AEROSPACE INFORMATION REPORT

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Superseding AIR1106A

(R) Some Factors Affecting Visibility of Aircraft Navigation and Anticollision Lights

RATIONALE

Information contained herein has been expanded from AIR1106A to include the use of Light Emitting Diode technology and more reference documents were added.

AIR1106B has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

This SAE Aerospace Information Report (AIR) is divided into four sections for two categories of readers. Sections 1 through 3 are primarily for the user of aircraft, whether as a pilot, crewmember, or in any other capacity, who does not need the more technical aspects of navigation and anticollision lighting, and its visibility. Section 4, on the other hand, is supplementary to Sections 1 through 3, primarily for the engineering designer, whether of aircraft or of aircraft exterior lighting, who needs to know certain technical aspects in greater depth, and/or needs the information to make important engineering decisions relevant to such lighting.

1. SCOPE

The scope of this SAE Aerospace Information Report (AIR) is to discuss factors affecting visibility of aircraft navigation and anticollision lights, enabling those concerned with their use to have a better technical understanding of such factors, and to aid in exercising appropriate judgment in the many possible flight eventualities.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

NOTE: The numbers associated with each reference document listed below are used for their identification in Section 3.

1. AS8037, Minimum Performance Standard for Aircraft Position Lights
2. AS8017, Minimum Performance Standard for Anticollision Light Systems
3. ARP991, Position and Anticollision Lights - Turbine Powered Fixed-Wing Aircraft
4. AIR1276, Aircraft Flashtube Anticollision Lighting Systems

2.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

TSO-C30c Technical Standard Order, Aircraft Position Lights

TSO-C96 Technical Standard Order, Anticollision Light Systems

AC20-74 Aircraft Position Lights and Anticollision Light Measurements

Code of Federal Regulations Title 14, Parts 23, 25, 27, 29 and 121. Some applicable sections may include, but are not limited to the following:

§2-.1385 Position light system installation

§2-.1387 Position light system dihedral angles

§2-.1389 Position light distribution and intensities

§2-.1391 Minimum intensities in the horizontal plane of forward and rear position lights

§2-.1393 Minimum intensities in any vertical plane of forward and rear position lights

§2-.1395 Maximum intensities in overlapping beams of forward and rear position lights

§2-.1397 Color Specifications

§2-.1401 Anticollision Light System

2.3 Other Publications

NOTE: The numbers associated with each reference document listed below are used for their identification in Section 3.

5. Reference Data for Radio Engineering, Sixth Edition, Second Printing, Howard W. Sams Co., Inc., ITT, Indianapolis, 1977.
6. Examination of Aircraft Interior Emergency Lighting in a Postcrash Fire Environment, James Demaree, DOT/FAA/CT-82-55, Final Report, Atlantic City, June 1982.
7. Handbook of Optics, Walter G. Driscoll, Editor, William Vaughan, Associate Editor, Sponsored by Optical Society of America, McGraw-Hill, p. 12-10, New York, NY, 1989.

8. IES Lighting Handbook, Reference Volume, John E. Kaufman, Editor, Jack F. Christensen, Associate Editor, Illuminating Engineering Society of North America, p. 3-5, New York, 1984.

9. Handbook of Optics, p. 12-21.

10. IES Lighting Handbook, Reference Volume, p. 3-8.

11. Handbook of Optics, p. 12-32.

12. Handbook of Optics, p. 12-15.

13. Handbook of Optics, p. 12-10.

14. Handbook of Optics, p. 1-8.

15. IES Lighting Handbook, Reference Volume, p. 1-6.

16. Aids to Navigation Manual, CG222, U.S. Coast Guard.

NOTE: The numbers associated with each reference document listed below are used for their identification in Section 4.

1. Handbook of Optics, p. 12-26.

2. Handbook of Optics, p. 12-27.

3. Handbook of Optics, p. 12-22.

4. IES Lighting Handbook, Reference Volume, p. 5-12, 5-13.

5. Visibility of Signal Lights, J. D. Lash and G. F. Prideau, Illuminating Engineering, November, 1943.

6. The Perception of Lights of Short Duration at Their Range Limits, A. Blondel and J. Rey, Transactions of the Illuminating Engineering Society, VII, 625, November, 1912. This is an English translation of two articles in the J.de Phy. et Radium, Vol. 1, Series 5, pp. 530, 643, 1911.

7. Effective Intensity of Flashing Lights, Theodore H. Projector, Illuminating Engineering, LII, 12, 630, December, 1957.

8. Computation of the Effective Intensity of Flashing Lights, Charles A. Douglas, Illuminating Engineering, LII, 12, 641, December, 1957.

9. IES Guide for Calculating the Effective Intensity of Flashing Signal Lights, Task Group of Aviation Committee, Illuminating Engineering, 747, November, 1964.

10. IES Guide, p. 749.

11. Projector, p. 636.

12. IES Guide, p. 749.

13. Projector, p. 638.

14. Projector, pp. 638-639.

15. Need for a Low Cost Short-Range Collision Prevention Device, Ted Linnert, National Transportation Safety Board Hearing into the Mid-Air Collision Problem, Airline Pilots Association, International, Washington, DC November 1969.

16. IES Lighting Handbook, Reference Volume, p. 3-23.

17. The Role of Exterior Lights in Mid-Air Collision Prevention, T. H. Projector, Contract No. FAA/BRD-127, Final Report No. 4, July, 1962.

18. Human Engineering Tests of Selected Aircraft Anticollision Light Systems, John E. Robinson, Contract ND as 57-5416, Contract No. as 59-6008.

19. ISO 11664-1:2007(E)/CIE S 014-1/E:2007: Joint ISO/CIE Standard: Colorimetry - Part 1: CIE Standard Colorimetric Observers," http://cie.co.at/index.php?i_ca_id=483

20. General Practice for the Measurement of Flashing Lights by Miller, C. C.; Davis, W. L.; Lee, S. E.; Gibbons, R. E.; Ohno, Y.

21. Analysis on Effective Intensity of Flashing Lights and Modification of Allard Method by Y. Ohno, D. Couzin.

22. Modified Allard Method for Effective Intensity of Flashing Lights by Y. Ohno, D. Couzin.

23. Physical Measurement of Flashing Lights - Now and Then by Y. Ohno.

2.4 Military Publications

Navy: MIL-L-006730 Lighting Equipment Exterior, Aircraft (General requirements for)

Air Force: MIL-L-6503H Lighting Equipment, Aircraft Specification for Installation of

3. DISCUSSION

Visibility of a light signal is determined by the amount of light arriving at the observer's eye through a medium or media of given conditions. In general, visibility will be greater when more illumination arrives at the observer's eye. This implies a brighter light is more visible than a less bright light. However, as will become evident in the following discussion, higher brightness levels may not be necessary or desirable because of other factors affecting visibility. This seeming contradiction will become more clear after reading the following sections. It is also a goal of this document to provide a better understanding of what factors affect visibility and what judgments need to be considered before any action is taken regarding the selection of a light source.

The factors of practical importance to visibility of aircraft navigation and anticollision lights fall into three major categories: (1) factors due to the lights; (2) factors due to the observer; and (3) factors due to the medium or media between the observer and the lights. Without regard to their order of importance, they can be listed as follows:

a. Light Source Factors:

   (1) FAA and Customer Requirements for navigation and anticollision lights

   (2) Intensity of the light source (and flash duration for ACLs) in the direction of the observer

   (3) Size of the light source

   (4) Color of the light source

b. Observer Factors:

   (1) Visual capabilities of the observer

   (2) Visual thresholds of the observer

   (3) Observer's state of visual adaptation

   (4) Effect of retinal location with regards to the impinging light image

(5) Effect of empty field myopia

(6) Observer alertness and search habits

(7) Observer distraction and fatigue

c. Media Factors:

(1) Effect of distance between the observer and the light source

(2) Atmospheric conditions and transmissivity

(3) Estimating visibility threshold ranges as a function of atmospheric conditions

(4) Location, size, and optical quality of cockpit windows

(5) Background luminance

(6) Other lights in the background

(7) Flashing versus steady-burning light sources for distance

3.1 Light Source Factors

Definition of which lights on an aircraft are "navigation lights" and which are "anticollision lights," and their required characteristics, are summarized.

3.1.1 Aircraft Navigation Lights

Navigation lights are alternatively designated as "position lights." They consist of: red lights on the left wing tip; green lights on the right wing tip; and white lights on the tail of the aircraft, or more recently on the trailing edge of each wing tip. These constitute the basic navigation lighting system, and are required for nighttime operations.[1]

The intensities of the red and green lights in the forward direction range from 40 cd as the minimum CFR requirement, to more than 300 cd in some cases. It is the practice to use dual light sources in position lights for redundancy on commercial aircraft.

Placing the white taillight on the trailing edge of the wing tips, or on the outboard trailing edges of the horizontal stabilizer, has two advantages: it makes maintenance easier, and provides more attitude information when viewed from the rear.

3.1.2 Anticollision Lights[2-4]

Anticollision lights are flashing lights generally of much higher intensity than navigation lights. They may be located on the top of the vertical fin, top and bottom of the fuselage or on the wing tips. Anticollision lights are generally either capacitor discharge (strobe) lights, rotating beacons, or electrically flashed incandescent lamps or other light sources (such as LEDs). Federal Aviation Regulations (FARs) require a minimum of 400 cd of "effective intensity" or 100 cd of either red or white light in the horizontal plane. Vertical coverage is 30 degrees above and below the horizontal plane for rotary wing aircraft, and 75 degrees above and below the horizontal plane for fixed wing aircraft. The intensity and configuration required depends on the date of certification of the airplane. The frequency of flashing can range from 40 to 100 flashes per minute (0.6 to 1.5 flashes per second). Strobe flashes typically have a flash duration of approximately 1 ms (or longer if other light sources such as LEDs are used). Many aircraft have red flashing lights on the top and bottom of the fuselage, with white flashing lights on the wingtips. Effective intensities can range from 100 to over 4000 cd.

