SUNLIGHT READABILITY AND LUMINANCE CHARACTERISTICS OF LIGHT-EMITTING DIODE PUSH BUTTON SWITCHES

Robert J. Fitch, B.S.E.E., M.B.A.

Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

May 2004

APPROVED:

Albert B. Grubbs, Jr., Major Professor and Chair of the Department of Engineering Technology
Don W. Guthrie, Committee Member
Michael R. Kozak, Committee Member
Roman Stemprok, Committee Member
Vijay Vaidyanathan, Committee Member
Oscar N. Garcia, Dean of the College of Engineering
Sandra L. Terrell, Interim Dean of the Robert B. Toulouse School of Graduate Studies

Fitch, Robert J., Sunlight readability and luminance characteristics of light-emitting diode push button switches. Master of Science (Engineering Technology), May 2004, 69 pp., 7 tables, 9 illustrations, references, 22 titles.

Lighted push button switches and indicators serve many purposes in cockpits, shipboard applications and military ground vehicles. The quality of lighting produced by switches is vital to operators' understanding of the information displayed. Utilizing LED technology in lighted switches has challenges that can adversely affect lighting quality. Incomplete data exists to educate consumers about potential differences in LED switch performance between different manufacturers.

LED switches from four different manufacturers were tested for six attributes of lighting quality: average luminance and power consumption at full voltage, sunlight readable contrast, luminance contrast under ambient sunlight, legend uniformity, and dual-color uniformity. Three of the four manufacturers have not developed LED push button switches that meet lighting quality standards established with incandescent technology.

ACKNOWLEDGMENTS

I thank Don Guthrie and John Dillow at Aerospace Optics, Fort Worth, Texas, for providing the test samples, lending the use of their laboratories, and providing tremendous support for this research. I thank Todd West, Craig Morgan, Craig Coley and Paul Wilson for their technical assistance. Thanks to Albert Grubbs, Jr., Michael Kozak, Roman Stemprok and Vijay Vaidyanathan for their guidance in developing this study. Finally, I thank Michelle Fitch, Perry McNeill and Charlie Baker for their encouragement and support.

CONTENTS

ACKNOWLEDGMENTS iii

TABLES vi

ILLUSTRATIONS vii

Chapter

1. INTRODUCTION 1

Sunlight Readability
Control Panel Dimming
Incandescent Lighting
LED Lighting
LED Challenges
Maintaining Lighting Quality with LEDs
Military Specifications
Purpose of the Study
Research Questions
Limitations
Assumptions

2. DEFINITIONS OF TERMS 20

Photometric Concepts

3. RESEARCH DESIGN 25

Samples
Instrumentation

4. EXPERIMENTS 28

Test 1: Luminance at Full Voltage
Test 2: Power at Full Voltage
Test 3: Sunlight Readable Contrast
Test 4: Luminance Contrast Under Ambient Sunlight Conditions
Test 5: Legend Uniformity
Test 6: Dual-Color Uniformity

5. CONCLUSIONS AND RECOMMENDATIONS 39

Conclusions
Recommendations

Appendix

A. PRODUCT SPECIFICATION AND DETAILS 41

B. INSTRUCTION AND CALIBRATION REPORTS 44

C. LUMINANCE MEASUREMENT POINTS 52

D. MEASUREMENT DATA 54

REFERENCES 68

TABLES

Table Page

1. Average Luminance at 28 V.. 29

2. Power Consumption at 28 V...30

3. Sunlight Readable Contrast... 33

4. Luminance Contrast Under Ambient Sunlight Conditions............................35

5. Legend Uniformity Ratios...37

6. Dual-Color Uniformity Ratios 38

7. Summary of Results...39

ILLUSTRATIONS

Figure Page

1. Illuminated push button switches……………………………………………………2
2. Typical dimming curve of an incandescent push button switch…………….....……7
3. Example of a 40 degree LED viewing angle…………………………..………....11
4. Photopic spectral luminous efficiency…………………………………………… 21
5. Luminous intensity………………………………………………………………..22
6. Luminance…………………………………………………………………….... 23
7. LED push button switches made by AOI, Eaton, Korry and Staco……………….26
8. Diagram of sunlight readable contrast test………………………………………32
9. Test setup for contrast measurements……………………………………………34

CHAPTER 1

INTRODUCTION

Illuminated push button switches have been prevalent in cockpit control panels for decades. Lighted switches are versatile tools by which pilots may control a wide variety of aircraft systems. The switch's face may display a short word or symbol upon being depressed, or be illuminated remotely, indicating a change in system status that requires attention. Depressing a lighted switch provides pilots with tactile feedback and visual verification that their intended command was executed. These features make push button switches popular for use with emergency and mission-critical systems.

Lighted push button switches are made of two basic parts: the cap assembly and the switch body. The cap assembly houses the outer face, lens, filters, and backlighting system. It slides snugly into the front of the switch body and is removable for lamp replacement. The switch body is mounted almost entirely behind the panel, hidden from the operator's view. Depressing the face with a fingertip toggles a set of miniature snap-action switches mounted within the switch body. Both the lighting terminals and switch contacts are accessible from the rear of the body. The cap assembly may also be installed without the miniature switches for use as an indicator. An example of lighted switches mounted in a panel is shown in Figure 1.

Fig. 1. Illuminated push button switches.

Switch faces may be specified in a variety of styles. The most common style has a matte black finish and a legend that is indiscernible until illuminated. When illuminated, the legend may appear in a variety of colors and is readable in direct sunlight conditions. Because the legend is permanently painted or etched into the cap assembly, several switches and indicators may be required to control more complex systems. Thus, modern aircraft often have dozens of lighted push buttons placed about the cockpit.

The evolution of touch screen displays in recent years has threatened to replace push button switches. Touch screen displays are programmable, allowing several conventional switches to be consolidated into one screen and consuming much less control panel space. Yet traditional illuminated push buttons, despite their fixed legends, are preferred over touch screens for their simple design and proven reliability [1]. Compared with programmable displays, push buttons require only simple voltage control and do not rely on complex support electronics. For these reasons illuminated push button switches continue to be designed into avionics instrumentation, shipboard applications, and ground vehicles.

Sunlight Readability

The intense sunlight that streams through cockpit windows at altitude can be problematic for pilots. Early designs of lighted push button switches presented two problems. First, bright sunlight shining directly or reflecting onto an unlighted switch face often made the legend visible. Sunlight penetrated the switch face and reflected back out through the legend characters. Even though the legend was not illuminated, the pilot could read it and mistake it for being on. This condition was termed ghosting.

The second problem with early lighted switch designs was legend washout. Switch faces with a reflective finish or weak backlighting allowed sunlight to wash out an illuminated legend. Although the legend was on, the pilot could not read it or could not tell that it was on.

Both of these problems are unacceptable for pilots and their crew. Operators must be able to detect a warning indicator with their peripheral vision the moment that it illuminates. Washout can delay pilots' response to the warning condition because they weren't immediately aware of it, or because they couldn't easily read the legend. Pilots must also be able to quickly scan their control panel and make decisions based on the status of their instrumentation. If washout or ghosting occurs, the status of certain systems may be unclear or misinterpreted. Pilots may have to remove their hand from the controls and shade part of the panel to determine if a switch face is on or off. In emergency situations, when response time and accuracy are critical, either problem can create a very hazardous environment.

A lighted switch's ability to prohibit ghosting and washout from occurring is known as sunlight readability. Due to the variation in sunlight conditions, human vision, and lighted switch quality, determining a switch's sunlight readability is subjective without a means of measuring it. Determining sunlight readability involves measuring the luminance contrast between the legend and its surrounding background. In the unlighted state, the legend should be indiscernible in bright sunlight conditions. Thus, there should be little contrast between the legend and its background. If the unlit legend appears either brighter or darker than its adjacent background, the legend will ghost.

In the illuminated state, the legend should greatly contrast with its adjacent background. If the background's brightness approaches that of the illuminated legend, the legend will appear washed-out.

The formal definition of sunlight readable contrast was developed jointly by the U.S. Department of Defense and lighted switch manufacturers in the early 1980s. The resulting method for determining sunlight readability was incorporated in 1983 into the military specification (MILSPEC) for illuminated switches, MIL-S-22885 revision D. It defined minimum sunlight readable contrast given the most demanding cockpit conditions. For over 20 years pilots and avionics designers have grown accustomed to the quality of lighting associated with this sunlight readability standard.

Control Panel Dimming

Cockpit lighting must be adjusted while flying at dusk or at night. The entire control panel must be dimmed to a brightness level that is suitable relative to exterior conditions. Panel equipment must be easily visible, but not so bright as to interfere with the pilot's ability to see exterior objects of interest. Therefore, the brightness level to which lighted switches must be dimmed depends on the brightness of other panel instruments and of objects outside the cockpit.

There are two general dimming scenarios that pilots encounter during night flying. The first is when the control panel is comprised of relatively bright instruments, such as LCD displays, or the objects outside are well-lit, such as airport runways. This condition requires standard dimming of lighted switches to about 15 footlamberts (fL). Standard dimming is a common requirement for business jets and commercial aircraft.

The second scenario is when the control panel contains mainly traditional backlit instruments, or exterior objects of interest are not well-lit. Traditional cockpit instruments are less bright than modern LCD displays, and typically dim to about 1 fL for night flying. This condition requires low-level dimming of lighted switches to about 1 fL. Low-level dimming is a common requirement for military planes and helicopters, and is also needed in a growing number of commercial aircraft conducting search and rescue as well as surveillance operations.

Pilots sometimes have a dial they may turn to dim the panel luminance. However, pilots needing standard dimming might not dim their panel to exactly 15 fL. Given the potential variation in external conditions and human brightness perception, operators might desire a panel luminance anywhere between 5 fL and 30 fL. Therefore, gradual luminance control is necessary through this range to fine-tune panel luminance as needed. The same is true of low-level dimming through the range of 0.5 fL to 3.0 fL.

Incandescent Lighting

The light source inside the cap assembly of illuminated switches has traditionally been incandescent lamps. Most common are T-1 and T-1¾ lamps which heat a tungsten filament until it emits visible light. Incandescent lamps radiate energy uniformly in nearly every direction. Their wide emission angle helps illuminate the switch face uniformly using only a few lamps. Typically between two and four lamps are installed inside a cap assembly.

The optical qualities inherent in incandescent lamps contributed to meeting the MILSPEC requirements for sunlight readability. Their high intensity and wide emission angle, coupled with improved lens design, helped lighted switch manufacturers achieve sunlight readability defined by MIL-S-22885.

Incandescent lamps support gradual luminance control of lighted switches. The intensity of an incandescent lamp is easily controlled by regulating its voltage. Lamp intensity decreases logarithmically as its voltage decreases linearly. A logarithmic change in luminance is perceived by the human eye as a gradual, linear change [2]. An example of an incandescent switch's dimming curve is shown in Figure 2. The logarithmic scale assigned to luminance reflects the human eye's perception of luminance change. Therefore, the more linear the dimming curve, the more linear the human eye perceives the change in luminance.

LED Lighting

The use of light-emitting diodes (LEDs) in illuminated push button switches began in the mid-1990s. Also called high-brightness LEDs (HBLEDs), these semiconductor devices are manufactured in a variety of different colors and package styles, such as T-1-size lamps and surface mount devices (SMDs).

LEDs offer several advantages over incandescent lamps. One is that their power usage is more efficient than that of incandescent lamps. A typical incandescent lamp produces 15 lumens per watt, while a single white LED can generate 30 lumens per watt [3]. Red LEDs can achieve 55 lumens per watt [4].

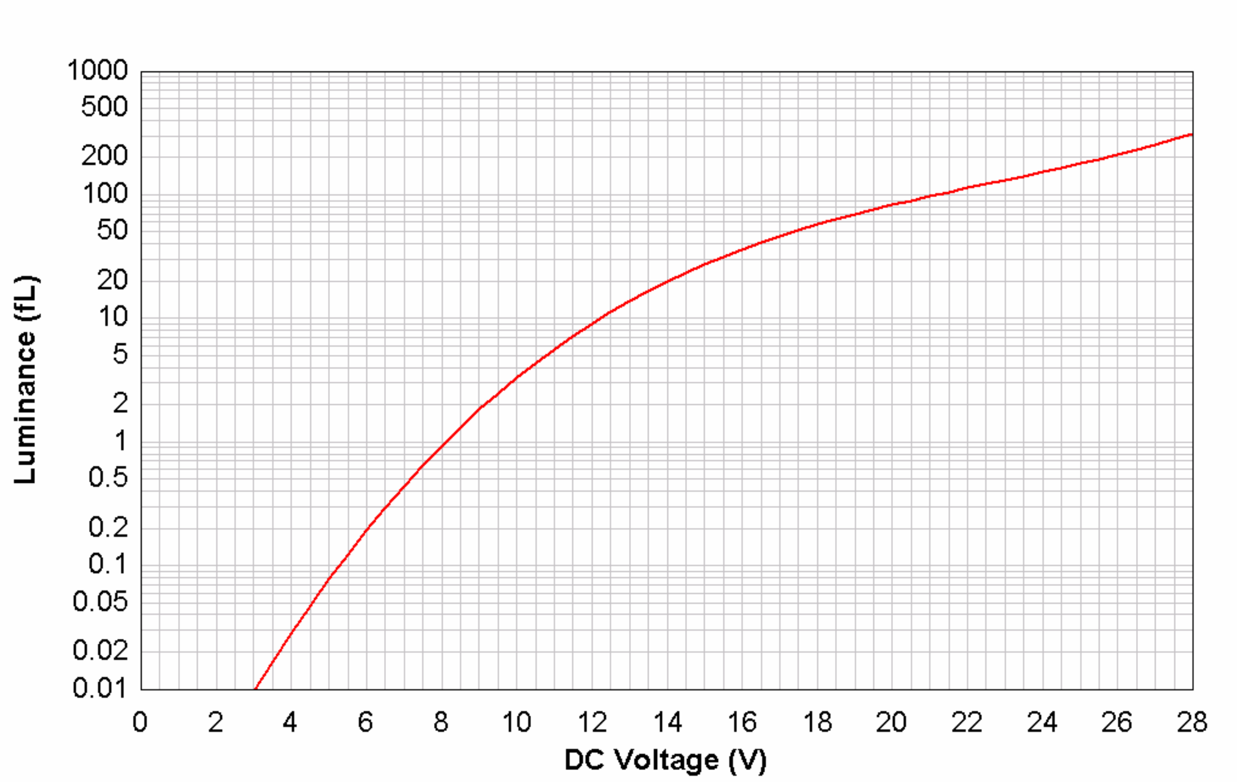


Fig. 2. Typical dimming curve of an incandescent push button switch.

