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All-Strobe Approach Lighting System: Research and Evaluation

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16. Abstract

In response to a congressional inquiry, the Federal Aviation Administration (FAA) Lighting Systems Office requested the FAA Airport Technology Research and Development Branch to conduct an evaluation of the effectiveness of an All-Strobe Approach Lighting System (ASALS) composed of 28 sequenced flashing lights for conveying required visual guidance information for a Category I precision approach. Contentions put forward by the developer of the ASALS are identified with special regard to the current standard for conducting Category I precision approaches, namely, the Medium-Intensity Approach Lighting System With Runway Alignment Indicator Lights (MALSR), which consists of 45 steady-burning lights and 5 strobe lights. The investigation consisted of assessing the validity of the vision science and performing flight evaluations of the new system.

The vision science was investigated by the FAA Office of Civil Aerospace Medical Institute (CAMI) and the Department of Transportation Volpe National Transportation Systems Center (VOLPE). One of the main contentions was that pilots could remain dark-adapted during an approach that would enable them to have better visual acuity after touchdown. However, the results of the CAMI and VOLPE investigations showed that the developer's contention was not valid. Many of the contentions were shown to be based on misinterpretations of visual phenomena and, thus, cannot be used as a rationale for changing airport lighting systems.

Flight evaluations were conducted by the FAA Airport Safety Technology Research and Development Section. A series of flight tests were conducted in which objective data in the form of measurements taken from the aircraft's data collection instruments were analyzed to indicate possible disparities between the two approach lighting systems that could affect pilot performance. These objective results were combined with subject interviews and questionnaires to give insight into the performance characteristics of the ASALS. These evaluation flights confirmed the CAMI and VOLPE findings. One hundred percent of the subject pilots concurred that the ASALS did not improve their visual acuity after touchdown and did not provide the necessary visual cues required for Category I precision approaches. After all factors were taken into consideration, the Developer's contentions were not confirmed by the proposed ASALS.

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LIST OF SYMBOLS AND ACRONYMS

ACY	Atlantic City International Airport
ALS	Approach light system
ALSF-2	High-Intensity Approach Lighting System With Sequenced Flashing Lights
ASALS	All-Strobe Approach Lighting System
CAMI	Civil Aerospace Medical Institute
CAT	Category
cd	Candela
cd/m^2	Candela-steridian per square meter
cd-sr	Candela-steridian
DCI	Data collection instruments
DH	Decision height
DOT	Department of Transportation
FAA	Federal Aviation Administration
GPS	Global positioning system
IESNA	Illuminating Engineering Society of North America
ILS	Instrument landing system
LAX	Los Angeles International Airport
m	Meter
m^2	Meter squared
MALSR	Medium-Intensity Approach Lighting System With RAIL
MOR	Meteorological optical range
ms	Milliseconds
NIST	National Institute of Standards and Technologies
NTSB	National Transportation Safety Board
ODALS	Omnidirectional Approach Light System
RAIL	Runway alignment indicator lights
RALST	Reconfigurable Approach Light System Testbed
REIL	Runway end identification lights
RVR	Runway visual range
s	Second
VASI	Visual approach slope indicator
VFR	Visual Flight Rules
VOLPE	DOT Volpe National Transportation Systems Center

EXECUTIVE SUMMARY

In response to a Congressional inquiry, the Federal Aviation Administration (FAA) Lighting Systems Office requested the FAA Airport Technology Research and Development Branch to conduct an investigation of an All-Strobe Approach Lighting System (ASALS). The purpose was to examine the system's effectiveness as a possible replacement for the current standard used for Category I precision approaches, namely, the Medium-Intensity Approach Lighting System With Runway Alignment Indicator Lights (MALSR). The ASALS is composed entirely of 28 sequenced flashing lights that are intended to convey all required visual guidance information for a Category I precision approach. A number of contentions put forward by the developer of the ASALS are identified in this technical note with special regard to the developer's claims that the MALSR should be replaced by the ASALS.

The FAA Office of Aerospace Medicine Civil Aerospace Medical Institute (CAMI) conducted a study investigating the validity of the Developer's claims with respect to prior and current vision science and performed an accident database search to find if glare conditions from approach lighting systems had contributed to aircraft accidents or incidents in the past. The arguments of the Developer and related references were examined in a separate study with respect to aviation applications by the Department of Transportation Volpe National Transportation Systems Center (VOLPE).

Flight evaluations were coordinated by the FAA Airport Safety Technology Research and Development section personnel. These flight evaluations simulated Category I precision approaches that pilots would normally encounter during poor visibility conditions when conducting precision approaches. Results from an assessment of the subject pilots' ability to track the extended runway centerline during approach, the ASALS's ability to convey required visual cues, the level of comfort with the ASALS, and visual acuity after rollout are presented in this technical note.

The Developer claimed that, in contrast to the FAA MALSR, the ASALS would enable a pilot's eyes to maintain a state of dark adaptation upon landing, and that this state of dark adaptation would greatly improve vision on the runway after landing. An extensive review of accident reports did not support the premise that there were any appreciable visual problems associated with MALSR operations. Furthermore, scientific evidence cited by the Developer in support of the ASALS was either a misinterpretation of the results, omitted important related data, or was not demonstrated to be relevant.

The nonsupporting results of the CAMI and VOLPE investigations were confirmed by the findings from the ASALS flight evaluations. One hundred percent of the subject pilots concurred that their visual acuity after touchdown with the ASALS was not improved over experiences with the MALSR. In addition, some pilots indicated that it took longer for them to get oriented for landing with the ASALS, most likely due to the delay in the sequence of lights relative to the presence of a continuous set of lights on the MALSR. All factors considered, the developer's contentions were not confirmed by the proposed ASALS.

INTRODUCTION

PURPOSE.

The Federal Aviation Administration (FAA) Lighting Systems Office initiated a study in response to a congressional inquiry with contentions by a company, hereafter referred to as the Developer, that an approach lighting system (ALS) with specially designed high-intensity condenser discharge lamps (strobes) could increase the accuracy of a pilot on approach to (1) a runway in Category (CAT) I precision approach conditions, (2) the runway visual range (RVR), and (3) visual acuity after touchdown compared to the FAA-approved Medium-Intensity Approach Lighting System with Runway Alignment Indicator Lights (MALSR).

The study addressed two related areas of interest: (1) an assessment of the contentions of the Developer and (2) a flight evaluation of the Developer's proposed system. These studies were conducted by the FAA Office of Aerospace Medicine Civil Aerospace Medical Institute (CAMI), the Department of Transportation (DOT) Volpe National Transportation Systems Center (VOLPE), and the FAA Airport Safety Technology Research and Development Section.

BACKGROUND.

MEDIUM-INTENSITY APPROACH LIGHTING SYSTEM. The MALSR used today was adopted by the FAA from a portable system tested by the United States Air Force shortly after World War II. The system was adapted for civilian aviation, which was designed to provide visual cues under CAT I precision approach conditions when RVR is between 2400 and 1800 ft, and presented to the pilots as an economical alternative to a more robust ALS, such as the High-Intensity Approach Lighting System With Sequenced Flashing Lights (ALSF-2) designed to operate in CAT II/III precision approach conditions with RVR below 1800 ft. The MALSR is used during precision approaches in conjunction with an instrument landing system (ILS) and glide slope indicator.

A typical MALSR system is composed of 18 PAR-56 steady-burning lamps located at the runway threshold, 9 towers spaced every 200 ft along the extended runway centerline with bars of 5 PAR-38 steady-burning lamps, and 5 sequenced, flashing strobe lights called runway alignment indicator lights (RAIL). The RAIL units are sequenced such that the furthest unit from the runway threshold illuminates first and turns off as the next closest unit illuminates and turns off. The sequence continues to the closest unit to the runway threshold, after which time, the cycle is repeated.

The strobe lights were designed to be conspicuous and to lead a pilot into the correct orientation of the approach. Pilots often refer to these strobes as rabbits, as they are chased into the steady-burning lights of the system. At the 1000-ft station, with station referring to distance from the runway threshold, there are three light bars (a total of 15 PAR-38 steady-burning lamps) that form a crossbar that serves as a reference point used by pilots as a distance-to-go mark. A diagram of a MALSR configuration is shown in figure 1. A typical installation, displaying the 1000-ft crossbar as seen from the ground, is shown in figure 2. (Note: the photograph was taken facing the runway threshold between the 1200- and 1400-ft stations.)

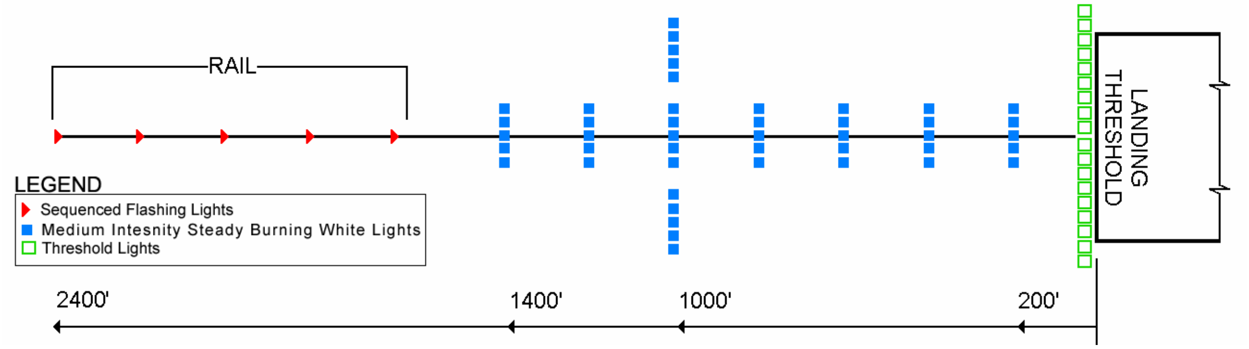

Figure 1. Diagram of the Configuration of a MALSR

Figure 2. A MALSR Showing the 1000-ft Station Crossbar

THE ALL-STROBE APPROACH LIGHTING SYSTEM. The Developer proposed an alternative to the MALSR called the All-Strobe Approach Lighting System (ASALS), which consists of 28 omnidirectional, sequenced, white flashing lights and a pair of modified runway end identification lights (REIL). These modified REIL units are flashing strobe lights that are located on the corners of the runway, offset by 75 ft, and contain no filters (white light) facing the ALS but contain red filters when facing the runway to give pilots approaching from the opposite side of the ALS a go-no-further indication. Standard REIL units are currently approved and used as either stand-alone units or as part of other ALSs, such as a Visual Flight Rules (VFR) ALS, known as the Omnidirectional Approach Light Systems (ODALS). The ODALS is also composed of omnidirectional strobe light fixtures, but the units are located only in the extended runway centerline and only one per tower.

The Developer claimed there are unique benefits to the optical heads used in the strobe lights of the ASALS. The 0-degree vertical intensity is claimed to be less than half the intensity of the optical head at a 2-degree vertical intensity. This is purported to reduce the effect of extraneous light, which is not usable by the pilot, emanating from the fixtures and reaching the ground or residents living near the system. (Note that these are proposed benefits of the design of the ASALS.)

The configuration of the system would be similar to the MALSR, with strobe light fixtures mounted on towers spaced at 200-ft intervals along the extended runway centerline from the runway threshold. Between the 2400-ft station and the 1200-ft station, the towers would have one, single strobe light fixture. Between the 1400-ft station and the 200-ft station, the towers would hold bars containing three strobe lights each. A crossbar would be formed at the 1000-ft station with three bars (a total of five strobes at that station), providing a distance-to-go indication to the pilot. Upon initial illumination, project personnel indicated to the Developer that the 1000-ft station was not identifiable. The Developer then removed two strobes from the 1400-ft station and two strobes from the 1200-ft station and mounted them at the 1000-ft position, making the 1000-ft station three bars of three strobes (a total of nine strobes at that station). A diagram of the final ASALS is shown in figure 3.

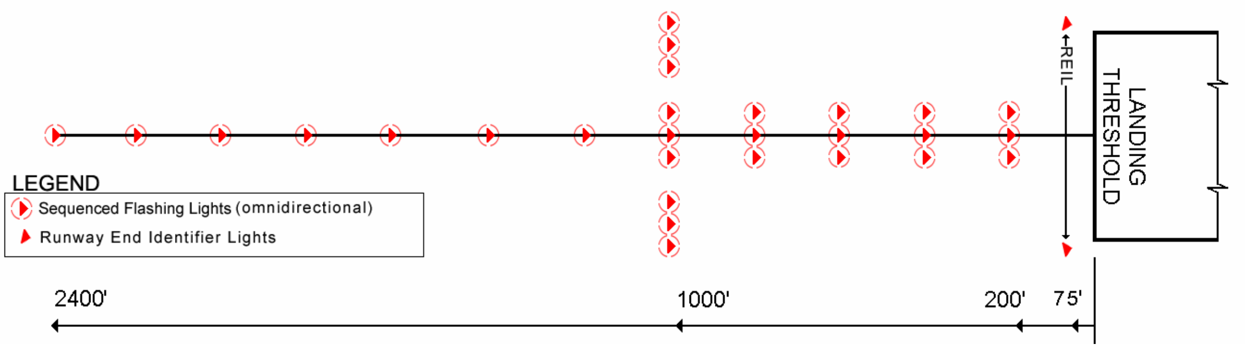

Figure 3. Diagram of the Configuration of an ASALS

The sequence of the flashing lights run from the furthest outboard to the closest inboard strobe light from the runway threshold, similar to the RAIL fixtures of the MALSR. However, at the 1000-ft station crossbar, all lights illuminate at the same time, while the strobe light fixtures across the entire bar of every tower from the 1000-ft to the 200-ft station illuminate at the same time in sequence. The REIL fixtures illuminate after the 200-ft station light bar. The diagram of the ASALS configuration, which also shows the sequence that the light units illuminate, is shown in figure 4.