Placing the white flashing lights on the wingtips may reduce problems resulting from reflections and/or backscatter that can interfere with crew vision. However, care must be given when placing the ACLs under the same lens as the Position Lights on the wingtips because these lenses are typically thin to match the wingtip profile. This in itself may produce unwanted reflections and/or backscatter.

3.1.3 Sources of Requirements

The sources of the minimum requirements for position and anticollision lighting for the three categories of aircraft are summarized as follows:

a. General Aviation: Applicable CFRs (see 2.2)

(1) Fixed Wing: Part 23

(2) Helicopters: Anticollision lights for helicopters are red flashing lights with a minimum of 150 cd in the horizontal plane, falling off to 15 cd at 30 degrees above and below the horizontal; Part 27

(3) Operating Requirements, Nighttime: Part 91

b. Commercial: Applicable CFRs (see 2.2)

(1) Fixed Wing: Part 25

(2) Transport Helicopters: Part 29

(3) Operating Requirements, Nighttime: Part 121

c. Military:

(1) Navy: MIL-L-006730

(2) Air Force: MIL-L-6503H

(3) Army: MIL-L-6503H

International standardization is attempted through documents published for civil aviation by the ICAO, and for military aviation by NATO.

Although military aircraft have many of the same lighting requirements as general aviation or commercial aircraft, there are additional special lights for specific military requirements. There are differences in intensity distribution requirements as well for the position and anticollision lights, which are given in the above documents.

Observations at a large airport at nighttime show there is considerable variety in the mechanization of the various basic requirements. From small to large aircraft, and even within a fleet of the same airline, differences are seen that relate to each model of aircraft. In all cases, however, at least the minimum requirements are satisfied.

3.2 Observer Factors

Many important factors arise in this category and are discussed to the extent they are relevant.

3.2.1 The Human Eye and Visibility

Fundamental to a better understanding of observer visibility is a basic knowledge of the human eye. As the key sensor in sending the information communicated by navigation and anticollision lights, the eye has certain special characteristics that are important here. These are: the pupil aperture, lens, distribution of sensors in the retina, color vision, thresholds of sensitivity, directional vision, residual effect of previous exposure to light or to the lack of it, the rate of recovery therefrom, age effects, and associated personal mental factors such as attention, concentration, alertness, search habits, distractions, and fatigue. It is to be assumed the observer here has normal healthy, properly qualified vision, or, if not, would not have a pilot's license.

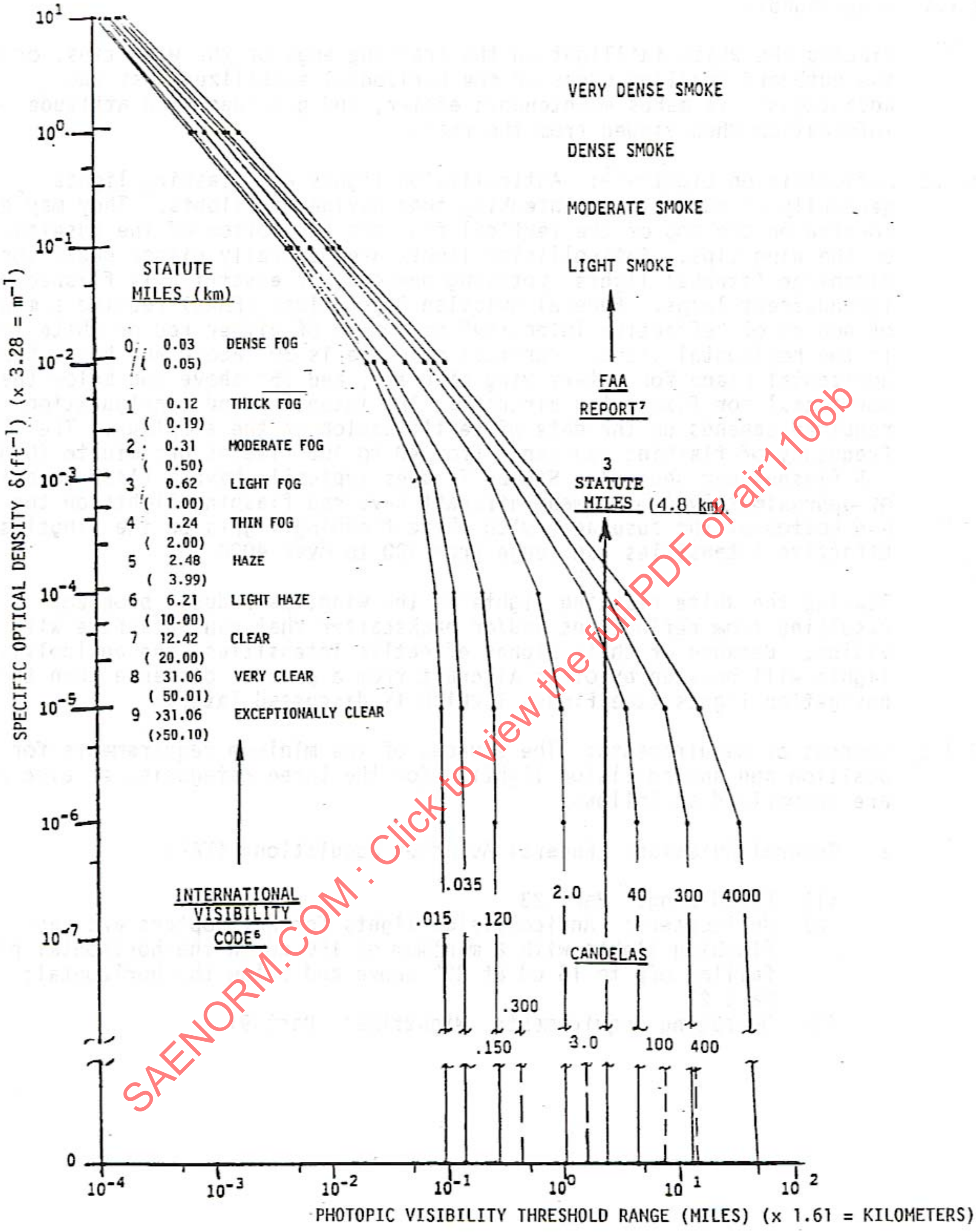

FIGURE 1 - SPECIFIC OPTICAL DENSITY VERSUS PHOTOPIC VISIBILITY THRESHOLD RANGE FOR FULLY DARK ADAPTED EYE

3.2.1.1 The Pupil of the Eye

The pupil of the eye is the variable aperture, the visual field stop, which is under the involuntary control of the iris, automatically adjusting to the flux of incoming light. The aperture diameter can range between about 2.5 mm and 8 mm, normally being at about 4 mm.[7] For a very low light level it would tend to be about 8 mm, and conversely at a very high light level to be at about 2.5 mm. The eyelid of course also assists in reducing excessive flux into the eye, but optically functions as a voluntary "blind" rather than an involuntary field stop.

The pupil, therefore, is important in determining the amount of light entering the eye, particularly when the light source is at a great distance. The threshold illuminance necessary to satisfy the threshold sensitivity of the eye is partly determined by the pupil aperture, and in turn helps determine how far and how well the eye can see.

3.2.1.2 The Lens of the Eye and Accommodation

The lens of the eye, directly behind the pupil, is able to change its shape, to "accommodate", to bring the object of interest into clear focus onto the retina. Accommodation for near and far objects is able to change rapidly. For distant and near field objects, the lens focus can switch repeatedly from a clear view of navigation lights of another aircraft at infinity to a view of the instrument panel, thereby converging the flux of incoming light photons onto the retinal sensors to produce clear but voluntarily changed images.

3.2.1.3 The Retina of the Eye

The retina has two kinds of sensors: rods and cones. Their discriminatory response to photons of different energies, their different sensitivities, and their retinal distributions are the bases for the unique light and color vision capabilities, threshold sensitivities, and directional and field depth sensing capabilities of the human eye. They are the key physiological bridge between the outside world and the inside of the human observer and his mental processes.

The function of the rods and cones differs, the rods being the source of scotopic or achromatic (white, gray, black) vision, whereas the cones are the source of photopic or color vision. Discussion of this subject is continued in greater detail in 4.1, 4.2, 4.3, and 4.4.

3.2.1.4 Visual Adaptation

The process of visual adaptation involves three major processes:[8] (1) change in pupil size, (2) neural adaptation, and (3) photochemical adaptation.

Change in pupil size has been previously described. It is an involuntary mechanism, adjusting automatically under control of the iris for very dim to very bright incoming light.

Neural adaptation is a process whereby the sensitivity of the visual system changes due to exposure to light below a luminance level of about 60 cd/ft^2 (646 cd/m^2). A 40 W frosted bulb has a luminance of about 58 cd/ft^2 (624 cd/m^2). Since such moderate exposure has not caused the photopigments in the cones to undergo bleaching, recovery is fast, less than 1 second, enabling the neural processes of the cones to respond immediately to new stimuli. This constitutes normal vision.

Photochemical adaptation, however, is the result of photopigments in the rods and cones having been bleached by luminance light levels above 60 cd/ft^2 (646 cd/m^2). In the dark, the pigments are regenerated, being ready again to function as usual. The regeneration, however, takes some finite time, with the result that changes in sensitivity lag behind stimulus changes. The cone system adapts much more rapidly than the rod system, as much as about 5 or 6 times faster. Even after exposure to a high luminance, the cones can regain nearly complete sensitivity in 10 to 12 minutes in the dark, whereas the rods will take 60 minutes or more to dark adapt.