The solid-state nature of LEDs, combined with their conservation of energy, permits them to operate at a lower temperature than incandescent lamps. Over two-thirds of the energy consumed by incandescent lamps is radiated as heat [5]. This heat can build up inside the cap assembly, making the switch face uncomfortable or even painful to touch. Traditional incandescent switches operating four 28 V lamps at full rated voltage typically generate switch face temperatures between 74 °C and 106 °C [6]. MIL-STD-1472, “Human Engineering Design Criteria,” recommends that the surface temperature of equipment such as lighted switches not exceed 60 °C [7]. The face temperature of LED switches generally falls below this limit.

Relative to incandescent lamps, LEDs maintain their color when dimmed for night flying. Due to the nature of incandescent filaments, lamps emit increasingly yellow light as they are dimmed. This tends to make a normally white legend appear yellow during night flying, making it difficult to distinguish from other intentionally yellow legends. LED switches, however, produce virtually the same color when dimmed for night flying as they do at full voltage. If, when dimmed, the reduction in power consumption results in a lower LED junction temperature, the LED's dominant wavelength may change just a few nm. However, the human eye can barely perceive changes that small [8].

Arguably the biggest advantage LEDs have over incandescent lamps is their lifespan. Heat and operating time degrade the filament inside incandescent lamps, making them increasingly susceptible to shock and vibration. Estimates vary, but incandescent lamp life is on the order of 10,000 hours of operation [9]-[11]. Re-lamping incandescent switches on a regular basis causes considerable downtime and maintenance expense.

LEDs are impervious to the shock and vibration common in aircraft, and last much longer than incandescent lamps. Rather than burning out, however, LEDs gradually lose intensity as their operating time increases. An LED's lifespan is about 100,000 hours of operation, when it reaches half of its original intensity. This is such an improvement over incandescent lamps, one lighted switch supplier advertises their LED products with "maintenance-free operation" and "life-of-the-platform service life" (used with permission) [5].

LED Challenges

The benefits of LED lighting don't come without challenges. LED intensity is a function of its forward current. Unlike incandescent lamps, which operate between 0 V and 28 V, LEDs typically operate within a range less than 1 V, such as 2.0 V to 2.7 V.

Operating an LED within its narrow voltage range produces its full range of intensity, from extinguishment through full intensity. Thus, very small changes in applied voltage yield large changes in forward current and intensity. This makes dimming LED switches more challenging than incandescent lamps.

Early attempts at dimming LED switches utilized pulse-width modulation (PWM). By varying the duty cycle of a square wave, an LED effectively blinks at a faster rate than the human eye can detect. The eye perceives an LED switch using PWM as dimming to some level, depending on the duty cycle applied.

An LED's instant-on, instant-off capability makes it compatible with PWM. The additional PWM circuitry needed to drive LED switches, however, isn't so compatible with aircraft. The square wave often creates unacceptable electrical interference in surrounding avionics systems. Therefore, acceptable PWM modules are challenging to build and add considerable cost to the system. If the period of the square wave is too low, motion flicker can occur when operators turn their heads while viewing the switch. Consumers wishing to upgrade their existing incandescent switches must redesign their power source to incorporate PWM. For these reasons, PWM is not generally accepted by the industry as the preferred method of powering LED switches.

Traditional voltage control remains the preferred method of powering LED switch and indicator lighting. This is due to the strong legacy of incandescent switch lighting. Upgrading to LED lighting is less costly if existing power supply and dimming schemes may be reused. The 28 V regulated power supply systems of the past continue to dominate new designs of control panel lighting.

Since LEDs alone are not compatible with 28 V incandescent systems, switch manufacturers must develop circuitry to manage low-voltage LED operation. The semiconductor core of LEDs is much more susceptible to electrostatic discharge (ESD) than incandescent lamps. Therefore, the circuitry must include protection from electrical events that could damage LEDs. Because the full intensity range of LEDs is covered by a few tenths of a volt, dimming must also be controlled with the circuitry. Ideally, LED switches should simulate the dimming curve of incandescent switches, simplifying the reuse of existing dimming systems, and allowing incandescent and LED switches to co-exist in the same cockpit without brightness disparities.

While LEDs maintain their color when dimmed for night flying, different colors can have different dimming curves. There are three primary families of LEDs. Red and yellow LEDs use aluminum indium gallium phosphide (AlInGaP) dies to produce their colors. Blue and green LEDs use a different die: indium gallium nitride (InGaN). Finally, white LEDs position an InGaN die behind a phosphor target. The short wavelengths emitted by the InGaN die excite the phosphor, making the phosphor appear white to the eye. Operating voltage and current characteristics vary between families, and sometimes between colors in the same family. Thus, if LEDs of different colors are present in the same LED switch, these variations can cause brightness differences between colors during standard or low-level dimming.

For example, suppose an LED switch uses white LEDs for the top half of the legend, and yellow LEDs for the bottom. If identical circuits are used to drive each half, the operator may find that setting the white half-legend for low-level dimming leaves the yellow half-legend too bright. Similarly, setting the yellow half-legend for low-level dimming may extinguish the white half-legend completely. If the top and bottom legends alternate during switch operation, this condition can be dangerous since the pilot cannot see the extinguished legend.

The high intensity possible with an LED is often attained at the expense of its viewing angle. LEDs do not emit light in every direction like incandescent lamps do. The package containing the LED die acts as a lens that focuses light in one direction. This creates a viewing angle, typically defined by manufacturers as the inclusive angle at which intensity decreases to half of its on-axis maximum. Both lamp-style and SMD packages are manufactured in a variety of different viewing angles. Often the more intense the LED, the narrower the viewing angle. When viewed from outside the viewing angle, intensity drops off rapidly. An example of an LED viewing angle plot is shown in Figure 3.

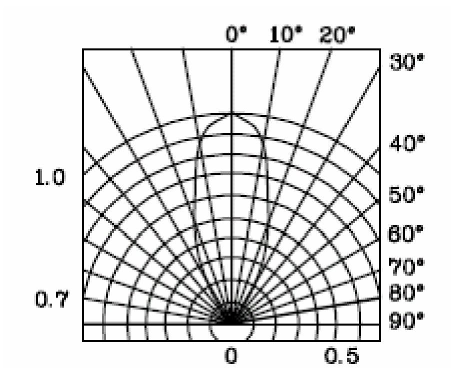


Fig. 3. Example of a 40 degree LED viewing angle.

LED viewing angles create a significant challenge for lighted switch manufacturers. Arranging LEDs inside a cap assembly is a balancing act between luminance, uniformity and power. LEDs with a narrow viewing angle, placed too close to the face, create hot spots in the legend. Hot spots are excessively bright portions of legend characters, relative to the surrounding legend luminance. Hot spots and dark spots degrade the legend's uniform, even luminance, or uniformity. Legends with poor uniformity can be very difficult to read and interpret.

Increasing the distance between LEDs and the face improves legend uniformity, but decreases overall luminance. The luminous intensity of a point source follows the inverse square law: it decreases with the square of the distance. Therefore, small changes in the distance between the LEDs and the face result in significant changes in legend luminance. Alternatively, choosing an LED with a wider viewing angle inevitably results in a less-intense LED. Improving uniformity can cause legend luminance to suffer dramatically.

Increasing LED voltage to improve overall legend luminance may be possible, depending on the forward current rating of the LEDs. Raising the current near an LED's maximum operating current can derate its lifespan, causing it to lose intensity much sooner than normal. Increasing an LED's current also increases its power consumption. The total power consumed by multiple LEDs and their support electronics is generally less than the power consumed by a traditional incandescent switch. Customers have come to expect such power efficiency of lighted switches, as more electronic systems tax limited aircraft power supplies. Thus, power consumption is a limiting factor when designing LED switches.

Maintaining Lighting Quality With LEDs

Today's high expectations of switch lighting are the result of years of improvements to incandescent switches. For over two decades, pilots have enjoyed excellent sunlight readability, good uniformity, and linear, voltage-controlled dimming with incandescent switches. Consumers are eager to utilize the advantages of LEDs, but not at the expense of established lighting quality. Unfortunately, the challenges associated with LED lighting often force switch manufacturers to make some trade-offs.

In order to maintain the lighting quality founded by incandescent switches, many factors must be fine-tuned in an LED switch design. Support electronics must be developed and matched to LED characteristics for proper voltage dimming. Luminance differences between legends of different colors must be minimized. Total power consumption must be controlled to accommodate increasing demands placed on cockpit power supplies. Legend luminance and uniformity are in such tight balance with each other that one of the two often suffers. Both legend luminance and uniformity affect sunlight readability, making it one of the more difficult quality measures to maintain with LEDs. Even as LED technology has advanced over the last decade, maintaining switch lighting quality using LEDs remains a challenging task.

Military Specifications

MILSPECs have long been used to set requirements for the design, manufacture and performance of military components and systems. MILSPECs are utilized by all branches of the armed forces to help ensure their equipment will perform under the extreme environmental and usage conditions found in military operations. Commercial customers often reference MILSPECs to satisfy their design criteria and ensure high quality standards. Most MILSPECs are public domain and are available online at http://assist.daps.dla.mil/quicksearch.

Until recently, the purchase of parts for military systems was limited to products qualified to applicable MILSPECs. Qualifying a product to a MILSPEC requires that the manufacturer regularly test the product per that MILSPEC's requirements. Buying qualified products made it easier for designers to ensure that the parts met MILSPEC performance standards. Beginning in 1994, military purchasers were allowed to buy commercial off-the-shelf (COTS) products [12]. This change in policy allowed them to buy parts not formally qualified to any MILSPEC. While this broadened the range of available products and suppliers, military buyers and program managers must discern for themselves whether or not COTS parts meet performance requirements.

Manufacturers may qualify their products to a MILSPEC by adhering to a specification sheet (slash sheet) for that MILSPEC, for example, MIL-PRF-22885/111. Slash sheets give manufacturers an opportunity to clarify specifications not explicitly stated in the MILSPEC. Where conflicting data exists between the MILSPEC and the slash sheet, the slash sheet takes precedence. In the case of specifying sunlight readability for switches, suppliers typically state minimum contrast criteria in their slash sheet. However, some manufacturers modify the contrast measurement procedure so much that it no longer tests for sunlight readable contrast. Other manufacturers exclude their LED lighting option from sunlight readability altogether. The lack of consistent sunlight readability data between suppliers makes it impossible for buyers to objectively compare products.

MIL-S-22885 has been the MILSPEC for illuminated push button switches since the early 1960s. MIL-S-22885 dictates minimum requirements for switch construction, performance, and endurance of mechanical, electrical and environmental stress. Also included are the measurement procedures used to verify these requirements.

After the requirement to buy MILSPEC parts was lifted, many MILSPECs were cancelled. However, the performance standards developed for lighted switches remains valid for consumers. Therefore, MIL-S-22885 revision E was renamed MIL-PRF-22885 revision F [13]. MIL-PRF-22885 is technically now a performance specification rather than a military specification, but is still loosely referred to as a MILSPEC. Both military and commercial consumers often reference MIL-PRF-22885 when defining performance requirements for their lighted switches and indicators.

Purpose of the Study

Inconsistent slash sheet criteria make it difficult for consumers to compare products qualified to the same MILSPEC. While COTS parts give consumers more choices than do MILSPEC parts alone, consumers must determine if COTS parts will perform as needed. The problem is consumers have incomplete information to determine if LED switches exhibit high-quality lighting, without testing the products themselves. The challenges of integrating LEDs into lighted switches cause some manufacturers to sacrifice lighting quality. While manufacturers typically specify the capabilities of their LED switches, they rarely disclose any shortcomings.

This study tests the lighting performance of LED switches for the benefit of consumers, switch manufacturers, and the avionics industry. The data should enable design engineers to objectively determine which LED switches meet their lighting requirements. This determination should save consumers considerable time and money by eliminating the need to replace LED switches that fail to meet lighting quality expectations. In addition, awareness of the importance of high-quality control panel lighting may raise consumer expectations of lighted push buttons and indicators.

Manufacturers should benefit from understanding the lighting performance of their LED switches relative to the state of the industry. If manufacturers are motivated to improve upon their weak points, the LED switch industry should strengthen as a whole. Subsequent product improvements should enhance the safety of flight for both military and commercial passengers and crews.

Research Questions

This study addresses six research questions:

1. Question: Do all four manufacturers' LED switches produce an average luminance of at least 300 fL?

   Null hypothesis 1: All four manufacturers' LED push button switches produce an average luminance greater than or equal to 300 fL when energized at full rated voltage.

   Alternative hypothesis 1: At least one manufacturer's LED push button switch does not produce an average luminance greater than or equal to 300 fL when energized at full rated voltage.

2. Question: Do all four manufacturers' LED switches consume less power than a typical ¾-inch incandescent switch?

   Null hypothesis 2: All four manufacturers' LED push button switches consume less than 2.7 W when energized at full rated voltage.

   Alternative hypothesis 2: At least one manufacturer's LED push button switch does not consume less than 2.7 W when energized at full rated voltage.

3. Question: Are all four manufacturers' LED switches sunlight readable?

   Null hypothesis 3: All four manufacturers' LED push button switches produce $C_L \geq 0.6$ and $|C_{UL}| \leq 0.1$ at $\phi_1 = \phi_2 = 15$ degrees, and $C_L \geq 0.3$ and $|C_{UL}| \leq 0.1$ at $\phi_1 = \phi_2 = 30$ degrees when measured in direct-reflected specular sunlight conditions.

   Alternative hypothesis 3: At least one manufacturer's LED push button switch does not produce $C_L \geq 0.6$ and $|C_{UL}| \leq 0.1$ at $\phi_1 = \phi_2 = 15$ degrees, and $C_L \geq 0.3$ and $|C_{UL}| \leq 0.1$ at $\phi_1 = \phi_2 = 30$ degrees when measured in direct-reflected specular sunlight conditions.

4. Question: Are all four manufacturers' LED switches legible in ambient sunlight conditions?

   Null hypothesis 4: All four manufacturers' LED push button switches produce $C_L \geq 0.6$ and $|C_{UL}| \leq 0.1$ at $\phi_1 = 45$ degrees and $\phi_2 = 0$ degrees when measured in ambient sunlight conditions.

   Alternative hypothesis 4: At least one manufacturer's LED push button switch does not produce $C_L \geq 0.6$ and $|C_{UL}| \leq 0.1$ at $\phi_1 = 45$ degrees and $\phi_2 = 0$ degrees when measured in ambient sunlight conditions.

5. Question: Do all four manufacturers' LED switch legends produce uniform luminance when dimmed from full luminance to 1 fL?

   Null hypothesis 5: All four manufacturers' LED push button switches produce character-to-character uniformity less than or equal to 2:1 when dimmed from full luminance to 1 fL.

Alternative hypothesis 5: At least one manufacturer's LED push button switch does not produce character-to-character uniformity less than or equal to 2:1 when dimmed from full luminance to 1 fL.

6. Question: Do all four manufacturers' LED switches with two different legend colors dim equally when dimmed from full brightness to 1 fL?

