus** is Director of Engineering for the Visual Simulation Systems division of FlightSafety International in St. Louis, MO. He has been designing visual systems for 25 years and has performed various system design and coordination functions in the development of the VITAL 7, 8, 9, and 10 visual system generations. Mr. Nigus is currently managing FlightSafety's visual system hardware, software, and display product engineering activities. He received his bachelor's degree in electrical engineering from the University of Missouri at Rolla and did his graduate work at Iowa State University.

**Brian K. Ford** is a Lead Realtime Software Engineer at FlightSafety International Visual Simulation Systems. For the past 10 years, he has been designing systems architecture and network communications for VITAL 8, 9 and 10 visual systems, as well as sensor features including video target tracking. He is currently designing and integrating VITAL 9 and 10 Common Database real-time publishers. Previously, he spent 5 years at the University of Missouri's Advanced Technology Center applying virtual reality and multimedia for use in elementary, secondary, and undergraduate education. He received Bachelor of Science degrees in both Electrical and Computer Engineering from the University of Missouri, Columbia.