The reduced visibility that everyone experiences after entering a dark movie theater from a sunlit outdoors is one example of "transient adaptation." If recovery is fast, namely less than 1 second, then neural processes only were involved in preceding visual observations. If, however, recovery is slow, longer than 1 second, then changes occurred in the photopigments during the preceding visual observations. Reduced visibility, moreover, can occur when a task to be performed follows a sustained viewing of not only a higher, but also a lower luminance than that involved in the task. One practical example is "empty field myopia."

3.2.1.4.1 Empty Field Myopia

There are a number of conditions encountered when flying at night, as well as daytime, where there is no detail of any kind to be seen outside the aircraft. Under these conditions, when the pilot looks outside the aircraft, his eyes will tend to be focused for a distance very close to the aircraft, of the order of 20 feet (6.1 m). Under these conditions, a light must be brighter or otherwise more distinctive to attract his attention. Transient adaptation hence is relevant as a factor involving visibility of aircraft navigation and anticollision lights.

3.2.1.5 Distribution of Rods and Cones in Retina

The rods and cones are not uniformly distributed in the retina.[9] There are approximately 120 million rods, the maximum concentration being in the peripheral region of the retina, falling off to none at the fovea centralis. The fovea is in a direct line behind the lens, and constitutes the sensory center for photopic vision. There are around 6 million cones in the retina, the greatest concentration being at the fovea, falling off outside this area to where the density of cones becomes relatively constant over the rest of the retina. The three kinds of cones are apparently equally distributed, except that the short wavelength (violet sensitive) cones are sparse or nonexistent in the fovea. As stated, there are no rods in the fovea either.

At dim luminance levels the rods determine sensitivity; at bright levels the cone system dominates. Hence, night vision is primarily determined by the rods; the cones, being less sensitive, are below their threshold in nighttime darkness. Day vision is determined primarily by the cones, the lens focusing the incoming light on the fovea for optimum light definition and color discrimination. Peripheral vision, however, is optimum because of the peripheral concentration of rods.

3.2.1.6 Visual Field of View

The visual field of view, besides basic eye properties, is determined by one's facial features for monocular (one eye) and binocular (two eyes) visibility.[10] Typically, monocular vision sideways is to about 60 degrees toward the nose and to about 90 degrees toward the side. Upward it is to about 50 degrees and downward to about 70 degrees. Binocular vision, however, results in overlap, both eyes sharing a central horizontal field of view of about 120 degrees. To direct this field of view in a different direction, one moves one's eyes or head accordingly.

Considering the viewing of the field by a pilot during flight, therefore, the primary objective is to see any objects in flight, namely other aircraft in daytime, or their navigation and anticollision lights at nighttime. The concentration on such viewing is three-dimensional, in contradistinction to the two-dimensional alertness required for automobile driving.

3.2.1.7 Visual Acuity and Light Source Size

The minimum angle of resolution, or the resolving power, of the human eye is about 1 minute of arc.[11] The reciprocal of the minimum angle of resolution is defined as "visual acuity." Normal visual acuity, therefore, is 1.0. This means that, if the size of the two or more objects, or their separation, subtends an arc smaller than 1 minute, they will tend to be seen as one object rather than as separate objects.

This is of particular relevance in viewing aircraft exterior lights. Their size, when seen from any great distance, appears to be that of a point source. This arises from the fact that the size of the object, as a function of distance relative to the observer, visually becomes smaller with distance. The transition distance at which a light source changes from being seen as an "areal source" to a "point source" is where conservatively its visual size subtends an arc of 2 minutes. Assuming a circular shape of the light source, this approximate transition point can be defined as the point at which the ratio of the radius of the light source to the distance of the observer from the center of the light source is equal to the tangent of 1 minute of arc, which is 2.9089×10^{-4}.

As a practical example, if the diameter of the light source is 5 inches (12.7 cm), the radius, therefore, being 2.5 inches (6.35 cm), the transition distance x at which the light source changes from being seen as an areal source to that of a point source is approximately:

$$x = \frac{2.5}{2.9089 \times 10^{-4}} \quad \text{(Eq. 1)}$$

Therefore: x = 8594 inches (21 829 cm), or 716 feet (218.3 m), or 0.14 miles (0.22 km).

As is evident, the transition can occur at relatively small distances. It also shows to what extent it is futile to increase the transition distance considerably by increasing the size of the light sources.

The diameter of an object, if the transition distance is to be 1 mile (1.61 km), would be about 3 feet (0.91 m). This means several objects clustered within a circle of 3 feet (0.91 m) would not be distinguished as separate at 1 mile (1.61 km) distance. Moreover, two lights of small diameter, such as 5 inches (12.7 cm), would have to be about 3 feet (0.91 m) apart to be seen as separate at a 1 mile (1.61 km) distance. There are, however, some aircraft exterior lighting applications where light sources with apparent extent larger than a point source have been found to be of value. In formation flying, for instance, lights of a larger size can provide better range information to the observer than small sources, being seen as areal sources within the relatively close spacings of formation flying.

3.2.1.8 Effects from Aging

As one's age increases, the eye gradually loses its flexibility and adaptability.[12] The range of accommodation for close vision, and the amount of light entering the eye due to pupil diameter reduction, are both reduced considerably. Add to this that speed of perception decreases, time needed for dark adaptation increases, and luminous thresholds are higher.

In young eyes, the retina receives radiation in the range between 380 to 950 nm with little attenuation. It is variable beyond 950 nm, with little beyond 1400 nm. Hence, any source with high infrared radiance should not be viewed directly.

The optics of the eye transmit more light at the long wavelengths (red end of the spectrum) than at the short wavelengths (blue end). In young eyes, on the average, around 70 to 85% of the visible spectrum reaches the retina. But, as one gets older, the transmittance becomes less at all wavelengths. This reduction is over four times greater at the short wavelength end, primarily because of the yellowing of the lens.

The eye also has internal scattering, due primarily to large particle scattering. Therefore, the amount of scattered light within the eye decreases slightly with wavelength. However, the amount of light scattered in the eye increases with age, due almost entirely to changes in the lens.

3.3 Media Factors

These include all factors between and around the light source and the observer that can affect visibility, including distance, atmospheric conditions, windows, other lights, background, etc.

3.3.1 Attenuation Due to Distance Alone

In the absence of atmospheric or any other attenuation, the illuminance of an observer's eye E, located at a distance x from a light source of intensity I, is given by the basic inverse square law of optics:

$$E = \frac{I}{x^2} \quad \text{(Eq. 2)}$$

As is seen from the equation, the illuminance at the eye is inversely proportional to the square of the distance. Therefore, disregarding all other parameters, the illuminance at the eye is reduced by a factor of $\frac{1}{x^2}$, compared to the intensity at the light source.

For example, an aircraft navigation light intensity (I) of 40 cd, at a distance of 1 foot (0.305 m) (x), would have an illuminance at the eye (E) of 40 lm/ft^2 (430 lm/m^2). However, at a distance of 1000 feet (305 m), the illuminance would be 4.00 x 10^{-5} lm/ft^2 (4.3 x 10^{-4} lm/m^2), having attenuated the illuminance to 1 millionth of its original value. Distance alone, therefore, can be a major factor in reducing the visible brightness of any light source.

3.3.2 Attenuation Due to Atmospheric Transmissivity

Besides attenuation due to distance as discussed in 3.3.1, the media through which the light travels can additionally attenuate the brightness. The atmosphere, with its wide variety of possible conditions, can have a wide variety of transmissivities. Transmissivity T_o is defined as the amount of radiant power transmitted per unit distance.

Transmittance T is the ratio of the amount of radiant power transmitted over the total pathlength, in other words to the end of the pathlength, relative to the amount of radiant power incident at the beginning of the pathlength. It can be stated as:

$$T = \frac{I_x}{I_o} \qquad \text{(Eq. 3)}$$

$$I_x = TI_o \qquad \text{(Eq. 4)}$$

Hence the intensity at the end of the distance x is the result of the initial intensity I_o being modified by the transmittance T of the atmosphere. The value of T for a perfectly clear atmosphere is approximately 1.0, but for all the other atmospheric conditions is always less than 1.0.

Since transmissivity T_o can be defined as the transmittance T per unit distance, the attenuation effect due to each successive unit distance on the summation of the effects of the previous unit distances can be stated as an exponential for the whole pathlength as follows:

$$T = T_o^{\,x} \qquad \text{(Eq. 5)}$$

Therefore:

$$I_x = T_o^{\,x} I_o \qquad \text{(Eq. 6)}$$

The exponential for transmittance can be stated in another useful way as follows (based on Lambert-Beer-Bouguer Absorption Law):

$$T = \frac{I_x}{I_o} = 10^{-\delta x} \qquad \text{(Eq. 7)}$$

where δ is the specific optical density per unit distance. If the log of the inverse of T is taken as:

$$\log\frac{1}{T} = \delta x \qquad \text{(Eq. 8)}$$

then:

$$\delta = \frac{\log\frac{1}{T}}{x} \qquad \text{(Eq. 9)}$$

For an example, see Figure 1. Consider an aircraft navigation light intensity of 40 cd, but as seen through a light fog. Let δ = 1.0 x 10^{-3}/feet (3.28 x 10^{-3}/m), and x is selected distances. The transmittance T and path end intensity I_x due to atmospheric attenuation alone would be as follows:

δ ft^{-1} (m^{-1})	x ft (m)	T	I_x cd
1 x 10^{-3} (3.28 x 10^{-3})	1 (0.305)	0.99	39.60
1 x 10^{-3} (3.28 x 10^{-3})	1000 (305)	0.10	4.00
1 x 10^{-3} (3.28 x 10^{-3})	5280 (1610)	5.25 x 10^{-6}	2.10 x 10^{-4}

These values do not include the inverse square attenuation due to distance, whereas Figure 1 does, as is discussed next.