   Null hypothesis 6: All four manufacturers' LED push button switches produce dual-color uniformity less than or equal to 2:1 when dimmed from full luminance to 1 fL.

   Alternative hypothesis 6: At least one manufacturer's LED push button switch does not produce dual-color uniformity less than or equal to 2:1 when dimmed from full luminance to 1 fL.

Limitations

This study is limited to ¾-inch illuminated push button switches with LED lighting and full rated voltage of 28 V dc. Manufacturers are limited to the five MILSPEC-qualified suppliers of ¾-inch illuminated push button switches. The study is limited to four manufacturers because one chose not to provide a quotation.

Ideally, each manufacturer would offer a product that meets all of the features specified in this study. Because LED lighting is a developmental technology for switch manufacturers, some suppliers had limited product options. Exceptions taken to the switch specification are listed in Appendix A.

Assumptions

Due to cost and time constraints, it was not practical to acquire enough switches to construct a statistical test procedure for each manufacturer. Thus, the sample size for each manufacturer is one switch. A manufacturer's single production lot of illuminated switches could range anywhere from one to hundreds or more units. It is assumed that switch performance variability in a lot is very low, based on the strict quality control required of a MILSPEC-qualified supplier. Therefore, it is assumed that all switches in a manufacturer's production lot either meet or don't meet each acceptance criterion based on sampling one observation from that manufacturer's lot.

Each manufacturer was requested to provide a switch that meets the same product specification. Therefore, it is assumed that the switches under test provide the same form, fit and function as far as the performance attributes studied in each of the six tests.

CHAPTER 2

DEFINITIONS OF TERMS

Photometry is defined as "the measurement of quantities associated with light" (used with permission) [14]. There are many ways to describe the nature and effects of light. Terms like footcandles, candlepower and lux are commonly used, sometimes incorrectly. It is important to understand the definitions and proper application of photometric terms.

Photometric Concepts

Light is radiant energy that the human eye can detect [14]. The human eye can detect radiant energy that has a wavelength between about 380 nm and 770 nm. However, the eye does not detect all wavelengths equally well. The eye's average efficiency at detecting radiant energy of different wavelengths was agreed upon by the International Commission on Illumination in 1924 [14]. The resulting photopic response curve is shown in Figure 4. The eye's peak efficiency is at 555 nm, in the green area of the visible spectrum. The eye's poorest efficiency is at the blue and red ends of the visible spectrum. Conceptually, a monochromatic light source at 510 nm would need to produce roughly twice as much radiant energy as a source at 555 nm for them to be perceived as having equal intensity.

LUMINOUS ENERGY

Luminous energy, or the quantity of light, is defined as

$$Q = \int_{380}^{770} K(\lambda)\, Q_{e}\lambda \, d\lambda$$

where K(λ) is the luminous efficacy as a function of wavelength and $Q_e\lambda$ is the spectral concentration of radiant energy [14]. Thus, light is radiant energy evaluated in terms of the photopic response curve.

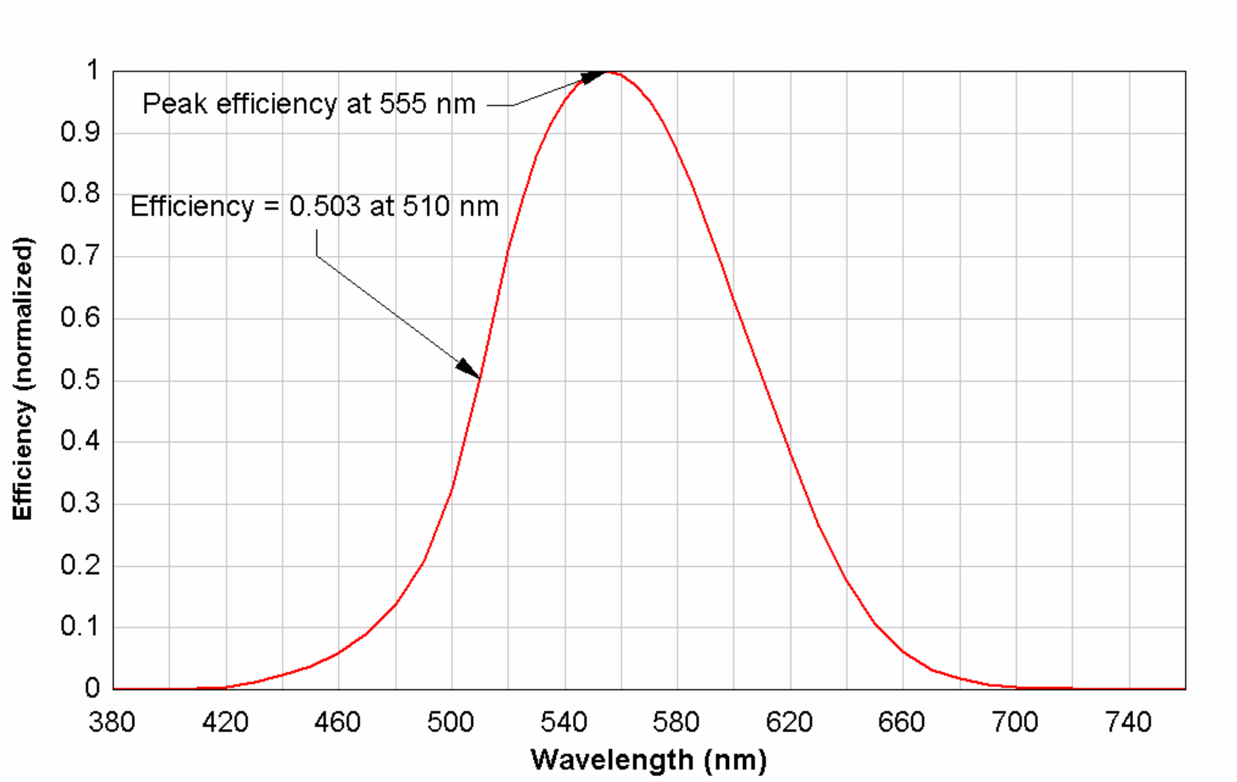


Fig. 4. Photopic spectral luminous efficiency (photopic response curve).

LUMINOUS FLUX

Luminous flux is the time rate of flow of light, expressed in lumens (lm) [14].

$$\mathbf{\Phi} = \frac{dQ}{dt}$$

Luminous flux is analogous to power for radiant energy in the visible spectrum.

LUMINOUS INTENSITY

Luminous intensity is luminous flux per unit solid angle in a given direction [14]. Luminous intensity, also called candlepower, is expressed in lumens per steradian, or candelas (cd).

$$I = \frac{d\,\mathbf{\Phi}}{d\omega}$$

where ω is the solid angle through which flux from a point source is radiated [14]. See Figure 5. Since a solid angle has a point as its apex, luminous intensity applies only to a point source. A spot on a surface may be treated as a point source if its dimensions are negligible compared with the distance from which it is viewed.

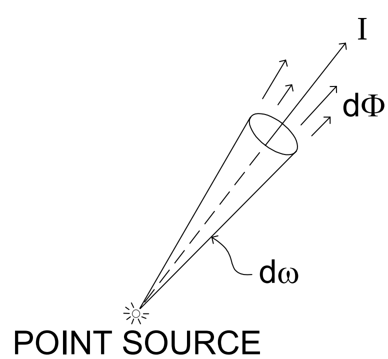


Fig. 5. Luminous intensity (used with permission) [14].

LUMINANCE

Luminance is luminous intensity per unit projected area of the source, where the projected area is on a plane perpendicular to the given direction [2]. Luminance is defined as

$$L = \frac{dI}{dA\,cos\theta}$$

as shown in Figure 6a [14]. The orthogonal projection of dA onto a plane perpendicular to L is better visualized in Figure 6b, simplifying the equation for L:

$$L = \frac{dI}{dA'}$$

Luminance is expressed in candelas per square meter (cd/m^2). The lambertian unit of luminance is footlambert (fL). Footlambert is used in this study due to its frequent use in MILSPECs and related industry literature.

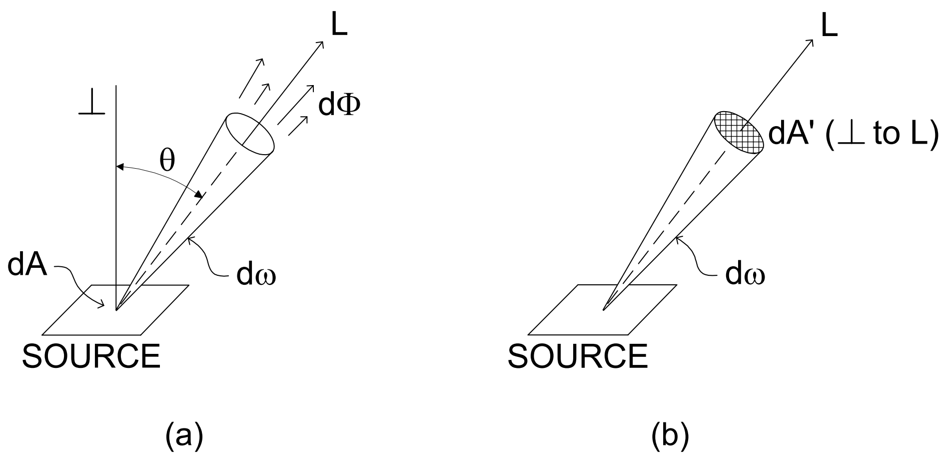


Fig. 6. (a) Luminance, referencing dA (used with permission) [14], (b) luminance, ref dA’.

BRIGHTNESS

The strict definition of brightness is the subjective strength of sensation that results from light reaching the eye [14]. Brightness is expressed in relative terms such as bright, brilliant, dim or dark. Brightness takes into consideration the definitely measurable luminance of a surface, plus conditions of observation that affect the eye. The human eye’s efficiency in detecting radiant energy changes under certain viewing conditions. For example, in a darkened environment, viewing a surface with luminance between 0.01 fL and 1 fL, the eye adjusts from photopic to mesopic vision [14]. After viewing surfaces with luminance less than 0.01 fL for several hours, the eye adjusts to scotopic vision and is said to be fully dark-adapted. During this transition, the eye's overall sensitivity increases and its spectral efficiency shifts, moving the peak efficiency towards shorter wavelengths. While brightness and luminance are not the same, they are often used interchangeably, especially when dealing with luminance levels greater than 1 fL.

ILLUMINANCE

Illuminance is "the areal density of the luminous flux *incident* at a point on a surface" (used with permission) [14]. Illuminance is defined as

$$E = \frac{d\,\mathbf{\Phi}}{dA}$$

Illuminance measures the amount of luminous flux falling onto a surface, not flux resulting from surface reflectivity or luminance of the surface itself. Illuminance is expressed in lumens per square meter, or lux (lx). One lumen per square foot is equal to one footcandle (fc), which is the unit used in this study.

CHAPTER 3

RESEARCH DESIGN

The research design was experimental. The study examined how utilizing LED push button switches designed by different manufacturers affects product performance along quantifiable measures. Products were tested based on six different hypotheses. Measurement procedures and criteria followed industry practices published in commonly-referenced military specifications (MILSPECS).

Samples

The five MILSPEC-qualified suppliers of ¾-inch illuminated push button switches are Aerospace Optics Inc. (AOI), Ducommun Technologies (Jay-El), Eaton Aerospace, Korry Electronics and StacoSwitch. Each company was requested to provide a quotation on their premier ¾-inch LED switch model as of July, 2003. The same switch specification was provided to each company. The specification was based on very common switch features utilized in commercial and military systems, shown in Appendix A. Although each supplier offers MILSPEC products, MILSPEC qualification of the switch was not a requirement in the specification. Where a supplier could not meet the specification, exceptions were granted as shown in Appendix A. Jay-El chose not to provide a quotation. One LED switch from each of the other four manufacturers was purchased.

The specified LED switch display was type S per MIL-PRF-22885:

> Sunlight readable (legend not visible until illuminated, then legend appears in color. Background is black). [13]

The legend was horizontally split in half, with the word “ENABLE” in white on the top and the word “MASTER” in green on the bottom. The four switches purchased are shown in Figure 7 and their model numbers are listed in Appendix A.

Fig. 7. LED push button switches made by (from l to r) AOI, Eaton, Korry and Staco.

Instrumentation

Luminance measurements were taken using a Photo Research PR-1980A Spectra® Pritchard® photometer system with a Macro-Spectar® MS-80 close-up objective lens [15]. The Pritchard system’s selectable aperture spot allows radiant energy to pass through a photopic filter, which is then detected by a photomultiplier tube. Because the area of the aperture spot is always on a plane perpendicular to the unit solid angle’s direction, luminance can be measured. Luminance is displayed in fL, accurate to within ± 4 % of the reading or ± 2 % of full scale, whichever is greater. Luminance measurement precision is ± ½ unit in the least significant digit.

Voltage and current measurements were taken using Keithley 179A digital multimeters. Voltage measurements are accurate to within 0.04 % + 1 digit, and current measurements are accurate to within 0.2 % + 2 digits. Voltage and current measurement precision is ± ½ unit in the least significant digit.

A Hoffman Engineering meter mover was used to mount the switch under test and the photometer. The meter mover allowed for steady movement of the switch and positioning of the photometer. The power supply used to energize the switch under test was a Hewlett Packard 6267B. Its output voltage was measured using a Keithley 179A multimeter.

Additional equipment used for luminance contrast testing included a Hoffman Engineering SRS-2 spectral reflectance standard. A Dolan-Jenner Model 180 Illuminator was used as the light source. Its intensity was controlled by a Topward 3301D power supply.

Calibration reports for the instrumentation are shown in Appendix B.

CHAPTER 4

EXPERIMENTS

All testing was performed in February, 2004 in a controlled laboratory environment. Ambient temperature was maintained at 24 °C ± 1 °C, and relative humidity was maintained at 35 % ± 5 %.

Before taking any measurements, the switch under test was energized at full rated voltage for 20 minutes. Junction temperature of an LED rises after ignition. Its spectral output changes for several minutes after ignition, until the junction reaches thermal equilibrium [8]. When energized by a voltage-regulated power supply, the switch's current flow may also change. Therefore, 20 minutes was allowed for the LEDs' characteristics to stabilize before taking measurements.

Test 1: Luminance at Full Voltage

LEDs are capable of producing more intensity than traditional incandescent lamps. Depending on the nature of the application, avionics designers may desire legend luminance that is comparable to or brighter than that of incandescent switches. Unfortunately, switch manufacturers do not always disclose typical luminance data for their LED products. This test measured the average luminance of the display, energized at full rated voltage.