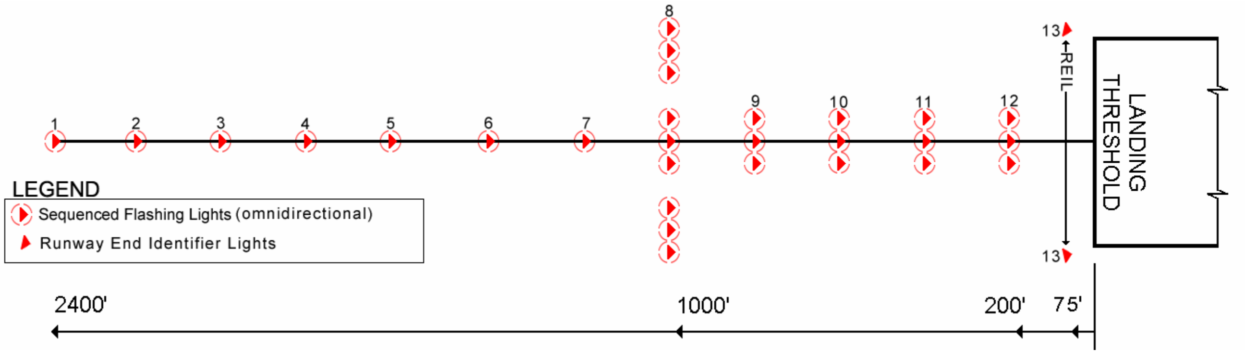

Figure 4. Diagram of the Configuration of an ASALS Showing the Sequence of Flashing Lights

The Developer states that each strobe light fixture flashes once per second in location sequence towards the runway. This indicates that, as there are 12 stations and one set of two REIL at the threshold, the time it takes the sequence of the system to complete one cycle is dependent on the duration of illumination of the light units at each of the 13 stations and the delay between them with the cycle repeating once per second. The Developer claims that the optical heads provide 5000 effective candlepower, the effective intensity of the light provided that the light was steady burning in all directions usable by the pilot. Additionally, the time duration from strobe light fixture illumination to light extinguishment was claimed to be 3 milliseconds (ms) = 0.003 seconds. The Developer's claims were not verified and were regarded as statements of fact during these tests. Details as to the time sequencing of the lights, specifically the delay in the sequence, were not provided by the Developer.

DISCUSSION

A REVIEW OF JUSTIFICATIONS FOR THE ASALS.

The ASALS proposal was not solicited by the FAA, since no history of accidents or related complaints involving MALSR performance had presented cause for alarm. Nevertheless, the Developer raised a number of arguments supporting the adoption of an ASALS, which are summarized below:

- As justified by equations produced by Blondel and Rey in 1911 as they appear adapted for use in FAA Specification E-1100a, "Photometric Test Procedures for Condenser-Discharge Lights," [1], steady-burning lights reduce the light intensity that reaches the eye by one-fifth. This is due to contractions of the eye's pupil from a wider-opening diameter to a smaller-opening diameter, caused by exposure to steady-burning lights. This, in turn, reduces the visual acuity of the pilot during a landing approach and just after touchdown.

- The effect of seeing one-fifth of the light intensity that reaches the eye subsequently reduces the RVR of the pilot to a distance less than half as far.

- The equations of Blondel and Rey [2] describe a universal visual response that shows a flashing light, on for durations of much less than 0.2 seconds, is five times more noticeable than a steady-burning light. This is often referred by the Developer as the "factor of 5 enhancement."

- The equations of Blondel and Rey [2] describe the response time for the loss of dark adaptation.

- As justified by studies conducted by Loewenfield in 1979 [3], a flashing light on for a very short duration would not cause the same amount of pupillary restriction as would a steady-burning light.

- There is a correlation between the pupil-opening diameters noted in the Loewenfield study [3] and the proposed 5:1 advantage in light intensity of the flashing lights versus the steady-burning lights.

- The Developer suggested that the use of an ASALS may prevent runway accidents, such as the 1991 Los Angeles International Airport (LAX) crash where a USAir 737 collided with a SkyWest Airlines' Metroliner while landing, which killed 34 passengers and crewmembers (NTSB/AAR-91/08:PB91-910409) [4].

It is important to note that these arguments appeared in a series of letters, correspondences, and articles provided to the FAA in support of the Developer's contentions. The cited sources mentioned above were included in these materials. These sources and arguments are examined in this technical note.

THEORIES EXPLAINING VISUAL PHENOMENA AND RESPONSE. The work of Blondel and Rey [2], along with other vision researchers such as Allard, Schmidt-Clausen, and Ohno-Clausen, have been used with consistent results in measuring the effective intensity of flashing-light sources for years [5]. Listed with respect to their authors, the integral form of Blondel-Rey equations, Allard's differential form, the Form Factor method, and the Modified Allard method are all used by visual science researchers of such governing agencies as the FAA, DOT, and National Institute of Standards and Technologies (NIST).

The reason that there are multiple methods for measuring the effective intensity of light is that there is no single equation that completely describes the human visual response to light. Often, equations and methods, such as the ones previously stated, require certain assumptions be met in order to use them. As an example, many equations that model visual range, which may be thought of as the farthest distance out to which a light source is noticeable, require that the light be described as a point source. In the instance of how noticeable the steady-burning lights of the MALSR are versus the flashing lights of the ASALS, the use of those visual range equations may not be used justifiably to define an advantage in perception.

ALSs are designed to provide visual guidance to pilots flying precision approaches in CAT I precision approach conditions. At distances normally associated with a pilot reaching a decision height (DH) along the glide slope of an approach, a steady-burning MALSR is much more adequately described as an extended source of light over an area rather than a point source. The levels of illuminance at the pilot's eye, which is light intensity on an area in this report described in terms of lux or candela-steridian (cd-sr) per square meter (m^2) (cd/m^2), will not accurately be predicted by such point source equations at that distance. This will be described further in the Evaluation Approach section by the results of the VOLPE and CAMI studies.

THE PROCESS OF VISUAL ADAPTATION. As referenced from the Illuminating Engineering Society of North America (IESNA) Lighting Handbook, Ninth Edition, [6] the human visual system is capable of adapting to an enormous range, approximately 12 log units, of encountered illuminances. These light levels are based on retinal illuminance, which is the illuminance at the eye dependent on surface illuminance. These levels fall into three categories: pupil area, ocular transmittance (the material of the eye and its light transmitting characteristics), and angle of the source to the direct line of sight.

Photopic vision occurs when retinal illuminances are above 3 cd/m^2 and is usually associated with daylight or brightly lit conditions. Receptors called cones, located in the fovea of the eye, are responsible for receiving illuminances in this range. Scotopic vision occurs at illuminances below 0.0001 cd/m^2 when visual acuity is resolved in the periphery of the fovea of the eye by receptors called rods. Scotopic vision is usually associated with very dark nights or near completely unlit areas. Mesopic vision occurs at illuminances in the intermediate range; this type of vision is likely to be encountered in the cockpit and is examined within the context of this technical note.

The process of visual adaptation involves a change in pupil size, neural adaptation, and photochemical adaptation. Photochemical adaptation involves the process of losing and regenerating photopigments after their interaction with light. When light is absorbed, the resulting chemical reaction in the eye produces electrical signals that the brain interprets as light. The loss of photopigments is called bleaching. During dark conditions, the eye regenerates these pigments in the order of minutes after exposure to high levels of illuminance. Cones recover to maximum sensitivity from 10 to 12 minutes after exposure, and rods recover to maximum sensitivity in an hour or more. In brief, neural adaptation is a very fast process that occurs in a time span of approximately 200 ms after exposure to light when photochemical response has not happened. The process of neural adaptation is very effective in visually adapting to illuminances of 2 to 3 log units in the photopic vision range.

Concerning changes in pupil size and directly quoting from the IESNA Lighting Handbook,

> "The iris constricts and dilates in response to increased and decreased levels of retinal illumination. Iris constriction has a shorter latency and is faster (approximately 0.3-s) than dilation (approximately 1.5-s). There are wide variations in pupil sizes among individuals and for any particular individual at different times for the same visual stimulus. Pupil size is influenced by emotions, such as fear or elation. Thus, for a given luminous stimulus, some uncertainty is associated with an individual's pupil size until it is measured. The typical range in pupil diameter for young people is from 3-mm for high retinal illuminances to 8-mm for low retinal illuminances. This change in pupil size in response to retinal illumination can only account for a 1.2 log unit change in sensitivity to light."

An observer who has completely recovered and is subjected to light of very low illuminance is called fully dark adapted. Any model of the visual adaptation process is multivariate, depending on many different factors including pupil size. Pupil response to the intensity of a light source is not directly proportional in a linear fashion to the ability of the observer to see and recognize the context of visual guidance information displayed by the presence of multiple light sources.

The work of Irene Loewenfeld, during her experiments of 1979 [3], characterized pupillary response to illuminated light sources for an extended period of 1 second compared to light sources illuminated for a brief period of 5 ms. The relevance of this study to the process of visual adaptation and potential use in approach lighting is addressed in the Evaluation Approach section of this report.

BLONDEL-REY EQUATION. The work of Blondel and Rey in 1911 that studied the detection of flashing lights that emit threshold illuminances, or the lowest level of detectable light intensity, was adapted for use by the FAA in Specification E-1100a published on March 21, 1968 [1]. On page 3 of reference 1, the Blondel-Rey equation relates the effective intensity of light I_e as a function of the instantaneous intensity I at any particular time, and the duration of the flash $\tau = t_2 - t_1$ where t_1 is the start of the flash and t_2 is the end of the flash. This equation is reproduced as equation 1.

$$I_e = \frac{\int_{t_1}^{t_2} I \cdot dt}{0.2 + (t_2 - t_1)} \tag{1}$$

If the time duration of the flash τ is very small in comparison to the constant of 0.2, then its addition in the denominator of equation 1 can be removed without introducing significant error. This reduces the coefficient of the integral to a factor of $5 = 1 / 0.2 \approx 1 / (0.2 + (t_2 - t_1))$. This factor is times the integral of the instantaneous intensity of the flashing-light source over the duration of the flash.

FAA Specification E-1100a also simplifies equation 1 so it may be used in a laboratory setting. Instead of starting a measurement of light intensity as soon as any light is emitted, measurements begin as soon as the effective intensity I_e is equal to the instantaneous intensity I at time t_1, which is where the measurement begins. If the assumption that $I_e = I$ is made also for when the measurement of light is ended at time t_2, then equation 1 may be approximated by

$$I_e = \frac{\int_{t_1}^{t_2} I \cdot dt}{0.2 + (t_2 - t_1)} \approx 5\bar{I}(t_2 - t_1) \tag{2}$$

where $\bar{I}$ = average intensity of the flashing source during the duration of measurement.

This means the effective intensity I_e may be approximated by five times the product of the average intensity of the source and the duration of the measurement of the flash. This is where the Developer incorrectly reaches the conclusion that there is a “factor of 5 enhancement” in light intensity and the associated enhancement in doubling RVR over steady-burning lights. While there is a factor of 5 enhancement in equation 2, a second important factor is present, namely, the time duration $(t_2 - t_1)$, which can be very small, e.g., 3 ms in the case of the Developer’s claim. Consequently, the average intensity must attain a much larger value to compensate for this short duration, and under the assumptions necessary for equation 2 to hold, this average intensity would be well beyond the light-intensity level necessary to appreciably limit the loss of dark adaptation. To accomplish the goal of limiting dark adaptation loss at distances encountered by a pilot on approach over an ALS prior to crossing the runway threshold, continual adjustments in intensity would have to be made to limit the illuminance that reaches the pilot as the aircraft distance to the system decreases. A more detailed explanation of this issue and the claimed enhancement in RVR through use of the ASALS will be addressed in the Evaluation Approach section of this report.

Although the Blondel-Rey method, as adapted in FAA Specification E-1100a, is convenient and accurate in many cases, the results of equation 2 does not match the results of other methods in some instances when the waveform differs. The waveform describes how the instantaneous light intensity varies between times t_1 and t_2.

Graphs of different waveforms are shown in figure 5, as taken from a NIST document, "Modified Allard Method for Effective Intensity of Flashing Lights" [5]. An example of a waveform would be the light intensity remaining constant for the duration of the measurement, which is a square wave. The square wave is what most would expect from a light source, an immediate and constant application of light intensity when the source is turned on followed by an immediate and complete cessation of light intensity when the source is turned off.

The square wave is modeled very well by the Blondel-Rey method, as the average intensity exactly matches the instantaneous intensity at any point in the duration of the measurement. An example of such a square wave is the "half-square" waveform, also known as a rectangular flash, labeled #1 in figure 5, where light intensity drops completely midway through the measurement. Other more complicated examples of waveforms are also shown in this figure.

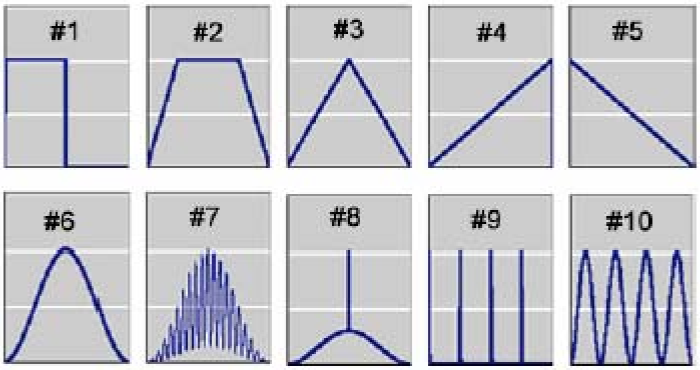

Figure 5. Examples of Different Waveforms

Recent studies have indicated that there is a dependence on the waveform used by the flashing-light source and its effective intensity. This will be addressed in the Evaluation Approach section of this report.

EVALUATION APPROACH

The contentions of the Developer were examined to determine if they held merit with respect to conditions normally associated with pilots on approach. FAA CAMI completed an analysis of the Developer's arguments, within the context of vision science by FAA CAMI, and an examination of the contentions of the Developer with respect to aviation applications by DOT VOLPE. The experiments consisted of flight evaluations of the ASALS and MALSR under simulated CAT I precision approach conditions with subject pilots; the results of these flights also provide a context for the results of the CAMI and VOLPE investigations as well as insights into human factors issues that may arise with the use of the ASALS.

THE FAA CAMI STUDY.

As part of its investigation, the CAMI Vision Research Team performed a literature search from which it prepared an annotated bibliography of relevant research. This section summarizes findings from this effort.

DEVELOPER CONTENTIONS AND VISION SCIENCE. In 1911, Blondel-Rey [2] found that, for dark-adapted subjects, the effective intensity (I_e = the luminous intensity of a steady-light source that has the same visual range as a flashing light under identical conditions of observation) [7] of a brief flash of light viewed at threshold luminance is described by the following expression:

$$I_e = \frac{\int_{t_1}^{t_2} I_o dt}{a + (t_2 - t_1)} \tag{3}$$

where I_o represents the corresponding threshold luminous intensity of a flashing light, a is an empirically derived constant ($a = 0.21$s), and $t_2 - t_1$ is the duration of the flash. Douglas [8] later extended the integral form of the Blondel-Rey equation to pulse trains (series of flashes that appear as a single flash). These methods for calculating effective intensity and those of the Form-Factor Method, developed in 1967 [9], have been widely accepted and found to be of practical use in the design and photometric testing of various signal lights, including condenser-discharge lights used in aviation [10 and 11].