3.3.3 Combined Distance-Media Attenuation

For the distance-attenuating equation of 3.3.1 to be valid, the transmittance must be 100% in all cases. For the media-attenuating equations of 3.3.2 to be valid, the light rays would have to remain parallel and not spread with distance. In real life, however, these are ideal special cases of the general case that light rays: (1) spread however minutely, and (2) are modified in intensity by media conditions. Hence, both effects are combined into the one general equation as follows (designated by some as Allard's Law):

$$E = \frac{I_o T_o^{\,x}}{x^2} \qquad \text{(Eq. 10)}$$

or

$$E = \frac{I_o T}{x^2} \qquad \text{(Eq. 11)}$$

Applying the general equation to the visibility of the navigation and anticollision lights of other aircraft, one key question is: what value is to be used for the threshold illuminance E_o at the observer's eye? This value is necessary for determining: (1) to what distance these lights can be seen under clear or variously adverse optical conditions; or alternatively, (2) what intensity of these light sources is required to be visible for a chosen set of distances and various adverse optical conditions.

3.3.3.1 Some Values of Eye Visibility Threshold Illuminance

The eye threshold illuminance E_o has been extensively investigated with varying methods and results. The threshold illuminance from a point source emitting white light, observed against a dark background, and with media conditions being fairly favorable, is of the order of "0.01 mile candles (0.0039 km candles)."

This unique way of expressing illuminance relates to the fundamental English illuminance unit of "foot candle," which is defined as: 1 lm of light flux falling on a unit area of 1 square foot. Hence, "0.01 mile candles" corresponds to 0.01 (0.0039) lm falling on 1 square mile (1 km^2) of area, implicitly at a distance of 1 mile (1 km) as will be discussed below. This in turn is equivalent to 3.59 x 10^{-10} lm/ft^2 (3.86 x 10^{-9} lm/m^2). Considering the normal eye pupil aperture diameter to be about 4 mm,[14] this would correspond to an eye pupil aperture area of 1.35 x 10^{-4} ft^2 (1.255 x 10^{-5} m^2). Hence, 0.01 mile candles (0.0039 km candles) would correspond to 4.85 x 10^{-14} lm per normal eye pupil aperture area.

Further, since the color of the light is described as "white," which photopically is a mixture of all colors, this presents a problem in estimating how many photons per second are falling on the pupil to stimulate a threshold sensation of white. Moreover, being a very low flux, it is probable it is a scotopic sensation, further complicating the estimation. However, to provide a relative feel for how low this flux can be, if hypothetically it is assumed that the flux is all at the most sensitive wavelengths of the scotopic or photopic eye sensitivities, the number of photons per second falling on the pupil of the eye for the scotopic peak at 510 nm would be about 72 photons per second, but for the photopic peak at 555 nm would be about 198 photons per second. Since the sensitivities at other than these two wavelengths are less, it implies a larger flux of photons per second would be necessary for a "white" light to be "just visible."

Another factor to consider is the light unit of "candle." As one expert puts it, "Although the basic concepts of radiometry and photometry constitute an elegant system, the conglomerate of terms, symbols and units that have been applied to these concepts is inelegant."[14] These require thorough study for their proper understanding.

Hence, without getting into the morass of light units other than necessary, suffice it to say the term "candle" is to be considered obsolete. In its place the term "candela" is to be used.[15] In concept and definition, "candle" is practically the same as "candela (cd);" only the name of the unit is changed. However, it must be noted candela is the basic unit of intensity, and is defined as "1 lm per steradian."

Therefore, in the context of the terminology "mile candle (kilometer candle)," primary interest is on the amount of lumens falling on a unit area as an illuminance, a unit cone angle of the point source being implied. Users of this terminology understand "0.01 mile candles (0.0039 km candles)" to mean: "The illuminance due to a light source of 0.01 cd (0.01 lm per steradian) on a surface area 1 mile (1 km) away." However, a cone angle of 1 steradian at a distance of 1 mile (1 km) defines an area of 1 $mile^2$ (1 km^2). Hence, 0.01 $lm/mile^2$ (0.0039 lm/km^2) is the illuminance of such a light source at a distance of 1 mile (1 km).

Other visibility thresholds are used for other fields. Experts concerned with marine navigation, for example, consider a visibility threshold of "0.5 mile candles (0.19 km candles)" as an acceptable practical value. The U.S. Coast Guard accepts this value.[16]

In the field of aviation, however, it is the consensus that a higher visibility threshold value should be used. Such factors as the higher speeds, the variety and multiplicity of other brightnesses in the background, the different levels of flight, etc., dictate a higher threshold. Since the visual range of runway lighting is computed on the basis of a visibility threshold of "2 mile candles (0.77 km candles)," this is used here for aircraft flight application.

This is equivalent to a source intensity of 2 cd (0.77 cd) emitting its light toward an observer 1 mile (1 km) away, the transmittance being 100%. As for the case for 0.01 mile candles (0.0039 km candles), the 2 mile candles (0.77 km candles) case translates into an illuminance of 2 $lm/mile^2$ (0.77 lm/km^2) at the observer. In turn, this corresponds to illuminances of 7.17×10^{-8} lm/ft^2 (7.7×10^{-7} lm/m^2) or 9.68×10^{-12} lm per normal eye pupil aperture area. Considered from the standpoint of green, red and white lights, this can correspond approximately to the following rates of photon flux for the respective colors:

Color	2.0 Mile Candles (0.77 km Candles) Visibility Threshold Flux Rate photons/second	
	Photopic	Scotopic
Green	39 597	14 407
Red	771 934	59 584 879
White*	552 137	19 875 741
Blue (1/3)	281 627	9 313
Green (1/3)	13 199	4 802
Red (1/3)	257 311	19 861 626
	552 137	19 875 741

*White: A representative approximation is made here dividing the total energy for white into three equal energy portions, and estimating the number of photons/second flux of three primary colors that could in equal energy proportions produce the sensation of "white." Hence, 3.23×10^{-12} lm per eye pupil aperture area are assigned to each color for estimating photon flux of blue (450 nm), green (555 nm) and red (660 nm).

As can be concluded from the above table, both photopically and scotopically, the ranking of visibility thresholds can be stated as follows:

lowest photon flux:	green
intermediate photon flux:	white
highest photon flux:	red

As also illustrated in 4.2, the threshold red photon flux photopically is 771 934 photons per second, compared to that scotopically as 59 584 879 photons per second. This shows that red photons will be sensed photopically as "red," to the exclusion of seeing them scotopically as "white" or "gray."

The highest flux levels are necessary to sense the photons of lowest visible photon energy, namely red. Therefore, from a visibility threshold flux standpoint, provided equal energy is emitted for each color, the navigation lights would be ranked: (1) green as most effective, (2) white as second most effective, and (3) red as third most effective.

3.3.4 Aircraft Window Transmittance

It is possible for aircraft windows to be additional sources of attenuation of navigation and anticollision lights of other aircraft. Such factors can be:

a. Dirty windows

b. Poor optical quality of the window

c. Poor optical condition of the window

d. Sun blinds and visors

The typical transmittance through windows soiled by exposure to various environmental conditions can be summarized broadly as follows:

Cleanliness Condition	Vertical Window	Sloped Window	Horizontal Window
Clean	0.9	0.8	0.7
Moderately Dirty	0.8	0.7	0.6
Very Dirty	0.7	0.6	0.5

It is obvious that aircraft windows should be kept clean for all flights.

Poor optical quality is more likely to be found in the formed plastic windows of small aircraft than in windows of airliners. However, depending on the number of panes and layers of materials of differing indices of refraction in a window, the transmittance through such a window is partially reduced due to multiple reflectances at every interface.

In a multilayered window, whenever the impinging light passes from a material of higher index of refraction to a material of lower index of refraction, total reflection can occur at any angle of incidence equal to or greater than the critical angle. This effectively can render the source of light either invisible, or, as is commonly experienced, because multiple images of the same source to be seen. In any case, the baseline transmittance is that available for a particular kind of window chosen by the manufacturer for production of an aircraft design.

Poor optical condition of a window can result from such factors as scratches, cracks, pits, or crazing of any materials involved. For instance, in an automobile used over several years, when the windshield is replaced with a new windshield, the observer is surprised to find his view through the new window is excellent; it is as if there were no windshield there. Shatterproof glass, with its intervening plastic layer, can become crazed over a period of time, microcracks or other deformities serving to compromise the transmittance of the window.

Sun blinds and visors, whether of an opaque or partially transmissive type, obviously curtail viewability by the observer. However, since the observer can optionally choose to use, adjust, or not use these, it becomes a question of observer judgment whether these should be used under particular circumstances. Alertness dictates as full a view as possible to the three-dimensional surroundings during flight. The near-misses of aircraft in flight these days also dictate an alertness comparable to that necessary for crowded freeway driving.

3.3.5 Background Light From Aircraft Exterior Lights

Direct light from the aircraft's own exterior lights is avoided by design. However, such light can be backscattered into the cockpit. Backscatter generally is the light reflected or refracted into the cockpit from the aircraft's own exterior lights by the variety of atmospheric conditions.