TEST PROCEDURE & RESULTS

Each switch's display was energized at 28.00 V ± 0.02 V dc. Average luminance of the entire display was measured with a photometer perpendicular to the switch face, as described in MIL-PRF-22885:

> 4.7.35 Luminance . . . all luminance measurements shall be taken in completely dark surroundings. All readings shall be point readings and averaged. Luminance readings shall be taken by a calibrated photoelectric photometer. . . . For points of measurement see figure 9 [Appendix C]. [13]

Luminance at three points per legend character was measured. Points of measurement followed MIL-PRF-22885 and are shown in Appendix C. Measurements for each switch were averaged and summarized in Table 1. Complete measurement data is listed in Appendix D.

Minimum average luminance is usually specified as 300 fL, as defined in JSSG-2010-5, Aircraft Lighting Handbook [2].

Table 1
Average Luminance at 28 V

	Average Luminance (fL)
Criterion	≥ 300
AOI	505
Eaton	521
Korry	404
Staco	151

Table 1 shows the average luminance of Staco’s LED switch is less than 300 fL. One manufacturer’s LED push button switch does not produce an average luminance greater than or equal to 300 fL when energized at full rated voltage. Therefore, null hypothesis 1 was rejected and alternative hypothesis 1 was accepted.

Test 2: Power at Full Voltage

LEDs use power more efficiently than incandescent lamps. Consumers have come to expect LED switches to consume less power than incandescent switches, as a means of decreasing power consumption of their avionics systems. However, switch manufacturers do not always provide current draw or power usage data for their LED products. This test measured the power consumption of the display, energized at full rated voltage.

TEST PROCEDURE & RESULTS

Each switch's legend was energized at 28.00 V ± 0.02 V dc. Total current flow of the entire display was measured with a multimeter in series with the switch. Power was calculated by multiplying the current times 28.00 V. Results are listed in Table 2.

Consumers expect power consumption to be less than the 2.7 W typical of a ¾-inch incandescent switch energized at 28 V [5].

Table 2
Power Consumption at 28 V

	Current (mA)	Power (W)
Criterion	-	< 2.70
AOI	40.71	1.14
Eaton	56.99	1.60
Korry	36.39	1.02
Staco	33.58	0.94

Table 2 shows all four manufacturers' LED push button switches consume less than 2.7 W when energized at full rated voltage. Therefore, null hypothesis 2 failed to be rejected.

Test 3: Sunlight Readable Contrast

Achieving sunlight readable contrast with LED push button switches is challenging for manufacturers. For consumers, determining whether or not an LED switch is sunlight readable is increasingly difficult to determine from supplier literature. Each of the five manufacturers claim sunlight readability in their product brochures, but some are unclear about defining it. This test measured sunlight readable contrast as defined in MIL-PRF-22885.

TEST PROCEDURE & RESULTS

Each switch's legend was energized at 28.00 V ± 0.02 V dc. Sunlight readable contrast was measured as defined in MIL-PRF-22885:

> 4.7.36 Sunlight readability . . . A light source of 3,000 degrees to 5,000 degrees Kelvin color temperature shall be directed at an angle of ϕ_1 = 15 degrees ±2 degrees to the normal of a diffuse reflectance standard (pressed barium sulfate or PTFE powder (polytetrafluorethylene resin) (see figure 10) [Figure 8]. The size of the light source shall be limited so that $\theta \leq$ 20 degrees. A photometer shall be positioned as an angle of ϕ_2 = 15 degrees ±2 degrees to the normal of the reflectance standard. The light source shall be adjusted to produce 10,000 footcandles illumination on the reflectance standard as measured by the photometer. The reflectance standard shall then be removed and replaced by the viewing surfaces of the display to be tested. Using this test configuration, the luminance of the legend, both illuminated and non-illuminated, plus that of the adjacent background areas, shall be measured. Three luminance readings per character shall be taken (see figure 9) [Appendix C]. From these readings, the following contrast ratios can be calculated for each character:
>
> The ON / BACKGROUND contrast $C_L = \frac{B2 - B1}{B1}$
>
> The OFF / BACKGROUND contrast $C_{UL} = \frac{B3 - B1}{B1}$
>
> B1 = Average background luminance
> B2 = Average character luminance, lighted
> B3 = Average character luminance, unlighted
>
> The test shall be repeated with ϕ_1 and ϕ_2 = 30 degrees ±2 degrees. Normal production units shall be tested. The sample units shall have two lines of characters which utilize at least three-fourths of the maximum horizontal length of the legend. The contrast readings for the characters with the highest and lowest average contrast on each unit shall be reported. [13]

A diagram of the test setup is shown in Figure 8. A photo of the test setup is shown in Figure 9.

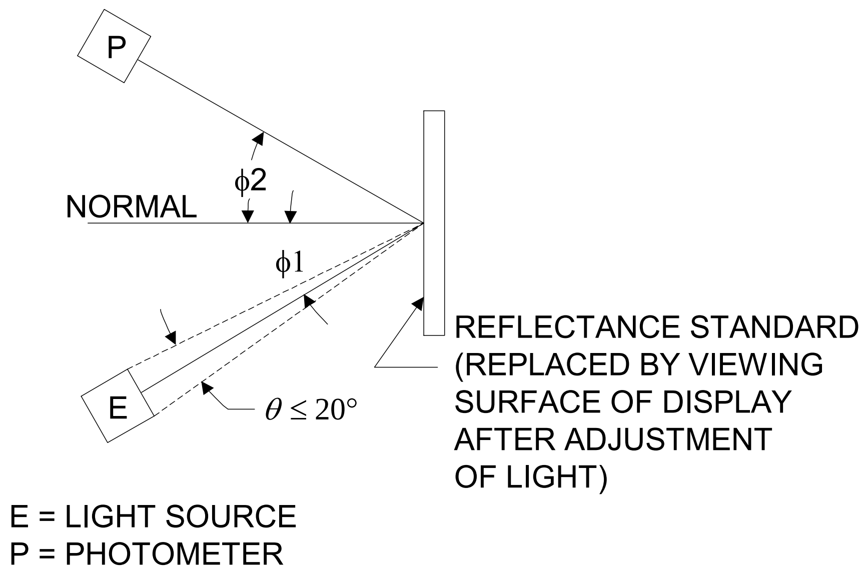


Fig. 8. Diagram of sunlight readable contrast test.

While the photometer measured luminance, illuminance was calculated by using a reflectance standard. The SRS-2 reflectance standard reflects incident light with near perfect diffusion. The *luminance* of a surface with perfect Lambertian diffusion is mathematically equal to the *illuminance* incident to the surface [16]. The SRS-2 has a reflectance factor of 0.988 at an inclusive angle ($\phi_1 + \phi_2$) of 45 degrees. The differences between the inclusive angles used in this test and 45 degrees were assumed to have negligible effects on the reflectance factor. For each set of angles, the light source was adjusted until the photometer measured 9880 fL $\pm$ 50 fL using the reflectance standard. Therefore, the light source produced between 9,950 fc and 10,050 fc of illumination on the reflectance standard and switch under test.

Contrast readings for the characters with the lowest C_L and for characters with the highest $|C_{UL}|$ are summarized in Tables 3a and 3b. Complete measurement data is listed in Appendix D.

Consumers expect sunlight readable contrast of LED switches to meet or exceed that of incandescent switches. Therefore, the criteria to achieve sunlight readable contrast are the average contrast criteria for incandescent switches as specified in MIL-PRF-22885/108 and MIL-PRF-22885/109 and listed in Tables 3a and 3b [17],[18].

Table 3a
Sunlight Readable Contrast
ϕ_1=ϕ_2=15 Degrees

	C_L	$\lvert C_{UL}\rvert$
Criteria	≥ 0.600	≤ 0.100
AOI, Φ_1=Φ_2=15°	0.996	0.095
Eaton, Φ_1=Φ_2=15°	0.197	0.180
Korry, Φ_1=Φ_2=15°	0.904	0.279
Staco, Φ_1=Φ_2=15°	-0.313	0.718

Table 3b
Sunlight Readable Contrast
ϕ_1=ϕ_2=30 Degrees

	C_L	$\lvert C_{UL}\rvert$
Criteria	≥ 0.300	≤ 0.100
AOI, Φ_1=Φ_2=30°	0.433	0.088
Eaton, Φ_1=Φ_2=30°	0.138	0.200
Korry, Φ_1=Φ_2=30°	0.577	0.185
Staco, Φ_1=Φ_2=30°	-0.118	0.176

Table 3 shows Eaton's, Korry's and Staco's LED switches do not achieve sunlight readable contrast. Three manufacturers' LED push button switches do not produce $C_L \geq 0.6$ and $|C_{UL}| \leq 0.1$ at $\phi_1 = \phi_2 = 15$ degrees, and $C_L \geq 0.3$ and $|C_{UL}| \leq 0.1$ at $\phi_1 = \phi_2 = 30$ degrees when measured in direct-reflected specular sunlight conditions. Therefore, null hypothesis 3 was rejected and alternative hypothesis 3 was accepted.

Test 4: Luminance Contrast Under Ambient Sunlight Conditions

Sunlight readable contrast evaluates switch lighting quality under intense conditions. The photometer is positioned to measure directly into the glare angle of the light source. This condition simulates the effect of direct sunlight entering the cockpit at an angle which reflects it off the control panel and into the pilot's eyes. Some

Fig. 9. Test setup for contrast measurements.

applications for lighted push button switches are subject to little or no direct sunlight, such as below-deck shipboard panels. Some switch manufacturers' slash sheets modify the sunlight readable contrast test to simulate diffuse ambient lighting instead of direct-reflected sunlight conditions.

The modified contrast test is a hybrid of two different tests. The modified test uses the angles ϕ_1 = 45 degrees and ϕ_2 = 0 degrees (see Figure 8) specified in MIL-P-7788. MIL-P-7788 defines "daylight contrast" for lighted panels using diffuse illumination of 50 fc at 45 degrees to the normal of the panel [19]. These angles place the light source at 45 degrees to the normal of the display, and the photometer perpendicular to the display. The modified test uses the light source intensity, measurement formulas and contrast criteria from MIL-PRF-22885. Thus, the modified test simulates a 10,000 fc diffuse ambient environment.

TEST PROCEDURE & RESULTS

Each switch's legend was energized at 28.00 V ± 0.02 V dc. Luminance contrast was measured as defined in MIL-PRF-22885, except with ϕ_1 = 45 degrees and ϕ_2 = 0 degrees. The light source was adjusted at these angles to produce between 9,950 fc and 10,050 fc of illumination.

Contrast readings for the characters with the lowest C_L and for characters with the highest $|C_{UL}|$ are summarized in Table 4. Complete measurement data is listed in Appendix D.

The criteria to achieve acceptable contrast are $C_L \geq 0.6$ and $|C_{UL}| \leq 0.1$, as defined in MIL-PRF-22885.

Table 4
Luminance Contrast Under Ambient Sunlight Conditions

	C_L	$\lvert C_{UL} \rvert$
Criteria	≥ 0.600	≤ 0.100
AOI, Φ_1=45°, Φ_2=0°	1.338	0.088
Eaton, Φ_1=45°, Φ_2=0°	1.607	0.230
Korry, Φ_1=45°, Φ_2=0°	1.081	0.320
Staco, Φ_1=45°, Φ_2=0°	0.193	0.371

Table 4 shows Eaton's, Korry's and Staco's LED switches do not achieve acceptable contrast. Three manufacturers' LED push button switches do not produce C_L ≥ 0.6 and $|C_{UL}|$ ≤ 0.1 at ϕ_1 = 45 degrees and ϕ_2 = 0 degrees when measured in ambient sunlight conditions. Therefore, null hypothesis 4 was rejected and alternative hypothesis 4 was accepted.

Test 5: Legend Uniformity

Legend uniformity is necessary for accurate switch legend interpretation. While legend uniformity was relatively inherent using incandescent lamps, LED lighting makes uniformity more challenging to attain. Legend uniformity using LEDs is even more difficult to maintain at standard and low-level dimming than at full luminance. This test measured character-to-character legend uniformity of each switch at full luminance (28 V), 15 fL, and 1 fL.

TEST PROCEDURE & RESULTS

Each switch's legend was energized at 28.00 V $\pm$ 0.02 V dc. Average luminance of each character was measured as described in MIL-PRF-22885 paragraph 4.7.35. Point measurements were averaged for each character. Uniformity ratio was calculated using the characters with the highest and lowest average luminance:

$$U = \frac{L_{high}}{L_{low}}$$

The procedure was repeated at an average display luminance of 15 fL $\pm$ 3 fL and 1 fL $\pm$ 0.3 fL. Uniformity ratios were expressed as "U to 1" (U:1). Legend uniformity ratios are listed in Table 5. Complete measurement data is listed in Appendix D.

Maximum uniformity ratio is usually specified as 2:1, as defined in MIL-STD-3009:

> 4.3.7 Luminance uniformity At any given luminance level, lighting components within a lighting subsystem shall provide luminance such that the average luminance ratio between lighted components shall not be greater than 2 to 1 [20].

Table 5
Legend Uniformity Ratios

	U at full luminance	U at 15 fL	U at 1 fL
Criteria	≤ 2.00:1	≤ 2.00:1	≤ 2.00:1
AOI	1.38:1	1.40:1	1.43:1
Eaton	1.61:1	4.77:1	12.1:1
Korry	1.72:1	1.93:1	4.14:1
Staco	3.43:1	7.15:1	10.5:1

Table 5 shows character-to-character uniformity of Eaton's, Korry's and Staco's LED switches is greater than 2:1. Three manufacturers' LED push button switches do not produce character-to-character uniformity less than or equal to 2:1 when dimmed from full luminance to 1 fL. Therefore, null hypothesis 5 was rejected and alternative hypothesis 5 was accepted.

Test 6: Dual-Color Uniformity

LEDs of different colors have different voltage, current and intensity characteristics. When different-colored LEDs are used to create split-legend displays, luminance disparities between legend colors can result. Luminance differences between split-legend colors are often more prominent at standard and low-level dimming than at full luminance. This test measured uniformity between different-colored legend halves of each switch at full luminance (28 V), 15 fL, and 1 fL.

TEST PROCEDURE & RESULTS

Each switch's legend was energized at 28.00 V ± 0.02 V dc. Average luminance of each half-legend was measured as described in MIL-PRF-22885 paragraph 4.7.35. Point measurements were averaged for each half-legend. Uniformity ratio was calculated using the half-legend luminance measurements:

$$U = \frac{L_{high}}{L_{low}}$$

Lighted switches with split-legend displays are typically configured for two-mode operation. In mode number one, one of the two legend halves is on. In mode number two, the other half-legend illuminates while the first half-legend either stays on or shuts off. To simulate this operation, each switch's bottom green legend was dimmed to an average luminance of 15 fL $\pm$ 3 fL. The top white legend was then energized at the same voltage as the bottom legend. The average luminance of the top legend was measured as before. Uniformity ratio was calculated by finding the quotient between the average luminance of each half-legend, placing the greater value in the numerator.