For example, FAA Specification E-1100a [1] states that the effective intensity of a brief ($t_2 - t_1 << a$), supra-threshold flash (condenser-discharge light) can be reasonably approximated by multiplying the integrated luminous intensity (in the expression above) by a factor one over the denominator ($5 \approx 1/(a + (t_2 - t_1))$) and changing the limits of integration to include the entire period of the flash (i.e., from the onset of the first to onset of the second flash). Recently, however, the NIST recognized that these methods are imprecise for some waveforms of single and multiple flashes [12] above threshold luminous intensities as observed by subjects under mesopic conditions (low ambient illumination or luminance of approximately 3.4×10^{-2} to 3.4 cd/m^2), such as that which may be found in a cockpit environment.

Current research on theoretical modeling of the visual response function for pulse trains appears to favor the Modified Allard Method [5], since this method was designed to compare favorably to the Blondel-Rey results for rectangular flashes. Another factor the proposal ignores is that the pilot's view of the ALS at decision height (and nearer to the runway threshold) may be better described as an extended source rather than the point source that these references attempt to model [13]. Therefore, the claim that an ASALS would be five times more visible at decision height would not only depend greatly on the pilot's state of dark adaptation, but also on the undefined photometric characteristics of the proposed system's strobe lights.

The Developer also suggests that RVR may be doubled (Note: Under clear conditions, RVR will increase by the square-root of 5 or 2.24 when a light source intensity is increased by a factor of 5). The claim was that this doubling is directly related to a correlation between the inverse of the visual time constant derived for the Blondel-Rey equation (i.e., $1/a$ = 5 $-\text{s}^{-1}$; where, $t_2 - t_1 <$ 0.2-s) and the 5-to-1 reduction in pupil area reported by Loewenfeld [3] for flash durations >0.2-s.

However, limiting the light that enters the eye to one-fifth that of a fully dark-adapted pupil would not necessarily reduce RVR by one-half for several reasons. While it is true that pupil diameter (area) is a factor affecting vision in low-light conditions, maximizing pupil diameter may not increase RVR appreciably and may, in some instances, decrease visual performance depending on the preadaptive conditions present in the cockpit prior to approach. The relationship between visual acuity and background luminance is plotted on the chart in figure 6. The shallow curve at low luminance is due to the rod response and the large sigmoid curve is due to the cone response (adapted from Riggs, 1965).

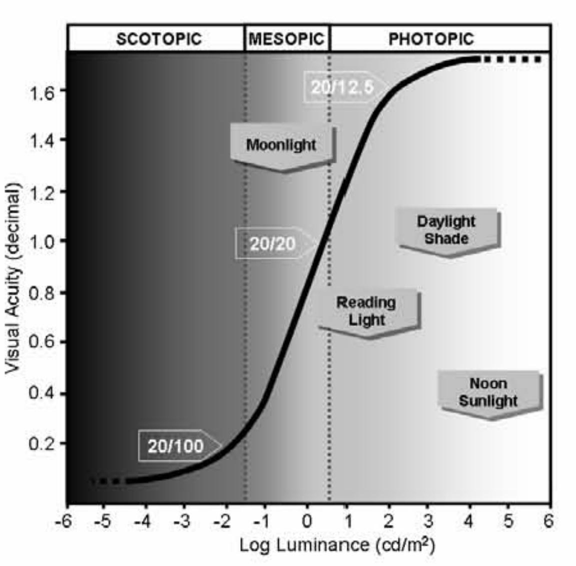

Figure 6. Relationship Between Visual Acuity and Encountered Luminance

Although large pupils allow more light to stimulate the observer's retina and reduce diffraction (i.e., the bending or scattering of light around the edge of the iris), resolution can be adversely affected by increased aberrations caused by the optics of the eye. Conversely, small pupils reduce optical aberrations, but resolution can be limited by diffraction [14].

A compromise between the diffraction and aberration limits would be a midsize pupil of about 3 to 5 mm in diameter [15 and 16]. Another factor to consider is that even those with 20/20 vision (emmetropic) under normal lighting conditions see as poorly as 20/200 when fully dark-adapted, as shown in figure 6 [17]. In this state, a large pupil diameter does not improve distant visual acuity. This is particularly true for low-contrast targets, such as those that may be encountered on a runway at night. This phenomenon is known as "night myopia" and is the result of the inactivity of the photoreceptors responsible for resolution of fine detail (cones) when the eye is dark-adapted.

As noted previously, the Loewenfeld study [3] also indicates how the use of strobe lights would affect the pupil by showing pupil responses to brief, repetitive, suprathreshold flashes of light of various frequencies and duration. For example, Loewenfeld describes the pupil response of two subjects (70-year-old male and 26-year-old female) exposed to brief (5 ms), repetitive flashes of suprathreshold light (15-foot candle). Within the first second after the first 5-ms flash both the 70- and 26-year-old subjects' pupil diameters contracted from 6.8 mm, initially, to 4.8 and 4.5 mm, respectively.

Figure 7 shows the pupil reactions of a 70-year-old male (solid line) and 26-year-old female (broken line) to slow and fast stimulation rates. Plot A shows both subjects' pupils take about a second to contract (from 7+ to 4 mm) after a delay of about 0.3 seconds (s) when exposed to a 1-s flash. Afterward, relaxation exhibited a slightly longer delay (0.5 s). In plot B, the pupil reactions to 5-ms flashes (flashes indicated by arrows), at rates of 1, 2, and 3 Hz are plotted. Initially, both contraction and relaxation cycles followed the stimuli fairly well with a similar latency as in plot A; however, the 70-year-old subject's average pupil diameter remains between 1/2 and 3/4 mm larger, and amplitude of response decreased with the fastest rate until it was almost imperceptible at 3 Hz [3].

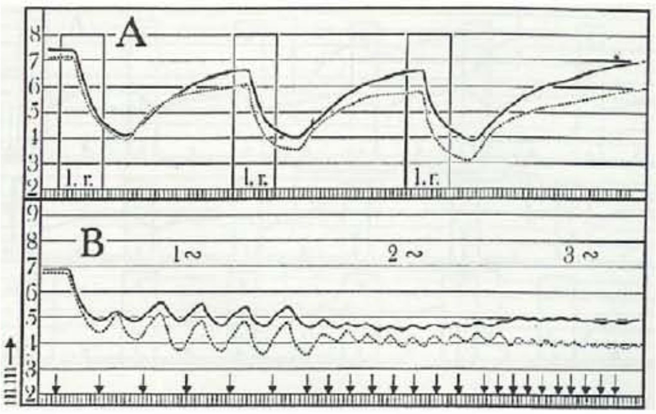

Figure 7. Pupil Reactions to Long-Duration (Plot A) and Short-Duration (Plot B) Light Pulses

At the frequency of 1 Hz, the 70-year-old subject's pupil diameters oscillate between 5.5 and 4.7 mm and the 26-year-old subject's between 5 and 3.6 mm. At 2 Hz, the 70-year-old subject's pupil diameters oscillated from 4.8 to 4.5 mm and the 26-year-old subject's from 4.5 to 3.9 mm. At 3 Hz, the 70-year-old subject's oscillations were almost imperceptible around 5 mm, while the 26-year-old subject's oscillations were very shallow, between 4.3 and 3.9 mm. The flash duration used in this instance is similar to that proposed for the ASALS (3 ms), and the effective flash intensity may be analogous to what a pilot may experience during final approach. These results indicate that an ASALS with a flash intensity above threshold levels would constrict a pilot's pupils well beyond the dark-adapted condition.

Images formed by light rays (or photons) entering the eye are focused by the cornea and crystalline lens onto the surface of the retina. The retina contains receptor cells (called rods and cones), which when stimulated by light, send signals to the brain that are subsequently interpreted as visual images. There are many more rods (about 130 million) than cones (about 7 million) and both are distributed disproportionately on the surface of the retina. Cones primarily occupy the fovea centralis or central retina, and the rods are more densely concentrated in the periphery.

Figure 8 shows that, at intermediate levels of illumination, the rods and cones function simultaneously. Visual performance depends on the level of dark adaptation and where the image is focused on the retina, due to variation in receptor density. This figure shows receptor density relative to retinal location in degrees about the fovea centralis (adapted from Osterberg, 1935).

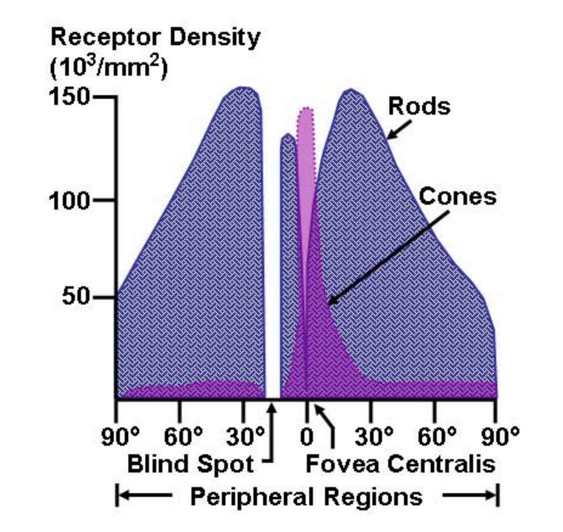

Figure 8. Rod and Cone Receptor Location and Density

The rods are predominantly responsible for vision under low luminance levels (i.e., scotopic $\leq 3.4\times10^{-2}$ cd/m^2), and cones function best at higher luminance levels (i.e., photopic ≥ 3.4 cd/m^2). Cones provide the capability for seeing color and resolving fine detail. After dark adaptation, cone function ceases ($\leq 3.4\times10^{-2}$ cd/m^2) and rod receptors process the available light in shades of gray and black [18].

The human eye's response range, or its ability to adjust to changes in the intensity of light, is extensive. Expressed in log units, this range of luminance represents more than 9 log units of brightness to which the human eye can comfortably respond. At the extremes of this range, time of exposure is a factor in whether or not an image can be resolved.

The eye's sensitivity to light increases significantly during dark adaptation. A change in the neural activity of the retina (i.e., inhibitory neural adaptation) increases its sensitivity to light by a factor of 1000 (3 log units) in a few milliseconds [19]; the change in pupil area takes about 1 second and adjusts the amount of light available to illumination of the retina by a factor of approximately 16, or just over 1 log unit [18, 20, and 21]. Also, the eye's sensitivity to light is altered by a factor of 100 million (8 log units) by a reversible photochemical reaction that changes the concentrations of photosensitive pigments in the retina (rhodopsin ⇔ all-*trans*-retinal + opsin). While the latter process is roughly two-thirds complete after about 10 minutes, it can take another 20 minutes or more to achieve full retinal sensitivity depending on the level of preadaptation illumination [19, 22, and 23].

Exposure to light begins to reverse dark adaptation almost immediately; however, a series of brief flashes can inhibit the process. When the dark-adapted eye is exposed to flashes of light of short duration, the pupillary response threshold is very low. Intensity and duration of the stimulus are only interchangeable for very short flashes (≤100 ms) [24 and 25], and small but distinct pupillary reactions may be observed well within the first log unit of luminance stimulus above the subject's scotopic visual threshold. Throughout the low-intensity range of luminance (≤3 log units), the pupillary contractions are slow, of low amplitude, short duration, and are preceded by a long latency. Once the intensity increases to approximately 3 log units above the subject's scotopic visual threshold, pupillary contractions become stronger and less variable. When luminance intensity is increased above this range, the pupillary response begins to increase in amplitude, speed, and duration of contraction until maximal values are reached at about 7 to 9 log units above the scotopic threshold [24]. A sudden increase in the effectiveness of the stimulus is noticed when the cone threshold is exceeded. Additional luminance intensity does not increase amplitude, speed, or latency of reactions, but can greatly prolong the contraction [26 and 27]. Furthermore, the pupil may remain in spastic miosis (delayed redilation) for several seconds due to the influence of afterimage [24].

Assuming the physiological responses described above are applicable for a pilot's state of dark adaptation during landing operation, an ASALS would constrict the pilot's pupils and possibly cause adverse visual effects. To avoid this, the intensity of the flashes would have to be continually reduced, in accordance to the Inverse Square Law and Allard's Law, as the aircraft descends to land in order to maintain the effective intensity of the flashes below the cone threshold. However, the proposed ASALS includes no mechanism to accomplish this gradual reduction in the flash intensity. The design and implementation of such a system is deemed highly impractical and laden with many uncertainties, including possible impacts on pilots in other aircraft who might also be simultaneously dependent on the lighting system.

There are several perceptual phenomena that may support the claim of enhanced detectability for a strobe light-based system under certain circumstances. The Broca-Sulzer Effect [28] states that a brief, relatively bright flash of light (optimal flash duration of 0.05 to 0.1 s) is subjectively perceived to be brighter than a longer flash of greater luminance intensity [29, 30, 31, and 32]. This is true for all adaptive states regardless of spectral composition and over virtually all areas of the retina [33 and 34]. This is thought to be a uniform neural response rather than a photochemical process [35]. A related phenomenon, the Brücke-Bartley Effect (brightness enhancement), states that below the critical flicker frequency (i.e., the frequency where a flashing light appears constant), the apparent brightness of a flashing light will gradually increase as the frequency is reduced and reach a point (approximately 8 to 10 Hz) where it appears brighter than an uninterrupted light source of equal luminance [36 and 37]. It is also understood that a small stationary spot of light projected on the retina will appear to fade after a few seconds. This fading, known as the Troxler's phenomenon, occurs long before an appreciable amount of retinal photopigment has begun to bleach [38]. These factors seem to suggest that an all-strobe approach light system, with an optimal flash duration and frequency, may appear more conspicuous than a steady-burn system at altitude. To properly assess this possibility, an extensive amount of research would be needed to examine the combinations and permutations of these phenomena within the context of ALSs.

THE DOT VOLPE EXAMINATION OF CONTENTIONS.

This effort examined the arguments by the Developer regarding the use of flashing lights in place of steady-burning lights for operational airport runways. Consideration of the claims of the Developer includes the following topics: interpretation and significance of the classical paper by Blondel and Rey [2] regarding the threshold detection of flashing lights compared to steady-burning lights, pupillary response of humans to flashing and steady-burning lights as reported by Loewenfeld [3], the impact of enhanced changes in light intensity on RVR, and the importance of related research on night vision.

RELEVANCE OF BLONDEL-REY EQUATION. Blondel and Rey addressed the threshold detection of flashing lights as compared to that of steady lights. The classical result has retained its integrity over nearly a century of follow-on work in the area. Sample improvements in the original work have included consideration of nonconstant illuminance and effects of multiple flashes. However, Blondel and Rey's work does not address high-intensity lights. Their work can be considered to deal only with dark-adaptation conditions, since the comparisons are limited to the threshold detection of light. High-intensity light effects are not included within the context of their work.