Due to the wide variety of sizes of particles and/or aerosols, and their number density in the atmosphere for the different atmospheric conditions, as the transmittance lessens, the scattering due to reflectance and refraction increases. Backscattered light typically is the second-most quantitative portion of the scattered light, the first-most quantitative portion being forward scattered light.

The effect resulting from steady-burning compared to flashing lights can be different. The effect of backscatter on a pilot from steady-burning lights may be to: (1) create a veiling foreground luminance, or (2) provide sufficient luminance to affect the pilot's level of dark adaptation.

When lights are flashed, the backscatter may be much more serious. For the first anticollision lights, the flashing effect was obtained by rotating a high intensity beam of light. Early flight evaluation of white lights showed that the moving beam viewed through any kind of visible moisture was rather disorienting to the pilots. This condition was remedied by the use of red color filters and locating the light on the top of the vertical fin to get it as far from the cockpit as possible.

The use of white electrically flashed lights such as strobes produces less problems but can still cause objectionable backscatter.

Location of these lights on the wingtips laterally separated from the pilot as far as possible provides the best solution to the backscatter problem. When flying through clouds at night, flashing lights should be turned off.

3.3.6 Other Background Lights

The exterior lights of other aircraft need to be viewed against a wide variety of backgrounds. The background may be a black sky at night, an overcast sky, scattered lights on the countryside, or closely clustered city lights. The intensities of such background lights can vary from faint stars to floodlights on the ground producing thousands of candelas. Also, colors can range through the complete spectrum. Therefore, it becomes important that the color, intensity, and flashing cycles to be used with aircraft lights be made to differ as much as possible from the various lights which may be encountered in the background under the different conditions.

3.3.6.1 Background Luminance

A light source is seen by virtue of its contrast in brightness and/or color with regards to the background against which it is viewed. A light of relatively low intensity may be seen in clear weather or considerable distances against an almost completely black sky background. The background brightness from typical dark night conditions to bright daylight conditions can vary on the order of one billion to one.

The background luminance (brightness) can also have a considerable effect on the level of adaptation of the observer. See 3.2.2.1.4.

It is possible, as mentioned above, that backscatter from lights close to the observer can, as the result of shining into a haze or fog, increase the foreground luminance. Under these conditions, forward scatter can be greater than backward scatter. Also, the sky brightness in the vicinity of a city or town, even though small, can be considerably higher than the natural background brightness elsewhere under the same meteorological conditions.

Note to the Reader:

At this point it is recommended to aircraft pilots and crews that the following portions of Section 4 be read carefully and applied to their own flights as appropriate:

a. 4.4.3 Threshold Visibility Ranges of Navigation and Anticollision Lights

b. 4.4.4 Estimation of Closure Times to Collision

c. 4.5.1.3 Practical Application of the D or A Rating

d. Tables 2, 3, 4, and 5

Section 4 covers the more technical aspects of threshold vision regarding: (1) the colors used for navigation and anticollision lights; (2) their visibility ranges when produced as flashes or as steady burning in all atmospheric conditions; and (3) a recommended method of rating different lights and lighting systems for these purposes, and how the ratings can be helpful in flight.

4. ADVANCED TECHNICAL DISCUSSION

4.1 Scotopic and Photopic Vision and Color

Scotopic vision is "achromatic" by definition; the rods sense all visible radiation, or lack of it, as white, gray, black. Photopic vision, however, is "chromatic;" the cones function as photon energy discriminators and sense incoming photons as the colors excited by and corresponding to their different energies. The energy of each photon is inversely proportional to its wavelength. It is more common practice to describe the relationship of photons to color by their wavelength rather than by their energy.

Scotopic and photopic vision differ in their sensitivities to the energy spectrum, hence wavelength spectrum, of visible photons. In general, rods have a sensitivity about 1000 times greater than that of the cones.[1] It takes a lower flux of photons to excite rods into sensations of white or gray, as compared to exciting the cones into color sensations. Research indicates that as few as about 54 to 148 photons at 510 nm (green) entering through the pupil of a dark adapted eye, as a flash of 1 ms flash width, can be "just visible" as a scotopic threshold sensation.[2] This in turn implies a photopic threshold at 555 nm (green) of around 54 000 to 148 000 visible photons per flash of 1 ms flash width through the pupil of the eye for color vision.

Cones, moreover, differ in their capability to sense color. Three basic kinds of cones exist, each being sensitive to photon energies corresponding to red, green or violet colors. This gives rise to the concept of "primary colors." However, "secondary color" sensations of yellow, blue and purple can be produced as the result of simultaneous excitation of the pair of "primary cones" responsible for the secondary color. This indicates that each kind of primary cone has a lower and higher range of photon energy to which it is sensitive, and which overlaps with that of each of the other two kinds of primary cones, enabling simultaneous excitation of them as a pair. Hence, the visible spectrum of colors is excited by photons ranging from highest to lowest energy in succession as follows: violet, blue, green, yellow, orange, red. Purple, not being a spectral color, is the exception, and results from the simultaneous excitation of violet and red sensitive primary cones, which primary colors are at opposite ends of the spectrum. That is why there is no purple in a single rainbow.

Both the rods and cones differ in their sensitivity to the different photon energies or colors. All visible photons are sensed by the rods as white, through grays, or black. In turn, it is also possible for the cones to produce white or gray sensations by the appropriate excitation of all three primaries, or all three secondaries, or one primary with its complementary secondary. Hence, white as a color sensation can be the result of a sufficiently intense excitation of the rods alone, or of all three kinds of primary cones, or the combination of both.

Spectrally, gray is the same as white, except that the intensity of excitation is less, shades of gray descending into black with descending intensity of excitation. Some experts disagree whether white, gray, and black are colors; hence the designation "achromatic." However, since the cones, the "color receptors," sense these the same as all other colors, and they are definable within a chromaticity diagram, technically they are colors. Moreover, common usage designates them as such.

4.2 The Standard Observer

Visibility factors should be based on the CIE 1931 Standard Colorimetric Observer using the photopic response and 2° field-of-view (Reference 19). The CIE 1976 CIELUV uniform color space should be used for color, intensity, luminance, and illuminance analyses and more recent CIE color spaces (like CIE 1994) should be considered. It is recommended that the CIE 1976 2 degree standard observer be used, "ISO 11664-1:2007(E)/CIE S 014-1/E:2007: Joint ISO/CIE Standard: Colorimetry - Part 1: CIE Standard Colorimetric Observers," http://cie.co.at/index.php?i_ca_id=483.

Individual observers can differ in their thresholds of sensitivity for scotopic and photopic vision. Research, however, shows that it is possible to define a "standard observer" with respect to sensitivity to the visible spectrum of photon energies for all observers. This is shown in Figure 2. The curves for scotopic and photopic vision show the relative efficiency of rods and cones as a function of wavelength when normalized to the same maximum of 1.0.

The curves of Figure 3, however, are developed by applying this data to the experimentally determined data point for a single millisecond flash. It was found that a maximum of 148 photons at 510 nm, the wavelength of maximum scotopic sensitivity, falling on the pupil of the eye, established the conservative scotopic threshold of visibility of a fully dark adapted eye. This is the basis of the scotopic curve in Figure 3. Since photopic vision requires a corresponding threshold visibility flux about 1000 times greater, the estimated data point at 555 nm establishes the estimated photopic curve in Figure 3. It should be noted again that photon energies are inversely related to their wavelengths; the lower the wavelength, the higher the energy per photon.

The unique display of the spectral visibility threshold flux curves for scotopic and photopic vision, as shown in Figure 3, is of particular technical and practical value as developed for this document. This represents the conservative "best visibility" that the human eye can have. Careful study of these two curves relative to each other will help explain why certain visual observations occur as they do, as will be discussed below.

In turn, the conclusions to be drawn from these curves can be applied practically and beneficially how to and when to use, or signal with, the lighting systems available, or interpret what is seen. They can be very important in the daytime as well as nighttime. Some of these conclusions are considered below as relevant visibility factors.

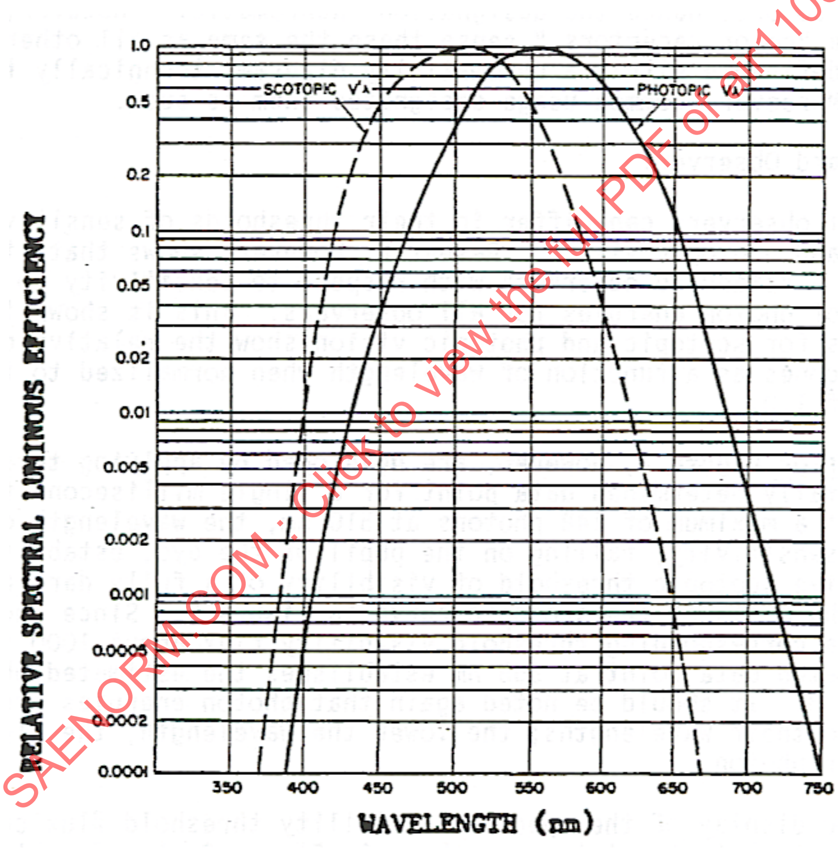

FIGURE 2 - RELATIVE SPECTRAL LUMINOUS EFFICIENCY VERSUS WAVELENGTH OF THE STANDARD OBSERVER[3]