The procedure was repeated, dimming the bottom green legend to an average luminance of 1 fL $\pm$ 0.3 fL. Resultant dual-color uniformity ratios are listed in Table 6. Complete measurement data is listed in Appendix D.

Maximum uniformity ratio is usually specified as 2:1, as defined in MIL-STD-3009.

Table 6
Dual-Color Uniformity Ratios

	U at full luminance	U at 15 fL	U at 1 fL
Criteria	≤ 2.00:1	≤ 2.00:1	≤ 2.00:1
AOI	1.06:1	1.05:1	1.06:1
Eaton	1.26:1	4.38:1	10.4:1
Korry	1.04:1	1.12:1	2.70:1
Staco	2.13:1	3.07:1	4.72:1

Table 6 shows dual-color uniformity of Eaton's, Korry's and Staco's LED switches is greater than 2:1. Three manufacturers' LED push button switches do not produce dual-color uniformity less than or equal to 2:1 when dimmed from full luminance to 1 fL. Therefore, null hypothesis 6 was rejected and alternative hypothesis 6 was accepted.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to evaluate the lighting performance of LED push button switches for the benefit of both consumers and manufacturers. Six key attributes of switch lighting quality were tested on products manufactured by four different manufacturers: Aerospace Optics, Eaton Aerospace, Korry Electronics and StacoSwitch.

Conclusions

Test results show all four manufacturers' LED switches consume less power than a typical ¾-inch incandescent switch. In no other test did all four manufacturers meet the acceptable criteria, supporting the consumer's need for detailed information on lighting performance of LED switches. One manufacturer does not meet the minimum average luminance criteria at full rated voltage. Three manufacturers do not meet the acceptable criteria concerning sunlight readability, contrast under ambient sunlight conditions, legend uniformity, and dual-color uniformity. Results are summarized in Table 7. "P" indicates passing and "F" indicates failing the criteria established in each test.

Table 7
Summary of Results

Mfg	Luminance	Power	Sunlight Readability	Contrast Under Ambient Sunlight	Legend Uniformity	Dual-Color Uniformity
AOI	P	P	P	P	P	P
Eaton	P	P	F	F	F	F
Korry	P	P	F	F	F	F
Staco	F	P	F	F	F	F

Avionics designers should note the disparity between average luminance of LED switches energized at 28 V, especially when trying to match luminance levels between newer and older switches in the same panel. Designers with many switches to install in a single cockpit should note the differences in power consumption of LED switches at full rated voltage. Consumers with sunlight readability needs should study the wide range of luminance contrast results between LED switch manufacturers. Care must be taken to assure LED switch legends are uniformly illuminated and legible. Designers with multicolor switch legends or different colors of switches in the same panel should be aware of potential legend luminance disparities, especially at dim settings.

Three manufacturers have not yet developed LED push button switches that meet the lighting quality standards previously established using incandescent technology. Both avionics designers and switch manufacturers should make efforts to improve LED switch lighting quality for the benefit of the industry.

Recommendations

Further study should be completed concerning LED switch lighting quality, such as:

- Uniform dimming between split-legends of other color combinations
- The effects of viewing angle on average luminance
- The effects of ambient temperature on average luminance
- Revisions to MILSPECs reflecting switch technology capabilities and system design requirements

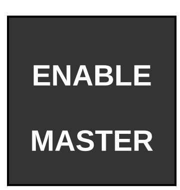
APPENDIX A

PRODUCT SPECIFICATION AND DETAILS

GENERAL PRODUCT SPECIFICATION

1.0	Specification:	LED Illuminated Push Button Switch
1.1	Revision:	A
1.2	Date:	07 July 2003
1.3	Notes:	Dimensions in inches unless otherwise specified
2.0	Mechanical Specifications:	
2.1	Panel cutout:	0.70 square
2.2	Panel thickness:	0.125
2.3	Operating temp:	-40 to +71 deg C
3.0	Switch Specifications:	
3.1	Switch form:	4PDT single break
3.2	Switch action:	Alternate action
3.3	Switch contacts:	Silver
3.4	Switch load:	7.5A min resistive at sea level
3.5	Terminations:	Crimp pin compatible with M39029/22-192
3.6.1	EMI/RFI shielding:	No
3.6.2	Drip proof:	No
3.6.3	Splash proof:	No
4.0	Lighting Requirements:	
4.1	Illumination type:	LED
4.2	Full voltage:	28 VDC yields min of 150 fL average luminance
4.3	Dimming voltage:	14 VDC yields 15 fL average luminance
4.4	Circuit:	Horizontal split, dual ground, common anode (current sinking)
4.5.1	Top legend:	ENABLE
4.5.2	Top legend color:	Aviation White per MIL-L-25050
4.5.3	Top font:	Gorton Condensed Gothic
4.5.4	Top char height:	0.125
4.5.5	Top display type:	Sunlight readable type S per MIL-PRF-22885
4.6.1	Bottom legend:	MASTER
4.6.2	Bottom legend color:	Aviation Green per MIL-L-25050
4.6.3	Bottom font:	Gorton Condensed Gothic
4.6.4	Bottom char height:	0.125
4.6.5	Bottom display type:	Sunlight readable type S per MIL-PRF-22885

Illuminated example (not to scale):



(White)

(Green)

PRODUCT DETAILS

Manufacturer:	Aerospace Optics Inc. Fort Worth, TX http://www.vivisun.com
Model Name:	VIVISUN® LED [21]
Part Number:	LED-6A-15-BB-32092 (2A1 ENABLE; 3G1 MASTER)
Exceptions taken to spec:	Font style is globe condensed

Manufacturer:	Eaton Aerospace Irvine, CA http://www.aerospace.eaton.com
Model Name:	Series 584
Part Number:	58480A2B5C2G28L5000N2(WG),P21,16 ENABLE/MASTER
Exceptions taken to spec:	Font style is futura medium condensed

Manufacturer:	Korry Electronics Co. Seattle, WA http://www.korry.com
Model Name:	Chromalux® 389 Quick Switch [22]
Part Number:	Undisclosed
Exceptions taken to spec:	None

Manufacturer:	StacoSwitch Costa Mesa, CA http://www.stacoswitch.com
Model Name:	Series 90, Model 99
Part Number:	991723-0246267722(ENABLE)(MASTER)
Exceptions taken to spec:	Switch form is DPDT Dimming control is PWM Top legend color is lime green Font style is condensed gothic

APPENDIX B

INSTRUMENTATION AND CALIBRATION REPORTS

INSTRUMENTATION

Instrument	Brand	Model
Photometer	Photo Research	PR-1980A
Objective lens	Photo Research	MS-80
Multimeters (2)	Keithley	179A
Meter mover	Hoffman Engineering	MM-31-80
Power supply	Hewlett Packard	6267B
Reflectance standard	Hoffman Engineering	SRS-2
Light source	Dolan-Jenner	Model 180
Power supply	Topward	3301D

QC -19C
2003 July 24
A.O.I. 8
D. West

From the Laboratories at
Hoffman Engineering Corporation
8 Riverbend Drive, P.O. Box 4430
Stamford, CT, U.S.A. 06907-0430
TEL: 203-425-8900 / FAX: 203-425-8910
EMAIL: Service@HoffmanEngineering.COM

Calibration Certificate

This Calibration is traceable to the National Institute of Standards and Technology in accordance with ISO 10012-1 and MIL-STD-45662A. The Calibration was accomplished by comparison to standards maintained by the laboratories at Hoffman Engineering Corporation. Complete compliance records and procedures are maintained by Hoffman Engineering Corporation and are available for inspection upon request.

CUSTOMER: AEROSPACE OPTICS INC.
3201 SANDY LANE
FORT WORTH TX
76112

PO #: 31344
MODEL #: 1980A
SERIAL #: C1297
ITEM: SPECTRA PHOTOMETER w/ MS-80 LENS

Item Condition/Special Customer Requests

As Received
- ☒ In Tolerance *
- ☐ Out of Tolerance *
- ☐ Inoperative
- ☐ Limited Calibration **

* Per referenced calibration procedure
**Limited by customer or equipment performance.

As Left
- ☒ In Tolerance *
- ☐ Out of Tolerance *
- ☐ Inoperative
- ☐ Limited Calibration **
- ☒ Adjusted

TEST PROCEDURE USED: 1980A

COMMENTS: LUMINANCE: NO CHANGE

TEMPERATURE: 72 ° F **RELATIVE HUMIDITY:** 44 %

CALIBRATED: July 16, 2003 **RECALIBRATION DUE:** July 16, 2004

TECHNICIAN: WLL **CERTIFIED BY** J. P. DeLancey
James L. DeLancey, Lab Manager

RMA/WO #: 13169

➤ ISO 9001 Certified ◄ CALIBRATION CERTIFICATE.DOT Rev J 5/10/02

Page 1 of 6

SIMCO electronics

783 N. GROVE ROAD, STE. 106
RICHARDSON, TX 75081

Certificate No. **2265490**

2003 Oct. 16

A.01 8

CERTIFICATE OF CALIBRATION FOR AEROSPACE OPTICS INC

Description: **KEITHLEY, 179A, DMM**

Serial No: **10071** Asset No: **QC-33** Simco ID: **17779-14**

Dept: **NONE** PO No: **31471**

Calibration Date: **10/07/03**	Calibration Interval: **12 Months**	Recall Date: **10/07/04**

Arrival Condition:	Service:
MEETS MANUFACTURER'S SPEC'S.	**CALIBRATED TO MFR SPEC,& CLEAN**

Procedure: **635-0085 REV 4** TUR/Cal Ratio: **≥ 4.00:1**
Temperature: **72°F** Relative Humidity: **46%**

Standards Used:

Type	Simco ID	Due Date	Intvl Mos	Acc/Unc	Trace No.
CALIBRATOR	17200*60	06/20/04	12	DCV +/- 8PPM	258738 DCV
CALIBRATOR	17200*60	06/20/04	12	ACV +/- 90PPM	0183/7291 ACV
CALIBRATOR	17200*60	06/20/04	12	OHMS +/- 15PPM	260586/98 RES
CALIBRATOR	17200*60	06/20/04	12	DC I +/- 60PPM	264703-01 DCI
CALIBRATOR	17200*60	06/20/04	12	AC I +/- 150PPM	0183/10163 AC
CALIBRATOR	17200*60	06/20/04	12	FREQ +/-0.01%	WWVB FREQ
DMM	17627*118	12/10/03	6	DCV +/-2.2 ppm	267222-02
DMM	17627*118	12/10/03	6	ACV +/-90 ppm	D5266

Work performed by:
Jon B. Taylor
Electronics Tech C (13087)

Reviewed by:

17 SIMCO

SIMCO Electronics' quality system conforms to ANSI/NCSL Z540-1 and all elements of ISO/IEC 17025 and as a result to ISO 9002. The Test uncertainty ratio is based on the uncertainty of the standards used. All calibrations are performed using internationally recognized standards traceable to the SI Units. Traceability is achieved through calibrations by the National Institute of Standards and Technology (NIST), other National Measurement Institutes (NMIs'), or by using natural physical constants, intrinsic standards or ratio calibration techniques. The information shown on this certificate applies only to the instrument identified above and may not be reproduced, except in full, without prior written consent from SIMCO Electronics.

Dated: **10/07/03**

Page 1 of 1

CALIBRATION REPORT

DESCRIPTION OF EQUIPMENT:	PROCEDURE USED:	CALIBRATION I.D. NUMBER:
Multimeter, 4.5 digit	CP-10	QC-35
MANUFACTURER:	**CALIBRATION INTERVAL:**	**DATE NEW:**
Keithly Instruments	6 months	21 June 1983
MODEL NUMBER:	**LOCATION OF EQUIPMENT:**	**TOLERANCE:**
179A	Quality Control, Light Lab 6, Bench J	DC Voltage only
SERIAL NUMBER:	**ASSIGNED TO:**	± 0.005Vdc @ 5.000Vdc
		± 0.05Vdc @ 28.00Vdc

STANDARDS USED:	CALIBRATION LABORATORY:
QC-33 Multimeter	Aerospace Optics, Inc. 3201 Sandy Lane Fort Worth, Texas 76112-7298

DATE:	2002 June 20	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	**ADJUSTED:**	No	**REL. HUMIDITY:**	56	%RH

RESULTS: STD. 5.000Vdc UUC: 5.000Vdc
STD. 28.00Vdc UUC: 27.99Vdc

DATE:	2002 December 24	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	**ADJUSTED:**	No	**REL. HUMIDITY:**	27	%RH

RESULTS: STD. 5.000Vdc UUC: 5.000VDC
STD. 28.00Vdc UUC: 27.99VDC

DATE:	2003 June 24	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	**ADJUSTED:**	No	**REL. HUMIDITY:**	44	%RH

RESULTS: STD. 5.00Vdc UUC: 5.00Vdc
STD. 28.0Vdc UUC: 28.0Vdc

DATE:	2003 December 16	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	**ADJUSTED:**	No	**REL. HUMIDITY:**	15	%RH

RESULTS: STD. 5.00Vdc UUC: 5.00Vdc
STD. 28.0Vdc UUC: 28.0Vdc

CALIBRATION REPORT

DESCRIPTION OF EQUIPMENT:	PROCEDURE USED:	CALIBRATION I.D. NUMBER:
DC Power Supply	CP-08	QC-49
MANUFACTURER:	CALIBRATION INTERVAL:	DATE NEW:
Hewlett Packard	6 months	07 May 1982
MODEL NUMBER:	LOCATION OF EQUIPMENT:	TOLERANCE:
6267B	Quality Control	± 2% of test Voltage
SERIAL NUMBER:	ASSIGNED TO:	5Vdc: ±.1Vdc
3217AO9884	Quality Control	28Vdc: ±.56Vdc

STANDARDS USED:	CALIBRATION LABORATORY:
QC-93 Multimeter	Aerospace Optics 3201 Sandy Lane Fort Worth, Texas 76112-7298

DATE:	2002 June 21	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	ADJUSTED:	No	REL. HUMIDITY:	57	%RH

Results:

Test Voltage	Droop @ .5A	QC-49	QC-93	% Deviation	Actual Deviation
5.000 Vdc	0.01 Vdc	5.000 Vdc	5.000 Vdc	0.000% Vdc	0.000 Vdc
28.000 Vdc	0.01 Vdc	28.000 Vdc	28.000 Vdc	0.000% Vdc	0.000 Vdc

DATE:	2002 December 26	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	ADJUSTED:	No	REL. HUMIDITY:	27	%RH

Results:

Test Voltage	Droop @ .5A	QC-49	QC-93	% Deviation	Actual Deviation
5.000 Vdc	0.01 Vdc	5.000 Vdc	5.000 Vdc	0.000% Vdc	0.000 Vdc
28.000 Vdc	0.01 Vdc	28.000 Vdc	28.000 Vdc	0.000% Vdc	0.000 Vdc

DATE:	2003 June 19	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	ADJUSTED:	No	REL. HUMIDITY:	46	%RH

Results:

Test Voltage	Droop @ .5A	QC-49	QC-93	% Deviation	Actual Deviation
5.000 Vdc	0.05 Vdc	5.000 Vdc	5.000 Vdc	0.000% Vdc	0.000 Vdc
28.000 Vdc	0.10 Vdc	28.000 Vdc	28.000 Vdc	0.000% Vdc	0.000 Vdc

DATE:	2003 December 18	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	ADJUSTED:	No	REL. HUMIDITY:	18	%RH

Results:

Test Voltage	Droop @ .5A	QC-49	QC-93	% Deviation	Actual Deviation
5.000 VDC	0.02 VDC	5.000 VDC	5.000 VDC	0.000% VDC	0.000 VDC
28.000 VDC	0.02 VDC	28.00 VDC	27.98 VDC	-0.071% VDC	-0.020 VDC

3CC 3 MAR '12

AO1 8

Entered
RC-192

From the Laboratories at
Hoffman Engineering Corporation
8 Riverbend Drive, P.O. Box 4430
Stamford, CT, U.S.A. 06907-0430
TEL: 203-425-8900 / FAX: 203-425-8910
EMAIL: Service@HoffmanEngineering.COM

Calibration Certificate

This Calibration is traceable to the National Institute of Standards and Technology in accordance with ISO 10012-1 and MIL-STD-45662A. The Calibration was accomplished by comparison to standards maintained by the laboratories at Hoffman Engineering Corporation. Complete compliance records and procedures are maintained by Hoffman Engineering Corporation and are available for inspection upon request.