SIGNIFICANCE OF BLONDEL AND REY'S RESULTS. Blondel and Rey found that the threshold illuminance for a single, steady-light source of constant intensity or illuminance depends on the light-source intensity and its duration. The illuminance threshold of a flashing-light source E is given by

$$E = \frac{E_o(a+t)}{t} \tag{4}$$

where a is a constant (0.21), E_o is the illuminance threshold of the steady-light source and t is time duration of the flash in seconds. Correspondingly, the effective intensity of a flashing-light source I_e (cd) relative to its instantaneous intensity over the duration of the flash I (cd) is

$$I_e = \frac{It}{a+t} \tag{5}$$

Graphical results of these expressions are shown in figure 9. The graph on the left shows the dependence of E on flash duration, while the one on the right shows the dependence of the effective light intensity I_e of a flash relative to its instantaneous on-time value. The two plots in each graph also show how these factors change with decreasing values of the constant a. The blue curve is for the Blondel-Rey value $a = 0.21$, and the red one is for $a = 0.10$. Curves for the latter value demonstrate what would happen to the effective light intensity when illuminance is greater than its threshold value as suggested by Douglas [8] who noted that *a* would decrease as illuminance or light intensity increases above threshold values.

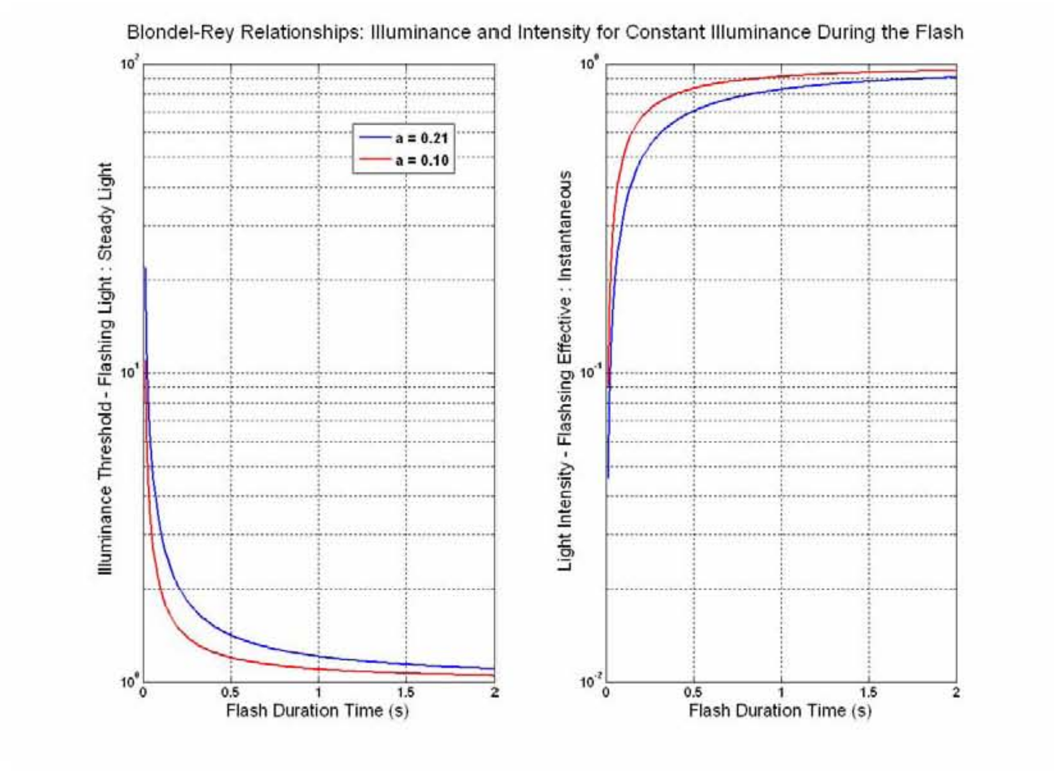

Figure 9. Relationship Between Illuminance Threshold and Flash Duration Time

The implications of these curves are very clear in two respects. First, for a flashing light to reach its detection threshold, its intensity (or the illuminance produced by the light at the location of the observer) must be greater than the intensity of a steady-light source by the factor shown in the graph on the left in figure 9. For example, a constant flashing light with duration of 0.2 s would require a threshold illuminance that is twice that of a steady-light source, and a flashing-light source that is approximately 0.01 seconds would require an illuminance that is 10-times larger than the threshold for a steady source. Another way of interpreting these results is in a form that evaluates the effectiveness of a flashing light. The graph on the right of figure 9 shows these results. For the two examples noted above, a flash duration of 0.2 s has an effective intensity of approximately 0.5 times (one-half) a steady-light source of the same intensity, and a flash duration of 0.018 s would have an effective intensity of 0.1 times (one tenth) that of a steady light.

In the second respect, the effects of flashing lights at higher-than-threshold intensities on the effective intensity of a flashing-light source is shown by comparing the responses in figure 9 for the two different values of *a*. The results are as expected—they force the results for flashing-light sources to approach the characteristics of steady lights. In other words, as light intensity increases above threshold values, flashing lights appear more and more like steady lights to observers as far as intensity is concerned. Thus, the advantage of steady-light sources over flashing lights, based on the threshold detection of lights, is reduced when the lights are above the threshold of detection; however, flashing lights only achieve equivalency when the duration of the flashing lights is greater than approximately 2 s.

PUPIL DILATION AND THE CLAIMED FACTOR OF 5 ENHANCEMENT. As demonstrated previously, Blondel and Rey did not conclude that there is a 5 to 1 advantage in using a single strobe light over a steady light. Rather, they discovered that the effectiveness (or apparent intensity) of a flashing light is less than that of a steady light according to equation 5. Thus, as the duration of a flashing-light source decreases, so does its effectiveness for detection at threshold, as shown in figure 9. As a consequence of the correct interpretation of Blondel and Rey, there is no association between the Blondel and Rey findings and pupil response to bright-light conditions under complete dark adaptation.

Loewenfeld's paper focuses primarily on pupil response to flashing lights of durations 1 and 3 seconds as well as 5 ms. Loewenfeld's results show the pupil response from dark adaptation to response states associated with sequences of bright-light flashes of different duration and frequency.

This is most interesting and relevant to the Developers' arguments. Pupillary responses for both sequences of these two types of light stimuli showed transition from dark adaptation beginning approximately 0.3 s after the turn-on time of the bright light. This lag in response time was the same for both long (1 s) and short (5 ms) flashes. Each type of light source showed evidence of effect and recovery phases that are typical of many physical phenomena.

In this case, light excitation began to produce pupillary contraction governed by a time constant after some latency delay period (~0.3 s), and after removal of the excitation and a comparable latency period (~0.3 s), the pupil diameter began to return to its original state via a transient curve that is governed by a second time constant. Figure 10 shows an illustration of a modeled pupillary response to a 1-s-duration bright-light stimulus from a dark-adaptation condition. This is based on the results in figure 7 that show Loewenfeld's results [3]. Note that this behavior is typical of numerous physical phenomena that are governed by a first-order response to forced stimuli. In this case, excitation is caused by the turn-on of light, and relaxation is due to the removal of light.

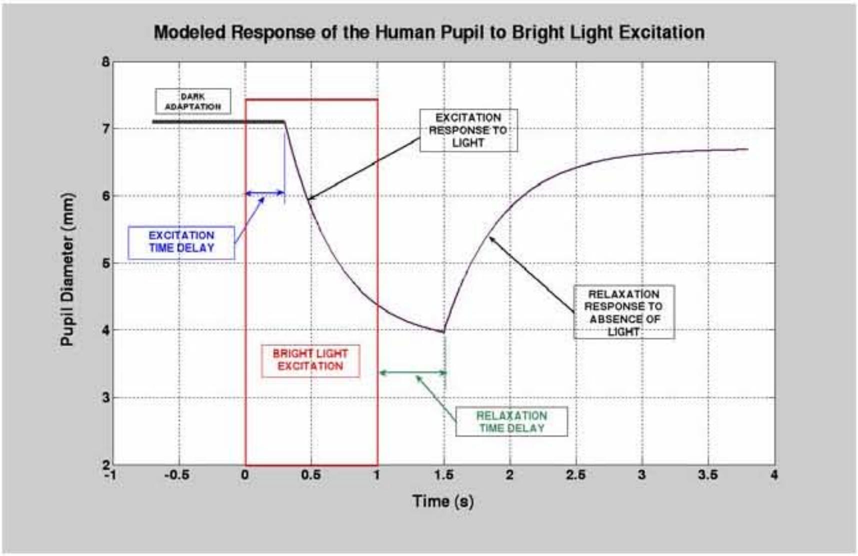

Figure 10. Modeled Response of Human Pupil to Bright-Light Excitation

The most relevant result is that the very short light flashes also produced significant contraction of pupil diameter, and these contractions were only slightly less than the full contraction associated with the much longer flashes. The difference is approximately 4 mm for the very short-duration flashes versus approximately 3.2 mm for the longer-duration flashes.

The Developer states that there is an inherent advantage of using very short-duration flashing lights in place of steady-burning lights. The Developer claims this is based solely on an advantage given to a pilot whose eyes are more adapted to flashing lights than to steady lights. Furthermore, this proposed advantage is measured by the relative difference in the areas of the pupil under these different conditions. Loewenfeld's results imply that the advantage would be a factor of ~1.6, which is much less than the Developer's claimed factor of 5. As will be shown in the following section, such an improvement would be inconsequential when examined in terms of RVR.

THE RVR AND DEPENDENCE ON LIGHT INTENSITY. To understand the effect of enhanced light intensity on runway RVR, the consequences of Allard's Law under different intensities must be assessed since this law expresses the properties of light propagating in the atmosphere. It combines the latter with knowledge of the detection threshold of light, and thereby governs the longest distance (or visibility) at which light sources can be detected. For an atmosphere that is described by an extinction coefficient σ (m^{-1}) and a threshold detection level E_T (lx) that is based on a background luminance condition B($cd\text{-}m^{-2}$), light intensities of I_1 and I_2 will result in respective RVR values of R_1(m) and R_2(m) that satisfy the following equations for the illuminance threshold E_T.

$$E_T = \frac{I_1}{R_1^2} e^{-\sigma R_1} \tag{6}$$

$$E_T = \frac{I_2}{R_2^2} e^{-\sigma R_2} \tag{7}$$

Dividing equation 6 by equation 7 gives

$$1 = \frac{I_1}{I_2} \frac{R_2^2}{R_1^2} e^{\sigma (R_2 - R_1)} \tag{8}$$

When I_2 is n times greater than I_1, rearranging terms in equation 8 leads to

$$\frac{R_2^2}{R_1^2} = \frac{I_2}{I_1} e^{-\sigma (R_2 - R_1)} = n e^{-\sigma (R_2 - R_1)} \tag{9}$$

This shows that the square of the ratio of RVR for different light source intensities is a nonlinear relationship that depends on the relative intensities of the light sources, the extinction coefficient of the atmosphere and the difference in the RVR values. The illuminance-threshold level E_T that is used by the FAA is given by

$$E_T = \max[6.8 \cdot 10^{-6}, 2.0 \cdot 10^{-6} B^{-.64}] \tag{10}$$

A convenient reference parameter for extinction coefficient is meteorological optical range (MOR), which is equal to RVR under daylight conditions.

$$MOR = \frac{3}{\sigma} \tag{11}$$

If the dimension of σ is m^{-1}, MOR is in meters, and if σ is in km^{-1}, MOR is in km.

A straightforward way of evaluating the attributes of illuminance with distance is to consider how R_1 and R_2 vary with different atmospheric conditions (extinction coefficient) for both nighttime and other background lighting conditions.

Since an increase in light intensity will always improve visibility or increase RVR, R_2 will always be greater than R_1, as seen in equation 9. The maximum enhancement occurs when the atmosphere is perfectly clear ($\sigma = 0$), and the factor by which this maximum occurs is $n^{1/2}$ or 2.24 when $n = 5$.

The dependence of these results on MOR is shown in figure 11. The upper curves show how RVR varies as MOR ranges from near zero (very poor visibility) to 3000 m (very good visibility) conditions. The detection threshold E_T for these curves was set at the nighttime value of $6.8 \cdot 10^{-6}$ l times with light-source intensities of 15, 500, and 5000 cd, corresponding to the nominal step settings 1, 3, and 5 intensities of runway edge lights used by controllers to illuminate centerline lights at airports. Responses to lights having five times higher intensities, 75, 2,500, and 25,000 cd, are also shown. The lower set of curves show the relative improvements in RVR for each of these light settings due to a factor of 5 increase in light intensities.

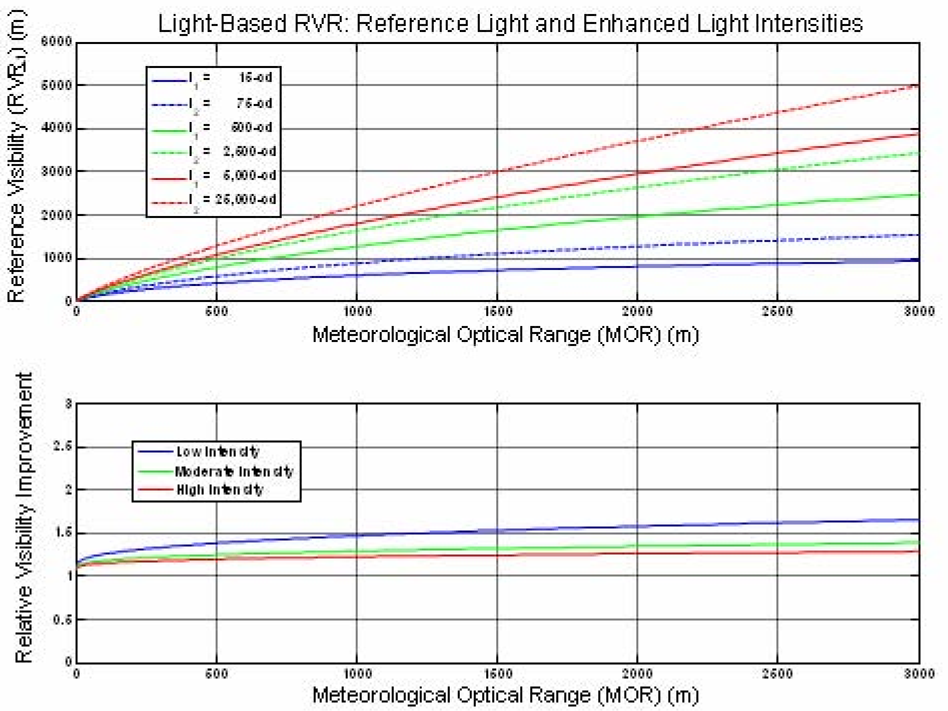

Figure 11. Light-Based RVR: Reference Light and Enhanced Light Intensities

These graphs show that, throughout the entire low-visibility regime as measured by MOR, the largest enhancement in visibility, due to an assumed factor of 5 increase in light intensity, ranges from 1.3 to 1.65, with the greatest benefit occurring at the lowest light setting step with light intensity of 15 cd. To achieve a factor of 5 enhancement in RVR or visibility, a much larger enhancement in light intensity would be required.