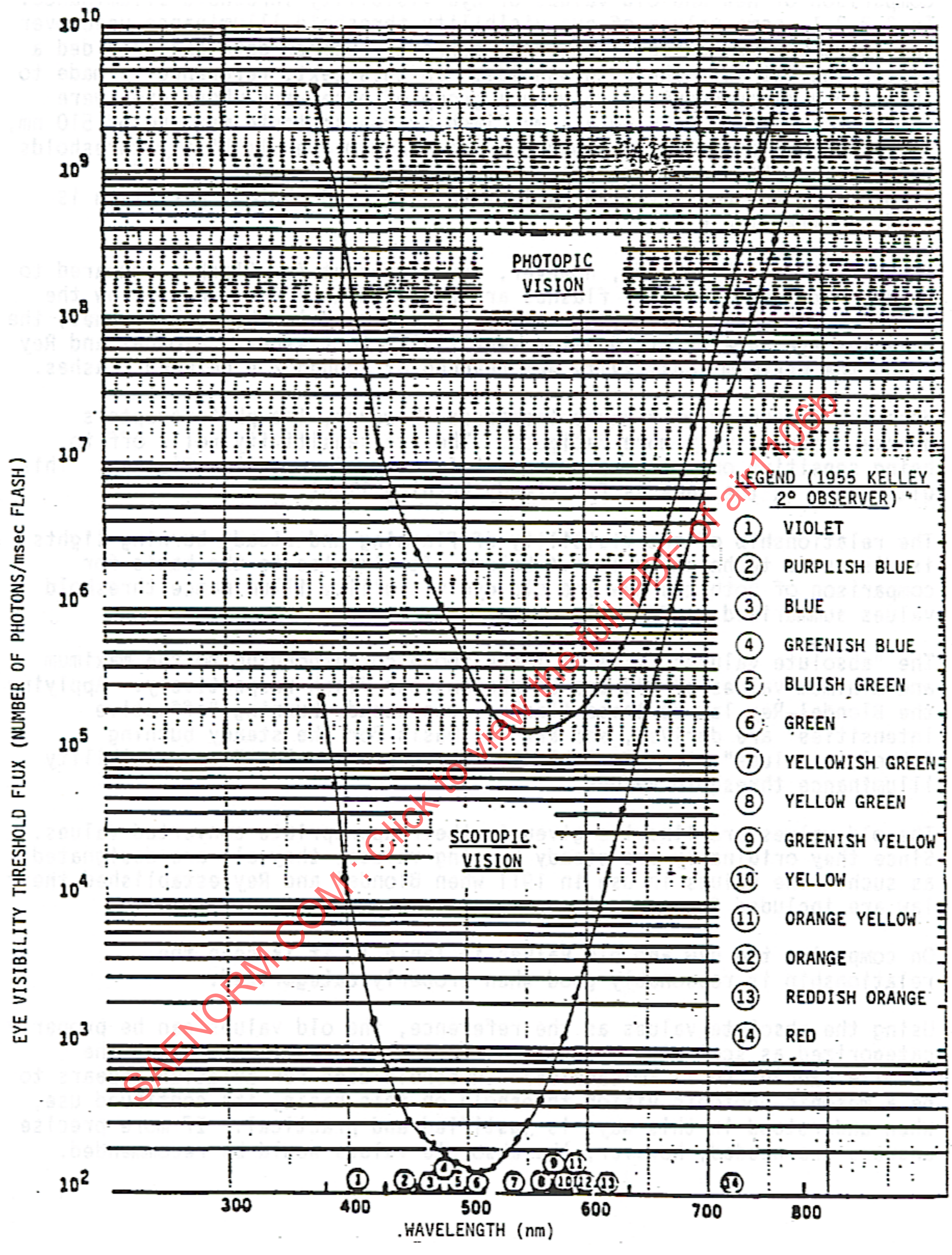

FIGURE 3 - EYE VISIBILITY THRESHOLD FLASH FLUX VERSUS WAVELENGTH, BASED ON DARK ADAPTED STANDARD OBSERVER

4.2.1 Comparison of New and Old Values of Eye Visibility Threshold Illuminance

In 3.3.3.1, some values of eye visibility threshold illuminance used over the years are summarized. However, current research data has provided a better insight into these thresholds. In this text, reference is made to laboratory measurements made with a group of observers whose eyes were fully dark adapted. Using a 1 ms flash at the scotopic maximum of 510 nm, it was established that the maximum and minimum eye visibility thresholds were 148 and 54 photons per flash respectively. For the sake of simplicity, the conservative maximum value of 148 photons per flash is used to establish Figure 3.

The visibility thresholds, however, are different for flashes compared to steady burning light. If flashes are repeated at a frequency below the critical flicker frequency, the longer the time delay between flashes, the more the eye retains its greater sensitivity to flashes. Blondel and Rey found the maximum sensitivity was reached at around 2 seconds between flashes.

When the frequency of flashes increases, however, the photoreceptors become progressively more fatigued. The eye sensitivity rolls off to being sensitive only to the average intensity of repeating flashes. This ultimately is the same as for steady burning light.

The relationship of the visibility of flashing and steady burning lights is discussed technically in 4.4. It likewise is the basis for comparison of both the new and old eye visibility illuminance threshold values summarized in Table 1.

The "absolute values" in Table 1 are those corresponding to the maximum and minimum values of 148 and 54 photons per flash respectively. Applying the Blondel-Rey law to these flashes, the steady burning "effective intensities" are derived, and are the basis for the steady burning "absolute values" given in Table 1. These are the "new" eye visibility illuminance threshold values.

The old values are likewise given in their appropriate converted values. Since they originally are steady burning values, they all are designated as such. The values in use in 1911 when Blondel and Rey established their law are included for comparison.

On comparing the new and old values in Table 1, it is seen the relationship is reasonably good when properly categorized.

Using the absolute values as the reference, the old values can be properly categorized as scotopic, mesopic, or photopic thresholds. Since the "2-mile candles (0.77 km candles)" threshold used for aviation appears to be a mesopic-photopic vision threshold on this basis, its continued use, when understood in this way, is justified and practical. If more precise answers are needed, however, the absolute values would be recommended.

TABLE 1 - EYE VISIBILITY ILLUMINANCE THRESHOLDS

Illuminance Threshold Basis	Case	Vision	Radiometric		Photometric	
			Threshold Flux photons/ft^2/flash	Threshold Flux photons/m^2/flash	Threshold Illuminance lumens/foot^2 (foot candles)	Threshold Illuminance lumens/meter^2 (lux)
Absolute: Max: 148 Photons: Min: 54 Photons:	Flash or Pulse (t=1 ms)	Scotopic (510 nm)	Max: 2.7357X10^5 Min: 9.9815X10^4	2.9432X10^6 1.0738X10^6	1.8297X10^{-10} 6.6760X10^{-11}	1.9685X10^{-9} 7.1823X10^{-10}
	(t=1 ms)	Photopic (555 nm)	Max: 2.7358X10^8 Min: 9.9815X10^7	2.9433X10^9 1.0738X10^9	6.6879X10^{-8} 2.4401X10^{-8}	7.1951X10^{-7} 2.6252X10^{-7}
			photons/ft^2/s	photons/m^2/s		
	Steady Burning or CW	Scotopic (510 nm)	Max: 1.3624X10^6 Min: 4.9708X10^5	1.4657X10^7 5.3478X10^6	9.1123X10^{-10} 3.3247X10^{-10}	9.8034X10^{-9} 3.5768X10^{-9}
		Photopic (555 nm)	Max: 1.3624X10^9 Min: 4.9708X10^8	1.4657X10^{10} 5.3478X10^9	3.3306X10^{-7} 1.2152X10^{-7}	3.5832X10^{-6} 1.3074X10^{-6}
2-Mile Candle: (aviation)	Steady Burning or CW	Mesopic-Photopic	2.9345X10^8	3.1571X10^8	7.1740X10^{-8}	7.7181X10^{-7}
0.5-Mile Candle: (maritime)	Steady Burning or CW	Mesopic-Photopic	7.3363X10^7	7.8927X10^8	1.7935X10^{-8}	1.9295X10^{-7}
0.01-Mile Candle: (white point source, dark background)	Steady Burning or CW	Scotopic	5.3630X10^5	5.7697X10^6	3.5870X10^{-10}	3.8590X10^{-9}
Blondel-Rey (1911):					Dark Lab:	1X10^{-7} 5-6X10^{-8}

4.3 The Photochromatic Interval Relative to Navigation and Anticollision Lights

Once again, the three colors used for aircraft navigation and anticollision lights are red, green and white. It is important to note that the intensity requirements for the steady burning position lights are considerably less than for the more intense strobing anticollision lights. Hence, color, intensity, and timing aspects of these signal lights are important to the information they are to convey.