CUSTOMER: VIVISUN
AEROSPACE OPTICS INC.
3201 SANDY LANE
FORT WORTH TX 76112

PO #: 31543
MODEL #: SRS-2
SERIAL #: 118
ITEM: SPECTRAL REFLECTANCE STANDARD

Item Condition/Special Customer Requests

As Received	As Left
☒ In Tolerance *	☒ In Tolerance *
☐ Out of Tolerance *	☐ Out of Tolerance *
☐ Inoperative	☐ Inoperative
☐ Limited Calibration **	☐ Limited Calibration **
* Per referenced calibration procedure	☒ Adjusted
**Limited by customer or equipment performance.	

TEST PROCEDURE USED: SRS-2

COMMENTS: SEE ATTACHED SHEET

TEMPERATURE: 72 ° F **RELATIVE HUMIDITY:** 40 %

CALIBRATED: November 7, 2003 **RECALIBRATION DUE:** November 7, 2004

TECHNICIAN: WLL **CERTIFIED BY** J L DeLancey
James L. DeLancey, Lab Manager

RMA/WO #: 13422

➢ ISO 9001 Certified ≺

CALIBRATION REPORT

DESCRIPTION OF EQUIPMENT:	PROCEDURE USED:	CALIBRATION I.D. NUMBER:
POWER SUPPLY, DC	CP-08	QC-116
MANUFACTURER:	CALIBRATION INTERVAL:	DATE NEW:
TOPWARD	6 months	04 April 1997
MODEL NUMBER:	LOCATION OF EQUIPMENT:	TOLERANCE:
3301D	Light Laboratory #6	±2% of test voltage
SERIAL NUMBER:	ASSIGNED TO:	(5VDC: ±0.1VDC)
992358	Q.C. technician	(28VDC: ±0.56VDC)

STANDARDS USED:	CALIBRATION LABORATORY:
QC-33 Multimeter	Aerospace Optics 3201 Sandy Lane Ft. Worth, TX. 76112

DATE:	2003 February 20	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	ADJUSTED:	No	REL. HUMIDITY:	41	%RH

RESULTS:

Test Voltage	QC-116	QC-33 Standard	Droop @.5a	% Dev. of Droop	Actual Deviation
5.000 VDC	5.0 VDC	5.025 VDC	4.934 VDC	-1.811% VDC	-0.091 VDC
28.000 VDC	28.0 VDC	28.04 VDC	27.890 VDC	-0.535% VDC	-0.150 VDC

DATE:	2003 August 20	DISPOSITION:	Accept	TEMPERATURE:	76	°F
TECHNICIAN:	D.W. West	ADJUSTED:	No	REL. HUMIDITY:	43	%RH

RESULTS:

Test Voltage	QC-116	QC-33 Standard	Droop @.5a	% Dev. of Droop	Actual Deviation
5.000 VDC	5.0 VDC	5.00 VDC	4.98 VDC	-0.400% VDC	-0.020 VDC
28.000 VDC	28.0 VDC	28.02 VDC	27.99 VDC	-0.107% VDC	-0.030 VDC

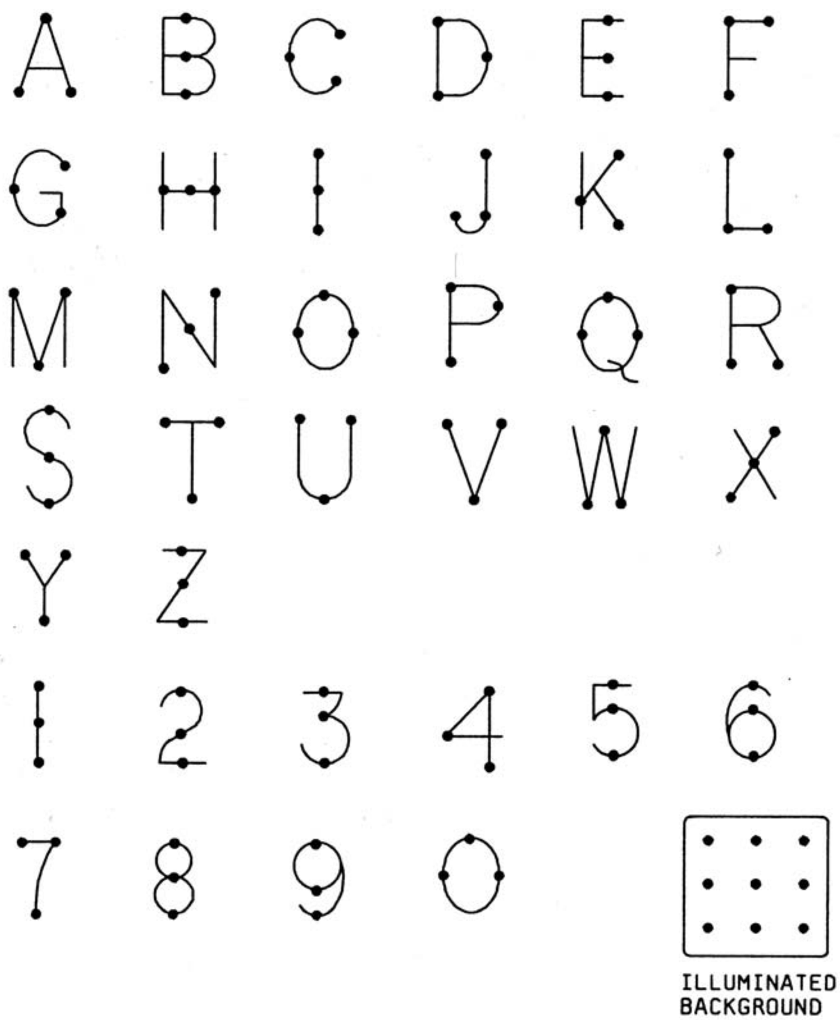
DATE:	2004 February 19	DISPOSITION:	Accept	TEMPERATURE:	75	°F
TECHNICIAN:	D.W. West	ADJUSTED:	No	REL. HUMIDITY:	34	%RH

RESULTS:

Test Voltage	QC-116	QC-33 Standard	Droop @.5a	% Dev. of Droop	Actual Deviation
5.000 VDC	5.0 VDC	5.02 VDC	5.01 VDC	-0.199% VDC	-0.010 VDC
28.000 VDC	28.0 VDC	28.05 VDC	28.03 VDC	-0.071% VDC	-0.020 VDC

APPENDIX C

LUMINANCE MEASUREMENT POINTS


ILLUMINATED
BACKGROUND

APPENDIX D

MEASUREMENT DATA

LUMINANCE MEASUREMENTS
DISPLAY AT FULL LUMINANCE (28V)

AOI	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	580	507	522	576	566	574	390	503	388	487	523	541
Point 2	483	486	545	484	537	544	468	521	387	526	468	572
Point 3	504	534	433	477	533	470	472	522	445	491	539	574
Character Avg	522	509	500	512	545	529	443	515	407	501	510	562
Display Avg	505											
CTC Uniformity	1.38											
Top Half Avg	520											
Bottom Half Avg	490											
Dual-Color Uniformity	1.06											

EATON	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	413	493	511	433	451	382	527	540	685	687	622	566
Point 2	455	483	476	482	498	408	500	641	639	665	577	498
Point 3	455	441	514	504	476	410	573	587	574	583	548	468
Character Avg	441	472	500	473	475	400	533	589	633	645	582	511
Display Avg	521											
CTC Uniformity	1.61											
Top Half Avg	460											
Bottom Half Avg	582											
Dual-Color Uniformity	1.26											

KORRY	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	298	355	412	479	477	360	276	385	455	477	423	355
Point 2	316	498	478	576	418	405	323	436	487	449	476	330
Point 3	263	476	437	455	402	318	359	403	411	406	386	267
Character Avg	292	443	442	503	432	361	319	408	451	444	428	317
Display Avg	404											
CTC Uniformity	1.72											
Top Half Avg	412											
Bottom Half Avg	395											
Dual-Color Uniformity	1.04											

STACO	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	169	257	187	133	202	133	110	122	72.6	64.4	97.0	88.9
Point 2	343	315	149	178	263	166	132	151	98.9	80.6	91.6	81.9
Point 3	240	196	180	164	270	156	143	85.8	82.4	85.2	95.3	53.0
Character Avg	251	256	172	158	245	152	128	120	84.6	76.7	94.6	74.6
Display Avg	151											
CTC Uniformity	3.43											
Top Half Avg	206											
Bottom Half Avg	96.4											
Dual-Color Uniformity	2.13											

LUMINANCE CONTRAST MEASUREMENTS

AOI	E				N				A				B				L				E			
Φ1=Φ2=15°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	415	394	427	412	418	400	423	414	409	423	408	413	424	404	427	418	438	435	420	431	437	455	436	443
B2	960	1004	895	953	915	912	937	921	909	1027	980	972	891	907	982	927	950	982	990	974	862	920	874	885
B3	452	505	392	450	367	461	445	424	455	474	429	453	401	441	438	427	438	470	472	460	402	471	463	445
CL				1.313				1.227				1.352				1.215				1.260				1.000
CUL				0.091				0.026				0.095				0.020				0.067				0.006
AOI	M				A				S				T				E				R			
Φ1=Φ2=15°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	393	400	412	402	410	424	417	417	434	431	409	425	428	447	487	454	441	428	462	444	431	456	459	449
B2	793	878	911	861	880	926	797	868	896	848	953	899	960	919	915	931	854	888	915	886	998	922	1046	989
B3	408	389	461	419	411	488	400	433	413	397	454	421	493	506	463	487	423	459	432	438	510	443	518	490
CL				1.143				1.081				1.117				1.051				0.996				1.204
CUL				0.044				0.038				-0.008				0.073				-0.013				0.093
AOI	E				N				A				B				L				E			
Φ1=Φ2=30°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	638	611	653	634	616	600	646	621	613	624	624	620	624	696	636	652	628	630	610	623	626	622	624	624
B2	1003	1006	871	960	827	925	1105	952	1011	865	936	937	1007	961	916	961	972	931	966	956	869	966	907	914
B3	654	674	573	634	561	679	773	671	677	535	632	615	574	681	537	597	604	603	673	627	548	657	659	621
CL				0.514				0.534				0.511				0.474				0.536				0.465
CUL				-0.001				0.081				-0.009				-0.084				0.006				-0.004
AOI	M				A				S				T				E				R			
Φ1=Φ2=30°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	612	662	635	636	625	655	652	644	650	620	603	624	609	654	712	658	648	636	670	651	633	655	635	641
B2	924	938	873	912	966	992	950	969	965	902	928	932	1004	1014	979	999	1055	962	1006	1008	985	1015	1088	1029
B3	638	624	590	617	669	691	626	662	656	598	605	620	697	717	667	694	748	642	645	678	696	694	703	698
CL				0.433				0.505				0.492				0.517				0.547				0.606
CUL				-0.030				0.028				-0.007				0.054				0.041				0.088

LUMINANCE CONTRAST MEASUREMENTS

AOI	E				N				A				B				L				E			
Φ1=45°, Φ2=0°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	332	319	312	321	313	342	333	329	339	316	348	334	369	350	329	349	340	329	326	332	348	379	363	363
B2	903	838	800	847	838	809	892	846	864	892	871	876	889	806	833	843	889	857	883	876	924	863	861	883
B3	332	354	281	322	308	326	346	327	306	317	423	349	291	313	359	321	300	334	346	327	327	315	361	334
CL				1.639				1.570				1.619				1.412				1.642				1.429
CUL				0.004				-0.008				0.043				-0.081				-0.015				-0.080
AOI	M				A				S				T				E				R			
Φ1=45°, Φ2=0°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	324	347	309	327	288	320	349	319	325	332	346	334	324	347	354	342	338	331	360	343	383	342	373	366
B2	806	769	845	807	840	755	874	823	773	767	805	782	842	898	815	852	963	870	863	899	944	992	902	946
B3	341	306	364	337	302	246	347	298	333	354	337	341	366	355	306	342	431	380	309	373	392	413	284	363
CL				1.469				1.580				1.338				1.493				1.620				1.585
CUL				0.032				-0.065				0.021				0.002				0.088				-0.008
EATON	E				N				A				B				L				E			
Φ1=Φ2=15°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	988	988	1059	1012	887	835	1053	925	941	951	1021	971	1101	810	777	896	911	1036	1008	985	1239	999	1148	1129
B2	1511	1410	1557	1493	1430	1409	1203	1347	1419	1533	1316	1423	1130	1301	1531	1321	1238	1687	1576	1500	1531	1212	1311	1351
B3	1085	933	1052	1023	950	925	770	882	979	1028	836	948	718	849	1056	874	847	1245	1154	1082	1197	860	946	1001
CL				0.475				0.457				0.465				0.474				0.523				0.197
CUL				0.012				-0.047				-0.024				-0.024				0.098				-0.113
EATON	M				A				S				T				E				R			
Φ1=Φ2=15°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	899	808	833	847	956	808	715	826	1066	854	767	896	1207	987	977	1057	943	684	912	846	1072	1017	779	956
B2	1581	1325	1448	1451	1596	1677	1377	1550	1613	1608	1670	1630	1396	1621	1361	1459	1499	1232	1272	1334	1419	1311	1530	1420
B3	1067	776	814	886	952	1099	820	957	947	977	1084	1003	772	1014	814	867	959	711	807	826	957	898	1143	999
CL				0.714				0.876				0.820				0.381				0.577				0.485
CUL				0.046				0.158				0.119				-0.180				-0.024				0.045