Estimates of these enhancements can be obtained from figure 11. For example, at a MOR of 3000 m, a 15-cd light source has an RVR of ~1000 m, while a 25,000-cd source has an RVR of ~5000 m—a factor of 5 enhancement in RVR. To achieve this enhancement under these atmospheric conditions, the light intensity would have had to be greater by a factor of ~1700. Note that this enhancement is far less than the theoretically largest enhancement of $1700^{\frac{1}{2}} \approx 41$ anticipated under extremely clear atmospheric conditions.

When atmospheric conditions worsen, i.e., as MOR gets smaller, the improvement also worsens. At an MOR of ~500 m, this same factor of ~1700 increase in light intensity improves RVR by only a factor of ~3.3. Several important realizations derive from this analysis:

- Increasing light-source intensity by a given factor does not result in a correspondingly equal increase in RVR.
- There is a maximum increase in RVR associated with an increase in light-source intensity, and this occurs only at very good visibility conditions.
- The effect of atmospheric extinction on RVR can greatly reduce the enhancement of RVR or visibility that can be realized from an enhancement in light-source intensity.
- The effective expectation of enhancement in RVR under poor visibility conditions for a factor of 5 enhancement in light intensity ranges from about 1.3 to 1.65 when MOR ranges from about 50-3000 m.
- When atmospheric effects are dominant (MOR is small or σ is large), the relative benefits of increasing light intensity as a means of increasing RVR are compromised or much less than one would normally expect intuitively. If one wants to increase visibility by a certain amount, just increase intensity by this same amount.

To explore further the behavior of RVR under very good atmospheric conditions ($\sigma=0.03\text{-}km^{-1}$), computations of R_1 and R_2 were made and plotted as shown in figure 12. These curves show that there is only a moderate improvement in RVR resulting from a factor of 5 enhancement in light-source intensity, and that this enhancement is nearly gone for R_1 (the reference RVR value) less than approximately 500 m (low-visibility conditions).

The improvement factor increases with RVR, but is still only ~1.5 for high-intensity lights at R_1=3000 m and ~1.4 for moderate-intensity lights. Note that the low-intensity sources terminate (produce maxima values of RVR) at [R_1; R_2] = [1453; 3167] m due to the illuminance of the light sources becoming less than the detection threshold beyond these distances. The greatest enhancement in this low-intensity case is ~2.2, somewhat less than the theoretical achievable limit of 2.24 that occurs at high-visibility conditions.

Figure 12 shows the enhancement in RVR due to a factor of 5 increase in light-source intensity under high-visibility nighttime conditions. The low, moderate, and high values of light intensities at nominal and factor of 5 enhancements are: I_1 = [15, 500, and 2,500] cd and I_2 = [75, 2,500, and 25,000] cd, respectively. Note that the low-intensity source I_1 = 15 cd increasing to I_2 = 75 cd curves approach limiting values of RVR_1 (1453 m) and RVR_2 (3167 m). This limit arises from the fact that the illuminance of the lowest light source is less than the detection threshold beyond this distance (RVR value). In other words, 15-cd lights cannot be seen beyond 1453 m.

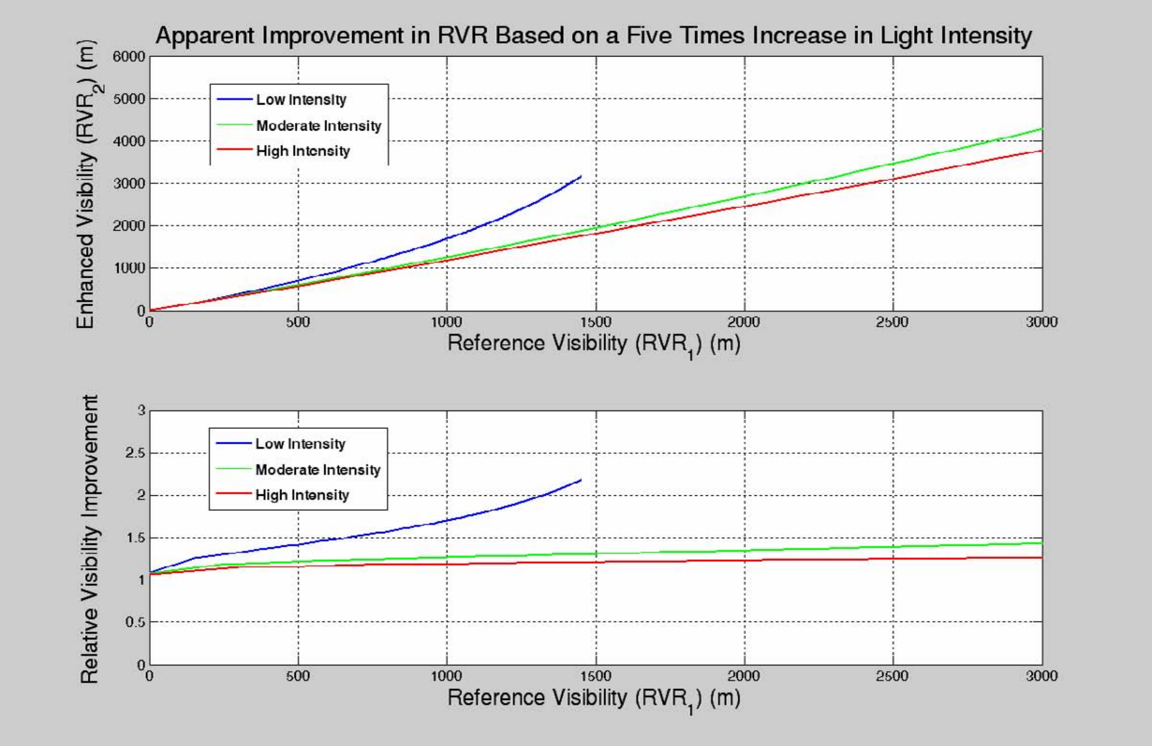

Figure 12. Apparent Improvement in RVR Based on a 5-Times Increase in Light Intensity

THE NATURE OF ALLARD'S LAW. To further illustrate the behavior of visibility of a light source, it is useful to examine the dependence of illuminance *E* on intensity *I* of a light source as a function of distance *R* from the source. This parameter is defined similarly to Allard's Law with (E_T, I_1, R_1) in equation 6 being replaced by (*E, I, R*).

$$E = \frac{I}{R^2} e^{-\sigma R} \tag{12}$$

The dependence of *E* as a function of distance and atmospheric extinction coefficient for different light-source intensities corresponding to light steps of 1 and 5 is shown in the series of graphs given in figure 13. Each subplot corresponds to different atmospheric visibility conditions as described by extinction coefficients σ of [0.1, 1.0, 10, and 100] km^{-1}. For reference, these values of σ represent daytime MOR of [30,000, 3,000, 300, and 30] m, respectively. The response for the base-light intensities of 15 cd (Step 1) and 10,000 cd (Step 5) are shown in blue, the responses for a factor of 3 enhancement of the Step 1 and factor of 5 enhancement for Step 5 in these intensities are shown with the adjacent red curves. Five thresholds for different background luminances B in footlamberts (fL) are also shown. These thresholds cover the range from the minimum threshold value at B = 1.975 fL, which the FAA established to represent nighttime conditions, to the highest level of daytime brightness *B* = 10,000 fL, which is the upper limit of ambient light sensor measurements employed by operational RVR systems deployed in the United States.

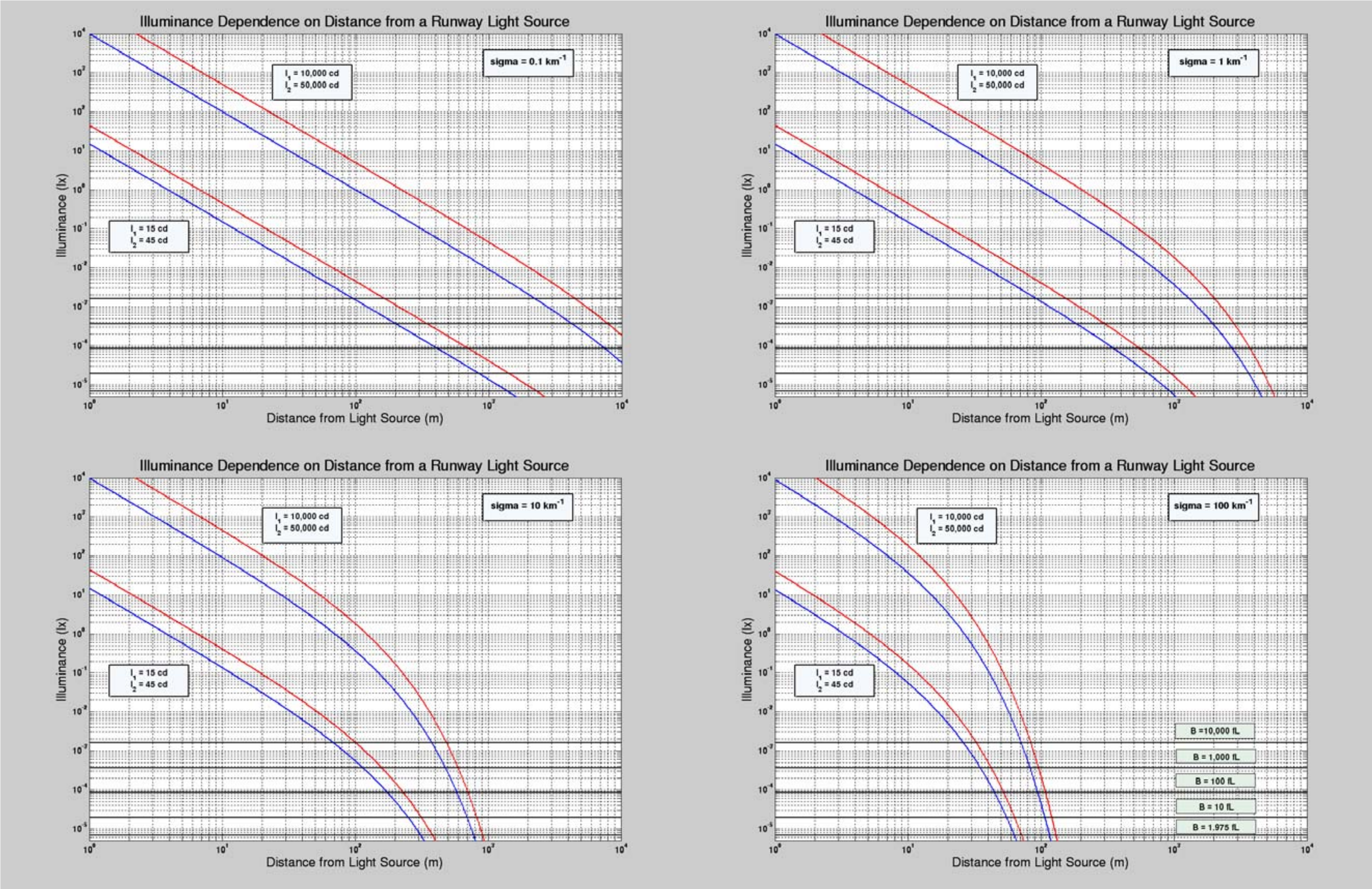

Figure 13. Four Plots of Illuminance Dependence on Distance From a Runway Light Source

In addition to showing how illuminance changes with distance, one can also use these curves to determine values of RVR for any indicated background luminance conditions. RVR values are obtained by simply noting the distance or location where the illuminance intersects the threshold. The effects of background luminance on RVR are readily seen in these curves, that is, as B increases RVR decreases. In other words, the intersection of the illuminance plots and detection threshold occurs at smaller distances or values of R as the luminance increases from nighttime through higher values of daytime luminance. The relative amount of decrease in RVR depends on both light intensity and extinction coefficient. For example, under high-visibility conditions (σ = 0.1 km^{-1}), RVR of a Step 1 low-intensity light of 15 cd, decreases from ~1400 m at night, down to ~95 m under bright daytime conditions, which is more than a factor of 10 decrease in RVR. A low-visibility condition of σ = 100-km^{-1} yields corresponding values of ~64 m and 26 m, respectively, which is just less than a factor of 3 decrease between nighttime and intense daylight conditions.

Another feature of these graphs relates to the transition from daytime values of RVR as determined from Koschmieder's Law and RVR as determined from Allard's Law. This sequence of curves clearly shows not only how E depends on distance, but also how RVR changes with atmospheric extinction coefficient, different light intensities, and background luminances. In this regard, note especially, the proximity of the intersections of the baseline light sources and their corresponding enhanced intensity curves with the various threshold illuminance values. Only when the visibility is very good, does one get near the maximum benefit of the enhanced light-source intensity (factors of 1.73 and 2.24 for increases in intensity of 3 and 5 factors, respectively). As visibility deteriorates (higher extinction coefficients), this advantage decreases considerably. Also, the advantage is smaller at nighttime than in daytime conditions.

The primary impact of these results, relative to any factor of 5 enhancement in effective light-source intensity, is clear. Even if there were an enhancement in effective light intensity of a flashing-light source relative to a steady light source of equal intensity, this advantage, in terms of enhancing RVR, is not only small, but also inconsequential relative to what can be achieved by simply increasing a runway's light-step setting.

THE FAA FLIGHT EVALUATIONS.

In coordination with the FAA Airport Safety Technology Research and Development Section Visual Guidance Team and the Atlantic City International Airport (ACY), the Developer installed an ASALS configuration at the approach end of Runway 4 at ACY where there is also an experimental Reconfigurable ALS Testbed (RALST). The RALST was set to a standard MALSR configuration for the purposes of flight-testing. A side view of the ASALS showing the vertical profile of the ASALS installation is shown in figure 14. (Note: the vertical scale is exaggerated relative to the horizontal to illustrate the profile.)