When the question is raised as to what the threshold visibility flux difference is between scotopic and photopic vision for either red or green or white, study of Figure 3 gives the answer. As will be discussed later (see 4.4), the "effective intensity" of a steady burning light source needs to be about 1/201 times that of the peak intensity of the flashes represented in Figure 3. Hence, as will be demonstrated in 4.4, and specifically 4.4.2, the ordinate of Figure 3 would need to be multiplied by the factor 4.98 to give the corresponding visually equivalent "steady burning" flux thresholds in photons per second.

As is seen for the red spectral region, the scotopic and photopic curves are relatively close together, typically less than a decade apart, whereas for the other color regions they are decades apart. Specifically for green, the scotopic-photopic difference is between 2-1/2 to 3 decades. This is known as the photochromatic interval. Photopically, white is the additive mixture in some manner of all three primary colors. Scotopically, white can also be excited by any one color of appropriate "dim" intensity. The scotopic-photopic difference, however, for the third primary color, violet, is about 4 decades.

In practice, this means that one's eyes, after some exposure to light, rarely will be fully dark adapted. Therefore, depending upon the color and degree of previous exposure, the threshold curves can be shifted upward and closer together, even change relative shape, and the scotopic curve can even end up above the photopic curve. This change in sensitivity, however, is temporary, gradually changing back to a dark adapted condition inn a dark environment. The photochromatic interval is the region of "mesopic" vision, in contradistinction to scotopic and photopic vision.

4.4 Visibility of Flashing versus Steady Burning Lights[5]

Both steady burning and flashing lights are necessary for the purpose each serves. When their visual effectiveness is considered for their respective applications, their requirements become dictated accordingly.

For aircraft anticollision lights, several factors make flashing lights more advantageous than steady burning lights. This is evident from the following:

a. A flashing light has greater conspicuity, or "attention-getting power," than a steady burning light.

b. A dark adapted eye has greater sensitivity for a flash of light than for a steady burning light, provided the flash repetition rate is maintained low within the "flicker" range.

c. A higher peak power per flash is achieved by the same or greater amount of energy being produced within the shorter time interval of a flash, than is produced by a steady burning light per second.

d. A greater visibility threshold range is achieved with the same amount of light energy in the form of a flash, in all optical conditions, than is achieved by a steady burning light emitting the same amount of energy per second.

e. It is possible, however, to determine a visually equivalent "effective intensity" of a steady burning light that has the same visual effect and range as a particular flashing light, or vice-versa; this is done by means of the Blondel-Rey equations (discussed below).

f. With such information, it is possible to make proper estimates of threshold visibility distance to neighboring aircraft with either steady burning navigation or flashing anticollision lights for all atmospheric conditions.

g. In turn, it is possible to make proper estimates of "closure time" between aircraft for a few typical flight velocities, which is important if a flight must depend only on "visual flight rules," and in all atmospheric conditions.

h. This, in turn, can form the practical basis for a much needed rating system for both navigation and anticollision lights.

A steady burning light emits a constant quantity of energy at a steady rate per second. This is different from taking all the energy in 1 second of flow, packing it into a very small fraction of a second to form a "flash" of light, and allowing it to repeat once a second. The total energy flow could be the same in both cases, but the effects on a "receiver" are radically different. It is analogous to being hit with snowflakes compared to being hit with a snowball.

It is possible, however, to determine a steady burning energy flow rate that is effectively equivalent visually to a particular energy flash. Known as the steady burning "effective intensity" corresponding to a particular flashing light source with specific flash parameters, it produces the same visual response as the particular flash. In practice, flashing light sources are limited in their flexibility to produce different flashes. Hence, their "effective intensity" is given as one of their characteristics. This enables proper estimation of their performance for a particular application.

When comparing a single flash with its steady burning "effective intensity" equivalent, two factors are important: (1) the illuminance threshold of a dark adapted human eye is lower for a light flash than for a steady burning light; and (2) it takes some multiple of flash energy to make up enough steady burning energy to produce the same visual response as one flash. In other words, a flash is more efficient in producing a visual response than a steady burning light.

The relationships that enable computation of the "effective intensity" for all kinds of light flashes and their related parameters are contained in the Blondel-Rey equations.

4.4.1 The Blondel-Rey Law and Equations

The Blondel-Rey Law and its equations are as fundamental to the psychophysics of the visibility of flashing and steady burning lights as Newton's equations are to the laws of motion. Based on research Blondel and Rey conducted over 75 years ago,[6] ensuing research by others has only served to confirm the validity of their law and its equations to this time. The reader is referred to the papers cited here for more complete and useful coverage of many, if not all, of the practical aspects of this subject.[7,8,9] Anyone needing this information in greater depth than is possible here should refer to these sources. Specific application is made here only to the navigation and anticollision lights.

The discussion establishes, to the extent possible, the unique conditions for obtaining visibility equivalence of a steady burning light source with a flashing light source. It will be seen that certain parameters are solely light parameters, and that the dependence on eye visibility threshold illuminance is determined by an experimental visibility time constant.

The Blondel-Rey equation for a square wave flash is:

$$\frac{E_o}{E} = \frac{t}{a+t} = \frac{I_o}{I} \tag{Eq. 12}$$

where:

E_o = the eye visibility threshold illuminance for a steady burning light

E = the eye visibility threshold illuminance of a visually equivalent flash

t = the duration of the square wave flash in seconds

a = the experimentally determined Blondel-Rey visual response time constant, which is 0.21 when the eye illuminance is at the visibility threshold level

I_o = the eye visibility threshold intensity for a steady burning light

I = the eye visibility threshold intensity of a visually equivalent flash

Keeping in mind that lumens are a light power unit, the ratios of illuminances $\frac{E_o}{E}$, and intensities $\frac{I_o}{I}$, reduce to equivalent ratios of quantities of lumens, in turn reducing to a dimensionless number. They are used here interchangeably as necessary.

Since, in real applications, the intensity-time waveform of a flash can vary, depending upon the kind of light source used, the Blondel-Rey equation is stated in the definite integral form to take account of the different waveform shapes:

$$I_e = \int_{t_1}^{t_2} I dt / [a + (t_2 - t_1)] \quad \text{(Eq. 13)}$$

where:

I_e = the "effective intensity" of a steady burning light (corresponding to I_o in the previous square wave equation)

I = the instantaneous intensity in candelas at any time t within the waveform of the flash

a = 0.2 as the value currently recommended for establishing uniformity in applications[10]

t_1 = time at the beginning of the flash, when $I = I_e$, in seconds

t_2 = time at the end of the flash, when $I = I_e$, in seconds

The definition of "effective intensity" can be stated as: the intensity from a steady burning light which produces the same visual response in the eye as the defined flash of light at visibility threshold. This equation is the general mathematical statement of the Blondel-Rey Law.

When the denominator below the definite integral is transposed as follows:

$$I_e [a + (t_2 - t_1)] = \int_{t_1}^{t_2} I dt \quad \text{(Eq. 14)}$$

The relationship stated in this manner effectively equates the steady burning energy with the flash energy. It also enables an interpretation of the equation not otherwise immediately obvious. When values of actual cases are used in the equation, as will be seen below, the true flash energy of the right side equates to the same value on the left side. But when it is asked what this signifies, the left side has a unique interpretation.

The factor $[a + (t_2-t_1)]$ is the "time" factor that dictates what the "effective intensity" I_e must be to produce the same visual response as the flash energy. It in turn also dictates "how long" the effective intensity must be on as a minimum to generate the same amount of steady burning visibility threshold energy as the flash energy.

As an example, if I_e = 400 cd, a corresponding square wave flash, where (t_2-t_1) = 1 ms, and a = 0.2, must have a peak intensity of I of 80 400 cd.

Then: steady burning energy = flash energy
(400 cd)(0.20 + 0.001 second) = (80 400 cd)(0.001 second)
80.40 cd-s = 80.40 cd-s

The value of the Blondel-Rey eye response time constant "a," having the dimensions of time, proves to have different values experimentally for different conditions, and hence is not an immutable "constant." It is dictated by one of the following:

a. The adaptation level of the observer at any particular time, namely by the eye's sensitivity or "illuminance threshold" at any time

b. The illuminance level of the flash if it is above the eye illuminance threshold

The value of "a" is then combined with the flash duration (t_2-t_1) to specify what the minimum "steady burning duration" must be to just generate the same amount of energy as the flash. In the example just given, that would be 201 ms. In practice, of course, the steady burning light is left to continue operating, but the same signalling stimulation of the eye could be achieved more efficiently with a flash or flashes.

The question of the Blondel-Rey constant "a" remains on open one. As an experimental constant determined for the eye illuminance threshold, it makes the Blondel-Rey equations valid when it is appropriately varied. However, it remains presently undefined regarding its causal factors. Blondel and Rey themselves took the average of seventeen observers, whose measured "a" values ranged from 0.15 to 0.30 seconds, to establish "a" as 0.21 second. In the ensuing research of others, attempts have been made to establish its true nature. Further research needs to be done.

One useful experimental relationship for determining "a" can be drawn from the extensive literature. Hampton (1934)[11] took the experimental data of Toulmin-Smith and Green (1933), and using the Blondel-Rey equation, derived the following relationship for a:

$$\begin{aligned}&(1)\ a = (0.0255/E)^{0.81}\ (E = \text{mile candles})\\ &(2)\ a = (0.00985/E)^{0.81}\ (E = \text{km candles})\end{aligned} \qquad \text{(Eq. 15)}$$

where:

E = the illuminance at the observer, in mile-candles, for illuminances above threshold, or E in kilometer-candles

Since the value of 0.21 second as determined by Blondel-Rey at threshold is confirmed, and the relationship of Hampton is validly useable over the range of eye illuminances above threshold of 0.2 to 4.0 mile candles (0.077 to 1.54 km candles), where "a" values range from 0.19 to 0.017 seconds, respectively, these can be used as necessary for practical applications.