LUMINANCE CONTRAST MEASUREMENTS
PAGE 3 OF 6

EATON	E				N				A				B				L				E			
Φ1=Φ2=30°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	1194	1091	1176	1154	1079	1065	1128	1091	1121	1037	1142	1100	1192	963	1044	1066	1426	1347	1259	1344	1569	1242	1553	1455
B2	1651	1604	1656	1637	1647	1534	1589	1590	1161	1597	1591	1450	1261	1622	1810	1564	1397	1514	1679	1530	1924	1503	1587	1671
B3	1256	1182	1221	1220	1219	1107	1201	1176	798	1188	1203	1063	926	1252	1440	1206	1110	1202	1384	1232	1688	1251	1335	1425
CL				0.419				0.458				0.318				0.467				0.138				0.149
CUL				0.057				0.078				-0.034				0.131				-0.083				-0.021

EATON	M				A				S				T				E				R			
Φ1=Φ2=30°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	1072	1143	1063	1093	1240	1053	1093	1129	1147	1022	954	1041	1503	1164	1007	1225	1184	899	1102	1062	1295	1262	1064	1207
B2	1804	1359	1697	1620	1797	1822	1373	1664	1714	2070	1491	1758	1855	1750	1506	1704	1474	1635	1376	1495	1751	1242	1455	1483
B3	1258	866	1140	1088	1235	1321	891	1149	1185	1545	1019	1250	1340	1318	1074	1244	1091	1218	1120	1143	1392	936	1156	1161
CL				0.483				0.474				0.689				0.391				0.408				0.228
CUL				-0.004				0.018				0.200				0.016				0.077				-0.038

EATON	E				N				A				B				L				E			
Φ1=45°, Φ2=0°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	240	245	231	239	309	260	286	285	271	298	272	280	319	250	274	281	235	225	281	247	237	216	213	222
B2	658	792	779	743	759	759	711	743	718	779	838	778	678	801	817	765	725	829	749	768	663	689	621	658
B3	245	331	305	294	272	260	250	261	243	247	308	266	227	303	308	279	262	307	255	275	267	260	189	239
CL				2.113				1.607				1.776				1.724				2.108				1.962
CUL				0.230				-0.085				-0.051				-0.006				0.112				0.075

EATON	M				A				S				T				E				R			
Φ1=45°, Φ2=0°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	234	281	278	264	259	216	274	250	270	312	260	281	298	256	207	254	288	260	231	260	258	262	235	252
B2	886	730	905	840	908	846	775	843	1011	1010	958	993	915	919	839	891	928	825	800	851	904	698	672	758
B3	369	191	319	293	245	277	195	239	307	371	350	343	277	288	239	268	298	210	229	246	327	185	188	233
CL				2.179				2.377				2.538				2.512				2.277				2.012
CUL				0.108				-0.043				0.221				0.057				-0.054				-0.073

LUMINANCE CONTRAST MEASUREMENTS

KORRY	E				N				A				B				L				E			
Φ1=Φ2=15°	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG
B1	333	319	344	332	323	308	304	312	328	297	303	309	339	316	300	318	307	309	305	307	279	303	332	305
B2	682	746	715	714	665	871	729	755	794	757	769	773	831	881	808	840	805	830	689	775	611	651	523	595
B3	293	330	384	336	284	362	287	311	385	298	318	334	400	369	394	388	356	345	362	354	339	357	283	326
CL				1.152				1.422				1.500				1.639				1.523				0.953
CUL				0.011				-0.002				0.079				0.218				0.154				0.071
KORRY	M				A				S				T				E				R			
Φ1=Φ2=15°	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG
B1	356	330	325	337	335	343	342	340	350	352	350	351	371	366	344	360	354	323	360	346	330	338	354	341
B2	776	779	753	769	824	785	811	807	1025	950	700	892	828	766	677	757	749	672	672	698	717	677	552	649
B3	465	404	355	408	433	375	423	410	550	478	318	449	426	375	298	366	386	280	358	341	449	421	347	406
CL				1.283				1.373				1.543				1.101				1.018				0.904
CUL				0.211				0.207				0.279				0.017				-0.013				0.191
KORRY	E				N				A				B				L				E			
Φ1=Φ2=30°	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG
B1	410	393	417	407	396	396	365	386	395	354	389	379	408	364	394	389	385	356	366	369	345	362	392	366
B2	742	816	634	731	782	759	698	746	682	779	715	725	844	776	670	763	813	606	657	692	596	631	506	578
B3	429	456	353	413	441	390	343	391	365	410	386	387	469	409	350	409	517	360	435	437	416	447	341	401
CL				0.797				0.935				0.912				0.964				0.875				0.577
CUL				0.015				0.015				0.020				0.053				0.185				0.096
KORRY	M				A				S				T				E				R			
Φ1=Φ2=30°	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG	PT1	PT2	PT3	AVG
B1	354	323	327	335	331	339	332	334	338	355	351	348	394	360	345	366	351	337	342	343	336	348	366	350
B2	595	675	595	622	680	653	717	683	827	721	629	726	707	645	562	638	664	593	593	617	616	556	505	559
B3	309	359	283	317	398	333	414	382	477	364	328	390	403	392	287	361	429	331	360	373	436	371	381	396
CL				0.858				1.046				1.085				0.742				0.796				0.597
CUL				-0.053				0.143				0.120				-0.015				0.087				0.131

KORRY	E				N				A				B				L				E			
Φ1=45°, Φ2=0°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	293	279	276	283	260	271	254	262	264	261	308	278	282	262	264	269	313	274	263	283	281	283	310	291
B2	641	611	513	588	578	881	787	749	632	855	838	775	733	910	688	777	875	807	708	797	700	676	575	650
B3	317	278	236	277	216	353	300	290	199	351	372	307	253	331	225	270	377	245	312	311	324	264	259	282
CL				1.081				1.861				1.791				1.885				1.812				1.232
CUL				-0.020				0.107				0.107				0.001				0.099				-0.031
KORRY	M				A				S				T				E				R			
Φ1=45°, Φ2=0°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	302	255	278	278	286	266	249	267	258	298	272	276	316	268	280	288	262	278	317	286	275	276	289	280
B2	776	682	605	688	666	696	713	692	753	772	690	738	730	663	685	693	678	765	688	710	653	641	684	659
B3	501	357	244	367	285	248	289	274	292	277	287	285	275	215	283	258	256	287	289	277	302	284	399	328
CL				1.471				1.591				1.675				1.405				1.487				1.355
CUL				0.320				0.026				0.034				-0.105				-0.029				0.173
STACO	E				N				A				B				L				E			
Φ1=Φ2=15°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	1643	1422	1395	1487	1304	1320	1284	1303	1152	1228	1554	1311	1004	1141	1413	1186	1534	1159	1376	1356	1465	1177	1211	1284
B2	865	3512	1590	1989	1285	1467	1611	1454	1496	1673	2150	1773	2476	2650	2048	2391	1857	2012	1459	1776	1181	735	731	882
B3	708	3282	1235	1742	1081	1281	1500	1287	1316	1206	1952	1491	2250	2232	1631	2038	1672	1694	1216	1527	1119	676	634	810
CL				0.338				0.116				0.352				1.016				0.309				-0.313
CUL				0.172				-0.012				0.137				0.718				0.126				-0.370
STACO	M				A				S				T				E				R			
Φ1=Φ2=15°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	1440	1534	1290	1421	1583	1933	1446	1654	1432	1023	1378	1278	1234	1299	1272	1268	1382	1467	1255	1368	1224	1299	1435	1319
B2	1549	1771	1875	1732	1806	1445	2042	1764	1492	2130	1043	1555	1518	849	1787	1385	2276	1878	1552	1902	1548	1833	1369	1583
B3	1441	1646	1618	1568	1750	1376	1918	1681	1427	2010	941	1459	1439	804	1552	1265	2322	1731	1450	1834	1513	1884	1397	1598
CL				0.218				0.067				0.217				0.092				0.390				0.200
CUL				0.103				0.017				0.142				-0.003				0.341				0.211

LUMINANCE CONTRAST MEASUREMENTS

STACO	E				N				A				B				L				E			
Φ1=Φ2=30°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	1435	1626	1719	1593	1760	1669	1548	1659	1613	1597	1690	1633	1445	1291	1569	1435	1348	1180	1619	1382	1113	1484	1403	1333
B2	1831	1919	2020	1923	1547	1718	1684	1650	1499	1940	1797	1745	1529	1427	1849	1602	1297	1750	1769	1605	1427	1102	1001	1177
B3	1697	1685	1825	1736	1465	1637	1587	1563	1318	1800	1611	1576	1343	1268	1642	1418	1208	1629	1674	1504	1357	1017	924	1099
CL				0.207				-0.006				0.069				0.116				0.161				-0.118
CUL				0.089				-0.058				-0.035				-0.012				0.088				-0.176

STACO	M				A				S				T				E				R			
Φ1=Φ2=30°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	1701	1819	1481	1667	1717	1714	1761	1731	1674	1639	1767	1693	1243	1461	1377	1360	1453	1518	1500	1490	1279	1401	1435	1372
B2	1825	1383	1535	1581	1862	1572	1374	1603	1406	1637	1547	1530	1371	1244	1601	1405	1501	1645	1345	1497	1662	1429	1363	1485
B3	1742	1311	1468	1507	1815	1533	1323	1557	1332	1542	1464	1446	1306	1190	1529	1342	1465	1589	1314	1456	1626	1398	1317	1447
CL				-0.052				-0.074				-0.096				0.033				0.004				0.082
CUL				-0.096				-0.100				-0.146				-0.014				-0.023				0.055

STACO	E				N				A				B				L				E			
Φ1=45°, Φ2=0°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	423	293	301	339	367	411	332	370	310	353	372	345	320	357	313	330	414	323	292	343	360	369	367	365
B2	599	833	634	689	693	849	685	742	617	562	564	581	422	550	537	503	480	536	521	512	585	605	494	561
B3	422	325	346	364	325	393	482	400	344	358	341	348	275	324	345	315	315	246	301	287	475	441	309	408
CL				1.031				1.006				0.684				0.524				0.494				0.536
CUL				0.075				0.081				0.008				-0.046				-0.162				0.118

STACO	M				A				S				T				E				R			
Φ1=45°, Φ2=0°	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG	PT 1	PT 2	PT 3	AVG
B1	339	284	387	337	274	335	286	298	362	352	364	359	359	407	318	361	295	291	382	323	412	342	338	364
B2	525	757	547	610	366	429	566	454	590	455	339	461	521	503	373	466	405	771	414	530	395	539	369	434
B3	415	596	374	462	264	303	473	347	532	333	269	378	452	416	274	381	255	681	278	405	315	410	308	344
CL				0.811				0.521				0.284				0.289				0.643				0.193
CUL				0.371				0.162				0.052				0.054				0.254				-0.054

LUMINANCE CONTRAST SUMMARY
PAGE 1 OF 2

AOI		E	N	A	B	L	E	M	A	S	T	E	R
$\Phi_1=\Phi_2=15°$	C_L	1.313	1.227	1.352	1.215	1.260	1.000	1.143	1.081	1.117	1.051	0.996	1.204
$\Phi_1=\Phi_2=15°$	$\|C_{UL}\|$	0.091	0.026	0.095	0.020	0.067	0.006	0.044	0.038	0.008	0.073	0.013	0.093
$\Phi_1=\Phi_2=30°$	C_L	0.514	0.534	0.511	0.474	0.536	0.465	0.433	0.505	0.492	0.517	0.547	0.606
$\Phi_1=\Phi_2=30°$	$\|C_{UL}\|$	0.001	0.081	0.009	0.084	0.006	0.004	0.030	0.028	0.007	0.054	0.041	0.088
$\Phi_1=45°$, $\Phi_2=0°$	C_L	1.639	1.570	1.619	1.412	1.642	1.429	1.469	1.580	1.338	1.493	1.620	1.585
$\Phi_1=45°$, $\Phi_2=0°$	$\|C_{UL}\|$	0.004	0.008	0.043	0.081	0.015	0.080	0.032	0.065	0.021	0.002	0.088	0.008
EATON		**E**	**N**	**A**	**B**	**L**	**E**	**M**	**A**	**S**	**T**	**E**	**R**
$\Phi_1=\Phi_2=15°$	C_L	0.475	0.457	0.465	0.474	0.523	0.197	0.714	0.876	0.820	0.381	0.577	0.485
$\Phi_1=\Phi_2=15°$	$\|C_{UL}\|$	0.012	0.047	0.024	0.024	0.098	0.113	0.046	0.158	0.119	0.180	0.024	0.045
$\Phi_1=\Phi_2=30°$	C_L	0.419	0.458	0.318	0.467	0.138	0.149	0.483	0.474	0.689	0.391	0.408	0.228
$\Phi_1=\Phi_2=30°$	$\|C_{UL}\|$	0.057	0.078	0.034	0.131	0.083	0.021	0.004	0.018	0.200	0.016	0.077	0.038
$\Phi_1=45°$, $\Phi_2=0°$	C_L	2.113	1.607	1.776	1.724	2.108	1.962	2.179	2.377	2.538	2.512	2.277	2.012
$\Phi_1=45°$, $\Phi_2=0°$	$\|C_{UL}\|$	0.230	0.085	0.051	0.006	0.112	0.075	0.108	0.043	0.221	0.057	0.054	0.073
KORRY		**E**	**N**	**A**	**B**	**L**	**E**	**M**	**A**	**S**	**T**	**E**	**R**
$\Phi_1=\Phi_2=15°$	C_L	1.152	1.422	1.500	1.639	1.523	0.953	1.283	1.373	1.543	1.101	1.018	0.904
$\Phi_1=\Phi_2=15°$	$\|C_{UL}\|$	0.011	0.002	0.079	0.218	0.154	0.071	0.211	0.207	0.279	0.017	0.013	0.191
$\Phi_1=\Phi_2=30°$	C_L	0.797	0.935	0.912	0.964	0.875	0.577	0.858	1.046	1.085	0.742	0.796	0.597
$\Phi_1=\Phi_2=30°$	$\|C_{UL}\|$	0.015	0.015	0.020	0.053	0.185	0.096	0.053	0.143	0.120	0.015	0.087	0.131
$\Phi_1=45°$, $\Phi_2=0°$	C_L	1.081	1.861	1.791	1.885	1.812	1.232	1.471	1.591	1.675	1.405	1.487	1.355
$\Phi_1=45°$, $\Phi_2=0°$	$\|C_{UL}\|$	0.020	0.107	0.107	0.001	0.099	0.031	0.320	0.026	0.034	0.105	0.029	0.173