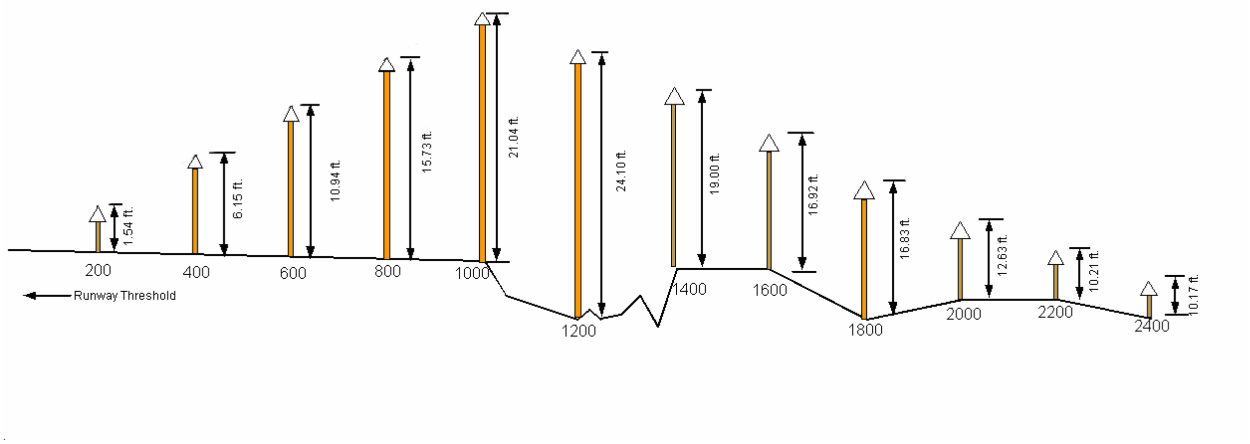

Figure 14. The ASALS Side View Showing Vertical Profile of Installed Towers

EVALUATION SUBJECT PILOTS. Evaluation subjects were selected from professional pilots within the FAA and civilian organizations.

GROUND AND PRELIMINARY FLIGHT EVALUATIONS. For safety reasons, the evaluation was conducted in three steps: ground evaluation, preliminary flight evaluation, and flight evaluation. The ground evaluation was performed by placing several members of the Visual Guidance Team at different locations around the airport, control tower, and road adjacent to the airport. During the ground evaluation the ASALS system was energized to take note of any effects that may occur with ground observers.

Although the Developer had taken lengths to decrease the output of light intensity through modification to the optical heads so that the light intensity was diminished along the horizontal, the effect was more distracting to ground observers than the MALSR configuration. This distracting effect was not deemed a risk worth mitigating by altering the ASALS configuration, and the Visual Guidance Team continued with preliminary flight evaluations. This is most likely because a one-half reduction in light intensity is not very much in terms of the human eye's ability to discern different levels of light, e.g., factors of 10^9 verses 2.

During the preliminary flight evaluation, no subject pilots noted any risk associated with using the system. This allowed subject flight evaluations to proceed. However, the air traffic controllers in the control tower located off of Runway 4 complained of the distracting nature of the ASALS light units. Consequently, the light units were baffled such that they could not be seen from the control tower while flight-testing was in progress. This did not affect the light intensity in the direction that approaches were made during flight evaluations.

FLIGHT EVALUATIONS. Flight evaluations were conducted to determine the effectiveness of the ASALS as a possible replacement for the MALSR standard for CAT I precision approachprecision approaches. These flight evaluations would specifically determine this by examining the following:

- The effectiveness of the system to deliver proper visual guidance through objective analysis of flight data

- The subject pilot's level of comfort with the ASALS capability to provide all forms of guidance necessary for successful approaches

- If the subject pilot's visual acuity was detrimentally affected or noticeably enhanced through the use of the ASALS, both during the approach and after the touchdown phase of landing

A series of flight tests in the FAA King Air N35 were conducted based on aircraft, safety pilot, and subject pilot availability. Objective data in the form of measurements taken from the King Air data collection instruments (DCI) were analyzed to indicate possible disparities between the two ALS that could affect pilot performance. These objective results were combined with subject pilot interviews and questionnaires to give insight into the performance characteristics of the ASALS.

All flights were conducted in VFR conditions, which are not the conditions that require an ALS. To simulate CAT I precision approach conditions, the flights were conducted under two different scenarios. One scenario was that during the approach only the runway lights were turned off, and each ALS was only illuminated during the last seconds before the DH of 200 ft. In CAT I precision approach minimums, pilots do not have these visual cues of the runway environment until this time. This was done to collect data to determine the effectiveness of the system to deliver proper visual guidance and the subject pilot's level of comfort with the ASALS capability to provide all forms of guidance necessary for successful CAT I precision approachprecision approaches.

During the second scenario, the approach resulted in a landing, and the runway lights were illuminated. These landing scenarios were used to collect subjective pilot data on the visual acuity after touchdown for each scenario, regardless of which ALS was used. Information was collected to determine if the subject pilot's visual acuity was detrimentally affected or noticeably enhanced through the use of the ASALS.

<u>DETERMINATION OF EFFECTIVE VISUAL GUIDANCE DURING APPROACH</u>. Approximately 150-250 global positioning system (GPS) data points per approach were taken for each system, which was dependent on the approach speeds and sampling rate. The results were imported into geographic information system software with aerial photos for reference. To facilitate the analysis of the GPS data, two bounding areas with sides aligned parallel to the extended runway centerline were created within the test area prior to runway threshold. These areas are considered in near alignment with the extended runway centerline, with the first area within 21 ft of either side of the extended runway centerline, and the second within 41 ft on either side of the extended runway centerline. The 21- and 41-ft values were chosen as approximately a quarter (42 ft out of the 160 ft runway width), and half (82 ft out of the 160 ft runway width) of the runway. Examining values smaller than these widths does not accommodate for the error inherit to GPS data, although it was recorded with differential Wide-Area Augmentation System enabled, and values larger than half the runway width did not provide enough resolution for proper comparison of the two ALSs.

An on-course percentage was used to create a measure of pilot accuracy and his or her ability to track the extended runway centerline. The on-course percentage was defined as the total amount of points falling within one of the bounding areas over the total amount of points taken prior to runway threshold.

The choice to limit the bounding area prior to runway threshold was necessary. This necessity was required as lengthening the bounding areas beyond the runway threshold would not accommodate proper analysis of alignment with the runway centerline on go-around approaches.

The bounding areas, shown in figure A-1 of appendix A, zoomed in to the Runway 4 threshold. The red line running through the center of the data points represents the extended runway centerline.

Two MALSR approaches were removed from this study because they were the first runs of August 31, 2006 and November 2, 2006 and well outside the deflection criteria established for the experiment due to technical difficulties in setting up the simulated ILS approach. However, this deflection led to the proposal of testing after and including November 20, 2006, when approaches would be flown at offset angles to Runway 4 parallel to the extended runway centerline, but with alternate left and right three-dot needle deflection. While this is still allowed in making a legal approach and within the normal flight envelop for a CAT I precision approach ILS, this offset is considered a worst-case scenario where a pilot may be during approach. This change in testing was added to determine the alignment guidance of each system, which is the major function of an ALS.

DETERMINATION OF VISUAL ACUITY AFTER TOUCHDOWN. The question regarding the subject pilot's visual acuity was presented to subject pilots both during testing activities and in a postflight briefing. During testing activities, subject pilots were asked to identify a number of randomized objects of interest at variable distances after crossing the runway threshold. The pilots would then visually re-acquire those objects for each approach, and state whether it was any more or less difficult to acquire those objects for each approach under the ASALS and MALSR.

The postflight briefing included a questionnaire regarding the ASALS's ability to provide all necessary visual guidance cues, each rated by a five-point Lykert scale. Subject pilots were also able to annotate comments for each question. The results from the inflight and postflight visual acuity inquiries are listed in the Results section under the FAA Flight Evaluation. All results from the postflight debriefing questionnaire are listed in appendix C.

RESULTS

THE CAMI STUDY.

Review of existing research found that there is some evidence to suggest that effective intensity of a flashing light of short duration (<0.2 s) may be more detectable (conspicuous) than a long-duration flash (≥1 s) for fully dark-adapted subjects under some conditions. The proposed system's effectiveness would be dependent on the strobe light's characteristics and the pilot's state of dark adaptation. Maximizing pupil diameter to allow additional light to fall on the retina may not improve distance acuity (i.e., RVR) for a fully dark-adapted individual. This is particularly true for low-contrast targets, such as those that may be encountered on a runway. Optimal vision performance, as it relates to pupil size, relies on maintaining a proper balance between the adverse effects of diffraction and increased optical aberrations inherent in the optics of the human eye.

The literature review suggests that ASALSs may only be successful if the effective intensity [23], flash frequency, and pulse duration are optimal to ensure good visual performance in the cockpit environment. At this time, there is no definitive data identifying how these parameters may relate to aircraft operations. The present proposal only makes vague reference to these parameters, but there are data available that could aid in the development of such a system. Research suggests that a strobe light system with certain limits on pulse duration (0.05 to 0.1 s) and frequency (8 to 10 Hz) may allow the eye's visual receptors and neural response characteristics to function optimally without compromising the pre-existing level of dark adaptation. Optimization would also be dependent on maintaining the intensity of the flashes to no more than 3 orders of magnitude above threshold. Since the cockpit adaptation luminance for a pilot on final approach would likely be somewhere in the mesopic range (>0.034 to <3.4-cd/m^2), intensity of the flashes at the pilot's eye would have to be maintained at or below 340-cd/m^2. Even though the latter condition is often satisfied, additional study is required to determine the precise combination of flash duration, frequency, and intensity for optimal visual performance in a cockpit environment. Once these parameters are known, more research would be necessary to determine whether such a system outperforms the existing steady-burn systems.

A database search of accidents involving visual difficulties caused by glare from steady-burn approach lights were factors in only two events [39]. One resulted in a short landing, and the other involved a landing that was too long (appendix D). Contrary to the suggestion made in the Developer's proposal, a National Transportation Safety Board (NTSB) investigation of the 1991 LAX accident indicated that glare from steady-burn approach lights did not play a role. The primary cause of the accident was poor ground-tracking procedures that led to a misplaced flight progress strip that resulted in a commuter aircraft being mistaken for the accident aircraft. A contributing factor was the mounting configuration of the SkyWest Airlines' Metroliner anticollision light and its alignment with the runway center lights, which may have prevented the US Air 737 pilot from seeing the aircraft sitting on the runway until it was too late to react. The NTSB report did suggest that the veiling glare produced by ramp lights positioned between the control tower and the runway prevented air traffic controllers from seeing the Metroliner that was sitting on the runway awaiting clearance for takeoff [4].

THE DOT VOLPE INVESTIGATION.

In addition to the arguments by the Developer being compromised due to the misinterpretation of scientific results, they are also narrow in light of the complexity of flashing-light phenomena. One potentially very important oversight in the discussion is how different types of lights affect fatigue. Bartley has shown that both flashing lights and highly contrasted fields of view can cause significant fatigue and discomfort [40]. Repeated contraction and dilation of the pupils in response to flashing lights and contrasts between black and white fields of vision, which might occur from both flashing and steady lights, can produce significant fatigue in individuals. These phenomena would have to be carefully considered in the context of any proposal to alter current ALSs. Other phenomena may also have to be considered as well, including

- the Bloch-Charpentier Law [41 and 42] that indicates the requirement for constancy of energy for short flashes near threshold.
- the Broca-Sulzer Effect [28] that indicates momentary luminosity of high-intensity flashes can appear up to as much as five times greater than a long-duration light.
- the Brűcke-Bartley Effect [43, 44, and 45] that indicates rapidly repeating flashes at supra-threshold levels below the critical fusion frequency can appear greater than steady lights.
- Weber's Law that indicates the proportionality between detectability of changes in luminance to background luminance.

The topic of flashing lights has generated much attention over the last two centuries as evidenced by the considerable amount of research in related areas. For more information, refer to the following related documents.

- "The Perception and Application of Flashing Lights," by contributors to the International Symposium, 19-22 April 1971, Imperial College, London, Great Britain (University of Toronto Press, Toronto, Canada), 1971, pp. 429. A copy of this was thoughtfully provided to the FAA by the Developer in 2006.
- The monograph on "Information, Sensation and Perception," by Kenneth H. Norwich (Academic Press, Inc., San Diego, California, 1993 and Internet Publication, Biopsychology.org, 2003)
- "Brightness Discrimination as a Function of the Duration of the Increment in Intensity" by C.H. Graham and E.H. Kemp, *Journal of General Physiology*, 21, 1938, pp. 635-650.
- "The Dependence of the Photopupil Response on Flash Duration and Intensity" by M. Alpern, D. W. McReady, Jr., and L. Barr, *The Journal of General Physiology*, 47, 1963, pp. 265-278.

Clearly, there is an extensive amount of important literature and understanding of the subject of flashing lights, as well as experience, within the FAA regarding their use at airports. The extensive review of these, along with related analyses and interpretations, have conclusively demonstrated that the Developer's contentions lack merit and, unfortunately, appear based, in part, on misinterpretations of known scientific facts.

THE FAA FLIGHT EVALUATIONS.

VISUAL GUIDANCE INFORMATION CONVEYED DURING APPROACH. An examination of information on altitude, heading, and roll values from King Air DCI revealed no striking differences between pilot performance during MALSR test approaches and ASALS test approaches with respect to glide-slope and roll guidance. Examining the aircraft GPS position data from these flights did reveal that, while both systems provided sufficient information to remain within a three-dot deviation of the simulated ILS, subject pilot performance and position were more likely to be consistent with the extended runway centerline on flights using the MALSR than that of the ASALS.

Figure A-2 of appendix A shows a view of all approaches conducted under the ASALS system. The test area was defined where the lighting system was energized and visible, shown in nearly full extent in figure A-2 as the transparent area encompassing all data points. Observing the lower portion of the test area in figure A-2, the profile of the approach points have a larger spread about the extended runway centerline as compared to figure A-3 of appendix A, which shows the MALSR flight test approaches.

In table 1, the points falling within 21- and 41-ft areas are shown, and the percentages in the final two columns represent the on-course percentages previously discussed.

Table 1. The ASALS Points Acquired Within Bounding Areas

Points Within 21-ft Bound	Points Within 41-ft Bound	Total Points Prior to Runway Threshold	21-ft Bound On-Course Percentage	41-ft Bound On-Course Percentage
1973	2271	2576	76.59%	88.16%

Table 2. The MALSR Points Acquired Within Bounding Areas

Points Within 21-ft Bound	Points Within 41-ft Bound	Total Points Prior to Runway Threshold	21-ft Bound On-Course Percentage	41-ft Bound On-Course Percentage
2013	2170	2332	86.32%	93.05%

The ASALS had a total on-course percentage of 77% of all points within 21 ft on either side of the extended runway centerline, and 88% were within 41 ft. This is in contrast to the results of table 2 that show points falling in the same areas for the MALSR, which yielded on-course percentages of 86% being within 21 ft of the extended runway centerline, and 93% of the points being within 41 ft.

The pilots who flew these approaches felt that the presentation of the ASALS did not convey proper visual guidance information as accurately when the approach was flown with greater deflection from the extended runway centerline. In table B-1 of appendix B, comments are listed with respect to both ALSs from the other days of testing. Many pilots made comments of “something missing,” “lacks contrast,” or “a black hole” when referring to the ASALS. Also, some pilots indicated that there was a perceived “pause” in the sequence, which may indicate a delay in processing the visual information when pilots remain focused on the ASALS until they perceive the correct guidance information. Comments from each pilot from the November 20, 2006, testing are listed in table B-2 of appendix B.

In addition to the comments made during the test, pilots completed post-test session questionnaires, which subjectively rated the ASALS’s ability to convey necessary information for different types of guidance using a five-point Lykert scale. The figures in appendix C describe detailed responses to each question about guidance of the ASALS.

VISUAL ACUITY ASSESSMENT AFTER TOUCHDOWN. There were no differences between the subject pilot’s ability to identify any object of the runway environment in their evaluation of either ALS. Questions regarding visual acuity were provided during the test and in the postflight debriefing. The results from this inquiry are available in figure 15.

<table>
<tr><th colspan="2">Question</th></tr>
<tr><td colspan="2">Visual acuity in the context of this project is the ability to see objects defined after touchdown on runway 4-22. Was there a noticeable difference in your visual acuity when using either approach lighting system?

If YES, please elaborate with information including which system and the degree to which your visual acuity was affected.</td></tr>
<tr><td>YES</td><td>NO</td></tr>
<tr><td>0% (0)</td><td>100% (11)</td></tr>
</table>

Comments:

- “I found no effect on visual distance.”

Figure 15. Visual Acuity Assessment

CONCLUSIONS

The investigations conducted by the Federal Aviation Administration (FAA) Office of Aerospace Medicine Civil Aerospace Medical Institute (CAMI) and the Department of Transportation (DOT) Volpe National Transportation Systems Center (VOLPE) concluded that there would be minimal, if any, improvement in the pilot's runway visual range (RVR) and visual acuity when using the All-Strobe Approach Lighting System (ASALS) when compared with the Medium-Intensity Approach Lighting System with Runway Alignment Indicator Lights (MALSR). The results of these studies were confirmed during flight evaluations by subject pilots at the FAA William J. Hughes Technical Center as coordinated by the Airport Safety Technology Research and Development Section, Visual Guidance Team. During testing, it was found that there was a lack of necessary visual guidance cues on approach for the ASALS as compared with the MALSR.

Since the data showed that ASALS was lacking in the provision of necessary visual guidance cues to conduct a Category (CAT) I precision approach and did not provide any visual acuity improvements over the existing system, the operational deployment of the ASALS would not achieve equivalency in performance to the MALSR.

THE CAMI STUDY.

At present, no appreciable problems with the existing steady-burn MALSR have been identified from a thorough examination of aircraft accidents. Due to the small number of accidents and incidents involving reports of glare from approach lights (2 of 45,817, less than 0.0044%) and the lack of common factors between the two reported incidents, no definitive conclusions regarding any deleterious effects of approach lighting on pilot performance can be drawn.

The use of strobe lights in an approach light system (ALS) may be beneficial for detection at altitude, but at decision height and below, their usefulness depends on whether the effective intensity, flash duration, and frequency can be calibrated to maximize visual performance in a mesopic environment (cockpit). Additionally, since the process of recovery from a dark-adaptation state following exposure to supra-threshold flashes appears to be no more effective than that following exposure to steady-burn lights, a significant improvement in RVR seems doubtful.

THE DOT VOLPE INVESTIGATION.

The contentions of the Developer were shown to be based on misinterpretations of visual phenomena and, thus, cannot be used as a rationale for changing ALS. It is inappropriate to attempt to relate pupil response of human subjects to lights that are of greater intensity than needed for detection to the Blondel and Rey results for the detection of such lights, whether they are steady or flashing. Indeed, the findings of Blondel and Rey relate only to light intensities that are just detectable and not to light levels that would affect (i.e., contract) a person's pupils. Even if there were merit in considering effects of pupil responses on pilot vision to different types of light, such as steady and flashing lights, the Developer chose to accept only one portion of the scientific findings of Loewenfeld for his argument, that is, the effects of steady lights on pupil diameter. The effects of a sequence of very short light flashes on pupil diameter were ignored, yet constitute another important set of data that produced similar pupil contractions. This omission, in and of itself, essentially countermands the Developer's premise regarding presumed benefits that would be gained from the proposed flashing-light system. Regarding possible improvements in RVR, it was shown that if an effective five-fold enhancement of intensity could be realized regardless of methodology, this improvement would produce, at most, a factor of ~2.2 increase in RVR and this improvement would occur only under clear atmospheric conditions; this benefit would diminish significantly as visibility conditions worsened.

THE FAA FLIGHT EVALUATIONS.

VISUAL GUIDANCE INFORMATION CONVEYED DURING APPROACH. As evidenced by the objective test data, there was a definite performance degradation of pilots flying under the ASALS when compared to the MALSR. Based on the added offset testing and comments made, when pilots try to process the visual guidance information provided by the ASALS, a delay is incurred in processing the information the ASALS is trying to convey. The delay is compounded as the pilot incorporates the ASALS information into his instrument scan and aggregates over the time the approach is conducted. This results in an apparent loss of performance when compared to the MALSR system, which does not exhibit this delay characteristic.

The delay may correlate to the sequence of the ASALS, where the 1000-ft station crossbar that indicates roll guidance and acts as a distance-to-go indication is illuminated. This illumination is dependent on the sequence of the system not defined by the Developer. If pilots do not receive the information indicated by the 1000-ft station crossbar at the right time in the sequence, then the pilot must concentrate on the system for a longer duration and receive those cues from the other stations with more than one strobe light unit. Effectively, the pilot is searching for the complete guidance needed. Alternatively, the pilot may wait the duration of the sequence for the 1000-ft crossbar to illuminate again. While this time may be relatively small, it does force the subject pilot to rely on visual memory. Dedication of time to a memory function interpreting visual information conveyed by the ASALS outside of the normal pilot scan is inefficient when compared to a steady source of visual guidance. The only other system currently used by the FAA completely composed of strobe lights is the Omnidirectional Approach Light Systems (ODALS), which is a Visual Flight Rules (VFR)-only system that conveys information about the extended runway centerline in a linear fashion without providing the same cues needed for a CAT I precision approach.

SUBJECT PILOT LEVEL OF COMFORT WITH THE ASALS. Averages of responses in postsession questionnaires indicated that the subject pilots felt the ASALS provided few inherit benefits over the standard MALSR. The level of comfort with the ASALS was rated, as an average, between "comfortable" and "neutral." However, approximately 27% of subject pilots who tested with further offset from the extended runway centerline indicated a preference for a steady-burning system to increase the level of comfort with the approach. Overall, the average subject pilot response to the ASALS, based on the rating systems provided, expressed a neutral or minimal guidance assessment over the current MALSR.

VISUAL ACUITY ASSESSMENT. An assertion was made by the Developer of the ASALS that the system improved the visual acuity of pilots after crossing the runway threshold. The ASALS was claimed to be superior to the MALSR as the flash delay was short enough not to close the pupils and restrict light entering the eye. This effect was evaluated by asking pilots to identify objects present on the runway after touchdown and to note any discomfort or noticeable visual acuity enhancement when conducting rollout under the ASALS versus the MALSR. Pilots successfully identified objects each time a member of the visual guidance team inquired during both MALSR and ASALS test approaches. No respondents indicated any enhanced visual acuity advantage when using the ASALS.

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APPENDIX A—BOUNDING AREAS FOR ON-COURSE DETERMINATION

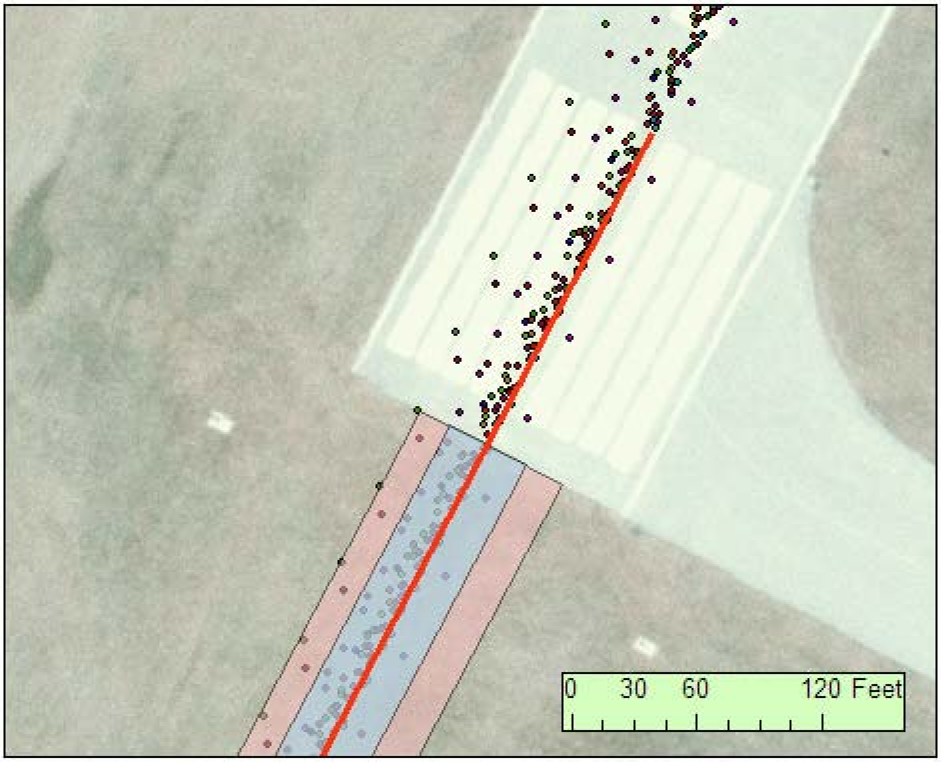

Figure A-1. Two Bounding Areas of Extended Runway Centerline

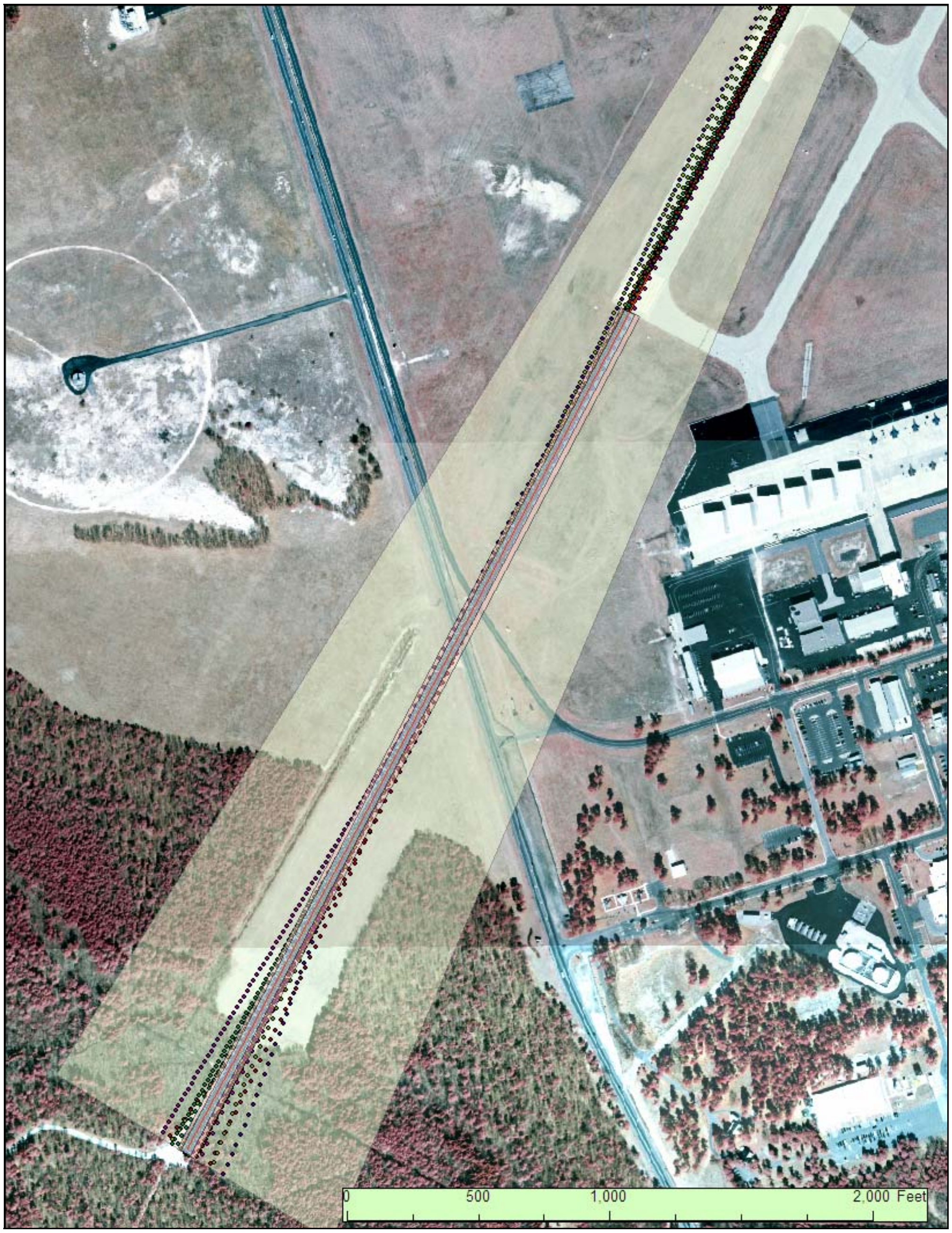

Figure A-2. The ACY ASALS Flight Test Approaches

Figure A-3. The ACY MALSR Flight Test Approaches

APPENDIX B—COMMENTS MADE BY SUBJECT PILOTS DURING TESTING

Table B-1. Comments Made During Testing

ASALS COMMENTS
“Only saw strobes in centerline fewer than expected to see, liked it had nice lead in wasn’t so bad when it got up close.”
“Not too bright.”
“Strobes can be better when coming out of the clouds. They can see the crossbar, good guidance for approach.”
“It took a few minutes for me to understand where I was with that presentation.”
“Much more recognizable that time, much more comfortable, with the presentation with info it was giving me.”
“It was providing me with lateral, as to where I was, definitely provided a lead into the centerline.”
“Notice a kind of pause in the sequence, I kind of knew where it was but it wasn’t outstanding.”
“Just seems like there’s something missing in that strobe thing, it draws you in but it just doesn’t give you the same confidence that the MALSR did. There’s just something missing.”
“Stayed on the runway a little longer, I could see down the runway not a problem”
“Only saw strobes they helped line me up on centerline quite nicely also marked the threshold too mainly just the runway.”
“Had Lasik surgery and because of the improvement in vision the strobes look harsher than the steady-burning which is softer.”
“I see them but I don’t know if I can read them or not.”
“Its not giving me the data I need to stay on course.”
“I do think the kind of angle you’re coming at is part of the situation.”
“That was better, that time I can see the linearity and effectiveness much better cause I was closer to final. It needs a little more contrast; it needs a little more color. When I’m on that line up it does look effective caught my attention it got me guided but so far off angle its tough cause I don’t have the contrast, change it to yellow flashing lights at the end or something to provide me that contrast.”
“It wasn’t something that I would’ve expected to see.”
“Having never seen that before it’s like I was busy looking at the flashing lights and not thinking about landing anymore so it took my mind off landing. But if this was normal then I won’t be surprised by it, so that’s not a good answer for the test but the very first time I saw them that’s what I said.”
“Its kind of like you do the outline but its like a black hole I’m flying into, with the [MALSR] approach lights there I know where I’m landing, but now I’m coming down there’s lights but there’s this hole because you don’t fill in the gap. You have this outline but the gap, so its kind of like not having them at all, its like flying into a hole so they don’t help much, I’m not impressed.”