LUMINANCE CONTRAST SUMMARY
PAGE 2 OF 2

STACO		E	N	A	B	L	E	M	A	S	T	E	R
$\Phi_1=\Phi_2=15°$	C_L	0.338	0.116	0.352	1.016	0.309	-0.313	0.218	0.067	0.217	0.092	0.390	0.200
$\Phi_1=\Phi_2=15°$	$\lvert C_{UL}\rvert$	0.172	0.012	0.137	0.718	0.126	0.370	0.103	0.017	0.142	0.003	0.341	0.211
$\Phi_1=\Phi_2=30°$	C_L	0.207	-0.006	0.069	0.116	0.161	-0.118	-0.052	-0.074	-0.096	0.033	0.004	0.082
$\Phi_1=\Phi_2=30°$	$\lvert C_{UL}\rvert$	0.089	0.058	0.035	0.012	0.088	0.176	0.096	0.100	0.146	0.014	0.023	0.055
$\Phi_1=45°$, $\Phi_2=0°$	C_L	1.031	1.006	0.684	0.524	0.494	0.536	0.811	0.521	0.284	0.289	0.643	0.193
$\Phi_1=45°$, $\Phi_2=0°$	$\lvert C_{UL}\rvert$	0.075	0.081	0.008	0.046	0.162	0.118	0.371	0.162	0.052	0.054	0.254	0.054

LUMINANCE MEASUREMENTS
DISPLAY AVERAGE AT 15 FL

AOI	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	15.7	14.2	14.4	15.7	16.2	16.6	11.3	14.1	11.0	13.8	15.4	15.1
Point 2	14.1	13.8	14.9	13.9	15.1	16.1	13.6	14.2	11.6	15.4	13.8	17.0
Point 3	14.9	14.1	12.5	13.2	15.0	13.9	13.3	13.7	12.3	13.9	15.7	16.9
Character Avg	14.9	14.0	13.9	14.2	15.4	15.5	12.7	14.0	11.6	14.4	15.0	16.3
Display Avg	14.3											
CTC Uniformity	1.40											

EATON	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	5.64	6.57	7.06	5.65	5.79	4.78	19.2	19.6	25.0	24.8	23.1	21.0
Point 2	6.27	6.88	6.01	6.29	6.32	5.04	18.8	23.4	22.1	24.8	22.1	19.1
Point 3	6.37	6.10	6.94	6.66	5.91	5.07	20.3	21.3	20.9	21.5	20.6	17.7
Character Avg	6.10	6.52	6.67	6.20	6.01	4.96	19.45	21.4	22.7	23.7	22.0	19.3
Display Avg	13.7											
CTC Uniformity	4.77											

KORRY	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	9.92	12.4	14.6	16.7	16.9	13.2	11.7	16.0	18.9	19.4	16.8	13.8
Point 2	10.4	16.6	16.1	19.9	14.3	14.9	13.8	18.7	20.3	18.0	18.8	12.6
Point 3	8.87	16.6	15.5	15.8	14.5	11.6	15.3	17.1	17.2	16.4	14.9	10.1
Character Avg	9.74	15.2	15.4	17.4	15.2	13.2	13.6	17.3	18.8	17.9	16.8	12.2
Display Avg	15.2											
CTC Uniformity	1.93											

STACO	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	16.5	27.4	19.6	14.0	20.7	13.6	6.38	8.44	4.75	3.02	4.78	4.28
Point 2	35.1	28.5	14.6	17.4	27.1	16.7	8.56	8.31	6.10	3.79	4.55	4.16
Point 3	24.0	20.4	17.2	15.9	28.8	15.3	9.67	6.01	5.41	3.90	4.71	2.63
Character Avg	25.2	25.4	17.1	15.8	25.5	15.2	8.20	7.59	5.42	3.57	4.68	3.69
Display Avg	13.1											
CTC Uniformity	7.15											

LUMINANCE MEASUREMENTS
DISPLAY AVERAGE AT 1 FL

AOI	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	0.921	0.938	0.865	0.989	1.045	1.107	0.674	0.863	0.754	0.847	0.953	1.019
Point 2	0.879	0.856	0.912	0.892	0.899	1.030	0.858	0.949	0.649	0.920	0.857	0.973
Point 3	0.991	0.871	0.751	0.830	0.955	0.886	0.834	0.860	0.775	0.820	0.940	1.120
Character Avg	0.930	0.888	0.843	0.904	0.966	1.008	0.789	0.891	0.726	0.862	0.917	1.037
Display Avg	0.897											
CTC Uniformity	1.43											

EATON	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	0.262	0.316	0.324	0.244	0.241	0.193	1.73	1.88	2.47	2.52	2.49	2.38
Point 2	0.291	0.325	0.275	0.282	0.269	0.206	1.73	2.21	2.31	2.60	2.40	2.12
Point 3	0.297	0.283	0.315	0.292	0.249	0.207	1.88	2.02	2.05	2.22	2.23	1.98
Character Avg	0.283	0.308	0.305	0.273	0.253	0.202	1.78	2.04	2.28	2.45	2.37	2.16
Display Avg	1.22											
CTC Uniformity	12.1											

KORRY	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	0.423	0.467	0.611	0.727	0.767	0.615	1.10	1.50	1.72	1.74	1.45	1.21
Point 2	0.445	0.703	0.703	0.863	0.644	0.695	1.27	1.75	1.84	1.58	1.62	1.13
Point 3	0.371	0.695	0.652	0.686	0.662	0.531	1.42	1.58	1.57	1.47	1.31	0.921
Character Avg	0.413	0.622	0.655	0.759	0.691	0.614	1.26	1.61	1.71	1.60	1.46	1.09
Display Avg	1.04											
CTC Uniformity	4.14											

STACO	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	1.46	2.35	1.66	1.22	1.68	1.18	0.418	0.534	0.290	0.185	0.282	0.229
Point 2	3.06	2.30	1.22	1.50	2.26	1.55	0.527	0.506	0.374	0.223	0.267	0.251
Point 3	2.17	1.74	1.46	1.37	2.54	1.39	0.568	0.369	0.322	0.232	0.286	0.162
Character Avg	2.23	2.13	1.45	1.36	2.16	1.37	0.504	0.470	0.329	0.213	0.278	0.214
Display Avg	1.06											
CTC Uniformity	10.5											

LUMINANCE MEASUREMENTS
BOTTOM HALF-LEGEND AVERAGE AT 15 FL

AOI	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	15.7	14.2	14.4	15.7	16.2	16.6	11.3	14.1	11.0	13.8	15.4	15.1
Point 2	14.1	13.8	14.9	13.9	15.1	16.1	13.6	14.2	11.6	15.4	13.8	17.0
Point 3	14.9	14.1	12.5	13.2	15.0	13.9	13.3	13.7	12.3	13.9	15.7	16.9
Character Avg	14.9	14.0	13.9	14.2	15.4	15.5	12.7	14.0	11.6	14.4	15.0	16.3

Top Half Avg	14.7
Bottom Half Avg	14.0
Dual-Color Uniformity	1.05

EATON	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	2.73	3.34	3.39	2.68	2.75	2.19	11.2	11.6	14.9	14.9	13.8	13.4
Point 2	3.10	3.36	2.99	3.01	3.03	2.35	10.8	14.0	13.2	14.9	13.3	11.6
Point 3	3.09	2.97	3.33	3.20	2.85	2.38	12.2	12.8	12.6	12.9	12.6	10.2
Character Avg	2.98	3.22	3.23	2.96	2.88	2.31	11.4	12.8	13.5	14.2	13.2	11.8

Top Half Avg	2.93
Bottom Half Avg	12.8
Dual-Color Uniformity	4.38

KORRY	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	9.92	12.4	14.6	16.7	16.9	13.2	11.7	16.0	18.9	19.4	16.8	13.8
Point 2	10.4	16.6	16.1	19.9	14.3	14.9	13.8	18.7	20.3	18.0	18.8	12.6
Point 3	8.87	16.6	15.5	15.8	14.5	11.6	15.3	17.1	17.2	16.4	14.9	10.1
Character Avg	9.74	15.2	15.4	17.4	15.2	13.2	13.6	17.3	18.8	17.9	16.8	12.2

Top Half Avg	14.4
Bottom Half Avg	16.1
Dual-Color Uniformity	1.12

STACO	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	40.9	62.1	46.5	32.6	44.4	30.2	19.7	21.7	13.6	9.31	14.2	11.4
Point 2	83.5	68.4	34.4	41.2	59.0	39.9	22.0	24.2	17.6	11.2	13.2	12.3
Point 3	58.8	48.3	38.9	37.1	67.3	31.4	26.1	16.7	14.7	11.7	13.9	7.93
Character Avg	61.1	59.6	39.9	37.0	56.9	33.8	22.6	20.9	15.3	10.7	13.8	10.5

Top Half Avg	48.1
Bottom Half Avg	15.6
Dual-Color Uniformity	3.07

LUMINANCE MEASUREMENTS
BOTTOM HALF-LEGEND AVERAGE AT 1 FL

AOI	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	0.921	0.938	0.865	0.989	1.045	1.107	0.674	0.863	0.754	0.847	0.953	1.019
Point 2	0.878	0.856	0.912	0.892	0.899	1.030	0.858	0.949	0.649	0.920	0.857	0.973
Point 3	0.991	0.871	0.751	0.830	0.955	0.886	0.834	0.860	0.775	0.820	0.940	1.120
Character Avg	0.930	0.888	0.843	0.904	0.966	1.008	0.789	0.891	0.726	0.862	0.917	1.037

Top Half Avg	0.923
Bottom Half Avg	0.870
Dual-Color Uniformity	1.06

EATON	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	0.075	0.093	0.096	0.075	0.072	0.056	0.599	0.681	0.920	0.973	0.987	0.946
Point 2	0.086	0.093	0.083	0.084	0.082	0.060	0.633	0.801	0.863	1.008	0.923	0.841
Point 3	0.089	0.083	0.093	0.085	0.073	0.061	0.677	0.746	0.788	0.894	0.876	0.781
Character Avg	0.083	0.090	0.091	0.081	0.076	0.059	0.636	0.743	0.857	0.958	0.929	0.856

Top Half Avg	0.080
Bottom Half Avg	0.830
Dual-Color Uniformity	10.4

KORRY	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	0.250	0.287	0.353	0.427	0.458	0.371	0.751	1.02	1.18	1.20	0.993	0.827
Point 2	0.261	0.407	0.413	0.501	0.371	0.415	0.887	1.21	1.26	1.10	1.10	0.754
Point 3	0.222	0.401	0.375	0.405	0.388	0.327	0.979	1.07	1.08	0.990	0.895	0.612
Character Avg	0.244	0.365	0.380	0.444	0.406	0.371	0.872	1.10	1.17	1.10	1.00	0.731

Top Half Avg	0.368
Bottom Half Avg	0.995
Dual-Color Uniformity	2.70

STACO	E	N	A	B	L	E	M	A	S	T	E	R
Point 1	4.19	6.54	4.69	3.35	4.77	3.14	1.29	1.57	0.903	0.577	0.896	0.763
Point 2	8.53	6.48	3.40	4.11	6.58	4.00	1.67	1.65	1.18	0.693	0.795	0.811
Point 3	6.07	4.78	4.04	3.81	7.07	3.33	1.75	1.15	1.05	0.738	0.878	0.458
Character Avg	6.26	5.93	4.04	3.76	6.14	3.49	1.57	1.46	1.04	0.669	0.856	0.677

Top Half Avg	4.94
Bottom Half Avg	1.05
Dual-Color Uniformity	4.72

REFERENCES

[1] C. Adams, “Switch evolution—slow but steady,” *Avionics Magazine,* pp. 38-40, May 2003.

[2] U.S. Department of Defense, “Crew systems aircraft lighting handbook,” Washington, D.C., Military specification JSSG-2010-5, Oct. 30, 1998.

[3] D. Green and M. Milanovic, “Solid-state lighting offers ‘vices’ as well as ‘virtues,’” *Laser Focus World,* pp. 99-103, Sep. 2003.

[4] A. Mills, “Solid-state lighting—a world of expanding opportunities at LED 2002,” *III-Vs Review,* vol. 16, no. 1, pp. 30-33, Jan. 2003.

[5] Aerospace Optics Inc., “VIVISUN LED—the complete switch,” Fort Worth, TX, data sheet LED-12-2001-04, Rev. B, 2002.

[6] Aerospace Optics Inc., “VIVISUN series 95,” Fort Worth, TX, data sheet 95-1-86-3, Rev. 1, 1986.

[7] U.S. Department of Defense, “Human engineering design criteria,” Washington, D.C., Military specification MIL-STD-1472F, Aug. 23, 1999.

[8] S. Jennato and G. McKee, “What color is my LED?” *Photonics Spectra,* pp. 207-210, May 2001.

[9] C. Fatt, C. Wai, K. Peng and N. Faralunisia, “Trends in visible LEDs,” *Displays & Indicators Supplement to EE Product News,* pp. 14-15, Apr. 2002.

[10] C. Rios, “Choosing illumination for switches,” *Electronic Products,* pp. 31-32, Jun. 2003.

[11] W. Shawlee 2, “Avionics system design: designing with LEDs,” *Avionics Magazine,* Aug. 2001.

[12] U.S. Department of Defense, “William J. Perry,” Washington, D.C., [Online] Available: http://www.defenselink.mil/specials/secdef_histories/bios/perry.htm.

[13] U.S. Department of Defense, “Switches, push button, illuminated, general specification for,” Washington, D.C., Military specification MIL-PRF-22885F, Jan. 23, 1998.

[14] Illuminating Engineering Society of North America, “Nomenclature and Definitions for Illuminating Engineering,” New York, NY, American National Standard ANSI/IESNA RP-16-1996, Nov. 29, 1996.

[15] Photo Research, Inc., Chatsworth, CA, http://www.photoresearch.com

[16] Photo Research, “Instruction and maintenance manual for the Spectra® Pritchard® Photometer Model 1980A,” Chatsworth, CA, 1975.

[17] U.S. Department of Defense, “Switches, pushbutton, illuminated, 4-lamp replaceable incandescent or non-replaceable light emitting diode (LED),” Washington, D.C., Military specification MIL-PRF-22885/108D, Dec. 11, 2001.

[18] U.S. Department of Defense, “Switches, pushbutton, illuminated, 4-lamp,” Washington, D.C., Military specification MIL-PRF-22885/109B, Apr. 18, 2001.

[19] U.S. Department of Defense, “Panels, information, integrally illuminated,” Washington, D.C., Military specification MIL-P-7788F, Nov. 16, 1992.

[20] U.S. Department of Defense, “Lighting, aircraft, night vision imaging system (NVIS) compatible,” Washington, D.C., Military specification MIL-STD-3009, Feb. 2, 2001.

[21] Aerospace Optics Inc., Fort Worth, TX, http://www.vivisun.com

[22] Korry Electronics Co., Seattle, WA, http://www.korry.com