Table B-1. Comments Made During Testing (Continued)

MALSR Comments
“I like the fixed segment lighting system cause that where my focus is when I coming in, I see the rabbits leading, where the rabbits lead me to a point. Where I know where I’m at above the ground, where that system running the whole thing running. Its kind of like a black hole void there as the whole light system is cycling, in my minds eye I don’t like that. It does give you information it lines you up but to me its like the fist time it was startling cause it was so tense cause of the strobes, and I kind of got used to it subsequently. It just doesn’t seem to give me the situational awareness that the MALSR does.”
“Excellent alignment, more easier on the eyes than the strobes, had no problems at all finding the threshold.”
“MALSR provided contrast different light coloring, different depth perception cause of the change of the geometric pattern, also gave some linearity with the runway by giving me lead in to the center, what the strobes do if you catch it right, it gives me ID that I’m in the airport environment but it doesn’t give me the line up that I’m looking for it makes me feel secure about landing, but again I’m not sure. I ‘d be interested to see as point what it would look like if I came in straight on it.”
“I like the normal one it’s the welcome mat that comes out, there is no question where the runway is with that because there as wide as the runway. With the All-strobes system there was a question where the center was, I know the runway is there somewhere, I’m sure it was somewhere, it was hard to find where I was in relation to the centerline.”
“Yeah the markings looked washed up, but so what, I’ve already made the decision to land I’m about to go into my flare.”

Table B-2. Comments Made by Pilots on 11/20/2006 Testing

MALSR RUN ONE
Pilot One: “I had the lights and it was an easy adjustment over and they pretty much guided me to the runway. I mean, they were pretty helpful. They looked like normal lights coming in.”
Pilot Two: “We’re used to seeing the MALSR.”
ASALS RUN TWO
Pilot One: “Sometimes I don’t know if they were distracting a little bit. But they kind of guided me right in there. They actually helped with the centerline track even though I was off to the right a little bit.”
“What is a little annoying, sometimes it’s on and then it’s off and you’re like, ‘Oh yeah, I can follow that…’”
Pilot Two: “I thought steady lights would have given me a place to shoot for so I think it took longer for me to perceive what I needed to do to get to the runway than with just steady flashing, or steady-burning lights.”
“You end up having to draw conclusions that you don’t have to draw when you have steady-burning lights.”

Table B-2. Comments Made by Pilots on 11/20/2006 Testing (Continued)

ASALS RUN THREE
Pilot One: "Well, that was interesting, being offset and coming in and trying to decipher the lights it takes a couple seconds." "Yeah, I didn't like it as much." "Straight in, you're fine. It takes a little while but right there was even worse." Pilot Two: "It was almost disorienting that time." "It took a good three to five seconds to discern what we should do to get there."
MALSR RUN FOUR
Pilot One: "That was much easier when I started to get over." "I was able to track right over and was there on the runway. I probably would have landed a little longer than I wanted."
ASALS RUN FIVE
Pilot One: "I still feel the same way, I was a little bit better this time because I knew what to expect. But they are still kind of in your face." "You know, I like the concept, but practical it's just not… it's funny, because when I flew this with [name omitted], I thought they were better but when you are actually flying them and you are trying to pay attention to the instruments back and forth I think that is where you get yourself disoriented." Pilot Two: "With those lights blinking like that with the thousand foot bar and then at the end of the runway, as kind of like REIL lights, the lights are bouncing around so much that it is much less friendly than steady-burning."
ASALS RUN SIX
Pilot One: "And you know, when I was with [name omitted] I was like, 'Oh, that's easy!' but when you are actually flying it's…" Pilot Two: "There is a certain definite time lag to orient with the strobes versus the steady-burning MALSR where there is no time lost deciphering what you are seeing."

APPENDIX C—POSTFLIGHT QUESTIONNAIRE RESULTS REGARDING ASALS

Question One				
“One a scale of 1 to 5, please indicate your level of comfort to flying the ALS.”				
1	2	3	4	5
18% (2)	18% (2)	36% (4)	27% (3)	0% (0)

Average Rating: 2.73

Rating System:
1 – Comfortable
3 – Neutral
5 – Unsafe

Comments:

- “I saw no benefit to Situational Awareness from these lights.”
- “The ASALS are good for runway alignment, but they are very obtrusive verses the MALSR.”
- “Lacks contrast that MALSR has, but doing approaches ok.”
- “Takes a couple of seconds to find the centerline, even a little disorienting”
- “It takes a finite time (4 seconds) to ‘process’ what you are seeing with the ASALS. This is precious time to wait to begin steering to the runway. MALSR does not have this problem.”
- “Uncomfortable when off to the side.”
- “Good SA for centerline.”

Figure C-1. Level of Comfort Results From Postbriefing

Question Two				
“Please rate the effectiveness of the ASALS in providing the following visual guidance during your approaches: Direction toward the runway threshold (initial guidance upon acquisition)”				
1	2	3	4	5
18% (2)	27% (3)	36% (4)	18% (2)	% (0)

Average Rating: 2.55

Rating System:
1 – Excellent Guidance
3 – Minimal Guidance
5 – No Guidance

Comments:

- “Level of intensity was good.”
- “Not having a ‘fixed’ lead in, seemed to leave a void in the center of the lighting system.”
- “Depth perception is definitely affected due to the black hole created w/ this lighting system.”
- “Lacks contrast.”
- “Straight on is ok. When offset the strobes overstep each other (edge + CC)”
- “I would not like anything less.”

Figure C-2. Effective Visual Guidance Upon Acquisition Results From Postbriefing

Question Three				
“Alignment with the runway centerline extended.”				
1	2	3	4	5
18% (2)	27% (3)	18% (2)	36% (4)	% (0)

Average Rating: 2.73

Rating System:
1 – Excellent Guidance
3 – Minimal Guidance
5 – No Guidance

Comments:

- “Alignment with runway centerline is the strong point of the system.”
- “No lineup.”
- “Because of the flashing 1000’ bar and REIL the guidance is compromised somewhat. This is because all flashers are not on centerline.”

Figure C-3. Alignment With Extended Centerline Results From Postbriefing

Question Four				
“Lateral rate of closure with the runway centerline extended (speed and/or deceleration).”				
1	2	3	4	5
% (0)	27% (3)	27% (3)	45% (5)	% (0)

Average Rating: 3.18

Rating System:
1 – Excellent Guidance
3 – Minimal Guidance
5 – No Guidance

Comments:

- “Steady-burning was much better but after ‘processing’ the ASALS rate of closure was OK.”
- “Hard to determine with only strobes.”

Figure C-4. Lateral Rate of Closure Results From Postbriefing

Question Five				
“Forward rate along the approach path using the lighting system as a reference.”				
1	2	3	4	5
9% (1)	18% (2)	45% (5)	27% (3)	0% (0)

Average Rating: 2.91

Rating System:
1 – Excellent Guidance
3 – Minimal Guidance
5 – No Guidance

Comments:

- “Gaps/distance between strobes cause a black hole effect and does not give”
- “Lights kept flashing not a steady reference.”
- “Much easier to measure forward rate against solid reference ie MALSR”
- “OK but not a ‘big’ indicator.”
- “In too close for rate estimation.”

Figure C-5. Forward Rate Results From Postbriefing

Question Six				
"Rate of vertical closure toward the lighting system."				
1	2	3	4	5
0% (0)	27% (3)	27% (3)	18% (2)	27% (3)

Average Rating: 3.45

Rating System:
1 – Excellent Guidance
3 – Minimal Guidance
5 – No Guidance

Comments:

- "Reliance on vertical closure with runway was based on PAPI and VASI and sight picture on windshield."
- "I didn't feel any vertical closure information with ASALS."

Figure C-6. Vertical Closure Results From Postbriefing

Question Seven				
"Position information in terms of distance remaining to the runway."				
1	2	3	4	5
0% (0)	36% (4)	27% (3)	36% (4)	0% (0)

Average Rating: 3

Rating System:
1 – Excellent Guidance
3 – Minimal Guidance
5 – No Guidance

Comments:

- "Make strobes extend out more system longer with lights."
- "Need more familiarity with system, some experience is with OLD system."
- "Once again, after processing time 1000' bar was somewhat helpful."
- "In too close for distance estimation."

Figure C-7. Distance Remaining Results From Postbriefing

Question Eight				
“Height above ground (altitude change).”				
1	2	3	4	5
0% (0)	9% (1)	27% (3)	36% (4)	27% (3)

Average Rating: 3.81

Rating System:
1 – Excellent Guidance
3 – Minimal Guidance
5 – No Guidance

Comments:

- “Needs more contrast”
- “I felt no altitude guidance with ASALS”
- “Not good for me.”

Figure C-8. Altitude Change From Postbriefing

Question Nine				
“Roll Guidance (wings at level).”				
1	2	3	4	5
0% (0)	20% (2)	20% (2)	50% (5)	10% (1)

Average Rating: 3.5

Rating System:
1 – Excellent Guidance
3 – Minimal Guidance
5 – No Guidance

Comments:

- “Uncertain.”
- “The farther offset from center the worse the roll guidance.”
- “Very poor when lateral.”

Figure C-9. Roll Guidance Results From Postbriefing

Question Ten				
“Rate the level of perceived task difficulty when flying over the approach lighting system.”				
1	2	3	4	5
20% (2)	20% (2)	30% (3)	30% (3)	0% (0)

Average Rating: 2.7

Rating System:
1 – Comfortable
3 – Neutral
5 – Unsafe

Comments:

- “Very distracting, flashing lights did not provide a ‘known quantity’ to judge distance, closure, or distance to runway threshold. Perhaps if the MALSR was ‘outlined’ with these strobes it might provide a benefit.’
- “If you’re off center to approach line, the strobes can be disorienting, and it takes the pilot time to correct and follow the guidance to the runway.”
- “Not unsafe but close to it when displaced from centerline.”
- “Good – not a big work load.”

Figure C-10. Task Difficulty Results From Postbriefing

APPENDIX D—THE NTSB ACCIDENT/INCIDENT DATABASE REVIEW FOR INCIDENCE OF APPROACH LIGHT GLARE INTERFERING WITH PILOT VISION

A review of the computerized National Transportation Safety Board (NTSB) database was conducted to identify aircraft accidents or incidents in which runway approach light glare was listed as a factor or cause in the mishap event.

The database was screened for the period of 1 January 1983 through 31 December 2000. During this period, a total of 45,817 aircraft accidents or incidents were recorded. To identify any records in which runway approach lighting was implicated as a cause or factor, the reports were screened for the words “approach lights” and “navaid.” This screen identified 107 records in which the terms appeared. Since the objective of this search was to identify accidents or incidents in which approach light glare was a factor or cause of the event, all daytime accidents and incidents were eliminated leaving 40 accidents or incidents that occurred at dawn, dusk, or at night.

In each of the 40 night, dawn, and dusk events, approach lights or navaids were mentioned in the report because the accident or incident involved the mishap aircraft colliding with lights or a navaid (localizer antennae, visual approach slope indicator (VASI), or instrument landing system (ILS) antennae). Of the 40 events, 2 were takeoff events, 4 events involved landing on unlighted runways, 1 event involved maneuvering to avoid deer on the runway, 1 event involved pilot incapacitation, 11 events involved runway overshoot (landing long), and 21 events involved landing short. In addition to colliding with an approach light or navaid, two event narratives contained comments that indicated that approach light glare was a factor.

13 October 1985, 1948 hours, Concord, CA. Ambient light condition, night—a general aviation pilot flying a Piper PA-28 landed short of the runway and collided with both the approach lights and an airport boundary fence. The pilot stated that she encountered excessive glare in her contact lenses from approach lights after she requested that the approach lights be turned up full bright. The National Transportation Safety Board (NTSB) determined the probable cause(s) as follows:

1. Planned approach inaccurate … Pilot in command.
2. Proper touchdown point: Not attained ... Pilot in command.
3. Go-around, not performed ... Pilot in command. and,
4. Visual/aural perception ... Pilot in command.

Note, glare or dazzle on contact lenses is a known hazard and has been reported in both day and night conditions. (Nakagawara)

15 July 1990, 0214 hours, Benton Harbor, MI. Ambient light condition, dark night—a commercial pilot flying a Lear LR-24D, flying an ILS approach to landing, broke out of the clouds at 1100 feet with an estimated 6-miles visibility. He reported that the high-intensity approach lights were on full bright and destroyed his night vision. After passing the approach lights, he was unable to see the runway surface and landed long, running off the departure end of the runway. The NTSB listed the probable cause as “Pilot-in-command’s misjudged approach to

landing, which resulted in the aircraft running off the departure end of the runway into a ravine. The late dark night IFR conditions contributed to the accident."

These two events have little in common except the comments regarding approach light intensity and that both occurred at night. The Piper PA-28 landed short, and the Lear LR-24-D landed long. The Lear pilot reported that he could not see the runway surface; the Piper PA-28 reported that the lights caused a distraction. Although the high-intensity approach light glare was common to both, the effect was obviously different.

Due to the small number of accidents and incidents involving reports of glare from approach lights (2 of 45,817) and the lack of common factors between the two reported incidents, no specific conclusions regarding approach lighting can be drawn. When one considers that 130 accident reports indicated that sun glare was a factor in the event, two reports of approach lighting glare would not appear significant.