It is now possible to apply the above information to the anticollision lights. Since the FAR requirements dictate a minimum "effective intensity" of 400 cd, and can range to over 4000 cd, these two values will be used here as baseline cases.

Since each can have an infinity of possibilities of different flash conditions that are visually equivalent, whatever applies to an "effective intensity," applies to any one of its family of possible flash conditions. Hence, visibility threshold ranges will be determined on the basis of these two "effective intensities," which in turn will apply to any corresponding flash conditions, regardless of waveform or any other distinguishing flash characteristics.

4.4.2 Anticollision Flash Sources

Turning to the specific light sources presently used for anticollision lights, they are principally of three kinds:

a. Flash lamps with condenser-discharge excitation

b. Incandescent lamps or LEDs (or other similar light sources)

c. Revolving beam lamps

Considering only the intensity distribution waveforms of each of these, they can be summarily described as follows:

a. Flash lamps with condenser-discharge excitation: a very high peak intensity with a very short flash duration, of the order of microseconds; hence, (t_2-t_1) is negligible in computing "effective intensity".

b. Incandescent lamps: a slow rise to a peak intensity, followed by a sharp fall to zero intensity.

c. Revolving beam lamps: a symmetrical, repeating waveform, similar to a sinusoid, determined by the number of revolutions per minute and the wave shape.

d. LED light sources: a rapid rise to a peak intensity, followed by a sharp fall to zero intensity (i.e., a square wave pulse)

The following Table 2 summarizes what the computed value of intensity I is for each of the above anticollision flash sources (which does not yet include LEDs), taking into consideration the realistic flash duration time of each. Since this data shows their relationship to their "effective intensity," which later will be used to determine their visibility threshold range, an eye illuminance threshold of 2 mile-candles (0.77 km candles) will be used, thus determining the Blondel-Rey constant to be 0.21 second.

This illustrates the computed intensity I necessary for each of the sources, as dictated by the flash parameters, and necessary to satisfy the CFR effective intensity requirements for anticollision lights. The column I $(t_2-t_1)/I_e(1)$ shows the ratio of the energy in one flash duration to the energy I_e in 1 second of steady burning luminous flux, to further illustrate the efficiency of flashes. When multiplied by 100, the ratios are in percent.

The inverse of this column gives the multiplying factor that the flash energy is multiplied by to derive 1 second of steady burning energy. This is the basis for multiplying the ordinate of Figure 3 by 4.98 to derive the equivalent steady burning threshold visibility energy fluxes. Likewise, the factor 1/201 for multiplying the flash computed intensity I to derive I_e is the factor:

$$\frac{(t_2 - t_1)}{\left[a + (t_2 - t_1)\right]} \quad \text{(Eq. 16)}$$

For more information about applying the Blondel-Rey CFR equation to LED (light emitting diode) anti-collision light flashing effective intensity, see the following references:

General Practice for the Measurement of Flashing Lights by Miller, C. C.; Davis, W. L.; Lee, S. E.; Gibbons, R. E.; Ohno, Y. [20]

Analysis on Effective Intensity of Flashing Lights And Modification of Allard Method by Y. Ohno, Dennis Couzin. [21]

Modified Allard Method for Effective Intensity of Flashing Lights by Y. Ohno, D. Couzin. [22]

Physical Measurement of Flashing Lights - Now and Then by Y. Ohno. [23]

4.4.3 Threshold Visibility Ranges of Navigation and Anticollision Lights

Consideration is next given to the visibility threshold range of such sources, and for all the atmospheric conditions as defined by the International Visibility Code. Since the computations are based on the "effective intensity" as required by the FAR for both navigation and anticollision lights, using an illuminance threshold of 2 mile candles (0.77 km candles), and applying the atmospheric transmittance equations in 3.3.2, the results are tabulated in Table 3. As is seen, use of the effective intensity for these determinations eliminates the need to use the more complex parameters of each flash other than for determining their effective intensity.

Another unique advantage of the concept of "effective intensity" is demonstrated in Table 3 (the D in the Table will be explained later). By definition, and by the Blondel-Rey Law, the "effective intensity" is the steady burning lower intensity that produces the same visual effect as a properly mated flash of higher intensity. But the attenuation due to distance and to atmospheric conditions produces the same percentage reduction in both with distance. Therefore, both uniquely will have the same threshold visibility distance under the same conditions. Only when one exceeds the other, as determined from the Blondel-Rey equations, does the "larger" have the greater threshold visibility range.

TABLE 2 - ANTICOLLISION FLASH SOURCE PARAMETERS

I_e (candelas)	Source	(t_2-t_1) (seconds)	$[a+(t_2-t_1)]$ (seconds)	$\bar{I}$ (candelas)	$I(t_2-t_1)$ (candela-seconds)	$I(t_2-t_1)/I_e(1)$
400	Flash Lamp with Condenser-Discharge Excitation	0.001	0.211	84 400	84.40	0.211
	Incandescent Lamp	0.338	0.548	649	219.36	0.5484
	Revolving Beam* Lamp	≈0.1	0.31	2 105	210.50	0.5263
4000	Flash Lamp with Condenser-Discharge Excitation	0.001	0.211	844 000	844.00	0.211
	Incandescent Lamp	0.338	0.548	6 485	2 191.93	0.5480
	Revolving Beam* Lamp	≈0.1	0.31	21 050	2 105.00	0.5263

*The revolving beam rpm was assumed to be 60, and the wave shape factor 5.10. The computation procedure is available in the IES Guide.[12]

TABLE 3 - ESTIMATED THRESHOLD VISIBILITY RANGE OF NAVIGATION AND ANTICOLLISION LIGHTS

(E_o = 2 MILE-CANDLES)
(E_o = 0.77 KILOMETER-CANDLES)

International Visibility Code Number	Atmospheric Condition	Minimum Specific Optical Density δ ft^{-1} (m^{-1})	NAVIGATION LIGHTS I_e=40cd ft(D) (m)	NAVIGATION LIGHTS I_e=300cd ft(D) (m)	ANTICOLLISION LIGHTS I_e=400cd ft(D) (m)	ANTICOLLISION LIGHTS I_e=4000cd ft(D) (m)
0	Dense Fog	>1.14 X 10^{-2} (>3.74 x 10^{-2})	<326 (3.72) (<99)	<389 (4.43) (<119)	<399 (4.55) (<122)	<473 (5.39) (<144)
1	Thick Fog	2.78 X 10^{-3} (9.12 x 10^{-3})	990 (2.75) (302)	1 236 (3.44) (377)	1 272 (3.54) (388)	1 566 (4.35) (477)
2	Moderate Fog	1.13 X 10^{-3} (3.71 x 10^{-3})	1 925 (2.18) (587)	2 499 (2.82) (762)	2 584 (2.92) (788)	3 285 (3.71) (1 002)
3	Light Fog	5.69 X 10^{-4} (1.87 x 10^{-3})	3 098 (1.76) (945)	4 179 (2.38) (1 274)	4 340 (2.47) (1 323)	5 685 (3.23) (1 733)
4	Thin Fog	2.78 X 10^{-4} (9.12 x 10^{-4})	4 905 (1.36) (1 495)	6 859 (1.91) (2 091)	7 272 (2.02) (2 217)	9 900 (2.75) (3 018)
5	Haze	1.46 X 10^{-4} (4.79 x 10^{-4})	7 121 (1.04) (2 171)	10 695 (1.56) (3 261)	11 253 (1.64) (3 431)	16 002 (2.34) (4 879)
6	Light Haze	5.69 X 10^{-5} (1.87 x 10^{-4})	11 267 (0.64) (3 435)	18 817 (1.07) (5 737)	20 047 (1.14) (6 112)	30 971 (1.76) (9 442)
7	Clear	2.78 X 10^{-5} (9.12 x 10^{-5})	14 716 (0.41) (4 487)	27 108 (0.75) (8 265)	29 244 (0.81) (8 916)	49 043 (1.37) (14 952)
8	Very Clear	9.27 X 10^{-6} (3.04 x 10^{-5})	19 203 (0.18) (5 855)	41 467 (0.38) (12 642)	45 745 (0.42) (13 947)	90 103 (0.84) (27 470)
9	Exceptionally Clear	<9.27 X 10^{-6} (<3.04 x 10^{-5})	>19 203 (<0.18) (>5 855)	>41 467 (<0.38) (>12 642)	>45 745 (<0.42) (>13 947)	>90 103 (<0.84) (>27 470)

It should be noted that, at the visibility threshold, each flash has only one unique "effective intensity;" but each "effective intensity" can have an infinite number of equivalent flashes.

Hence, to generalize for all normal and adverse optical conditions, at the visibility threshold:

a. When the intensity of a steady burning light source is equivalent to the "effective intensity" of a flash, both have the same visibility threshold range

b. When the intensity of a steady burning light source is less than the "effective intensity" of a flash, the flash will have the greater visibility threshold range

c. When the intensity of a steady burning light source is greater than the "effective intensity" of a flash, the steady burning light source will have the greater visibility threshold range

d. When the flashes are continuously repeated, but at a frequency below the critical flicker frequency, where the flashes are seen as separate, as is the case with anticollision lights (as summarized in Table 2), the "effective intensity" is that of a single flash,[13] for which the three generalizations in a, b, and c above then hold true

e. When the flashes have an illuminance above the visibility threshold, due either to greater intensity of the flash source, greater proximity of the viewer to the source, or greater transmittance of the medium, the Blondel-Rey constant "a" progresses to lower values determined from the Hampton equation given above in 4.4.1 over the range of conditions for which it is valid. The statements of a, b, and c above then hold true when this "effective intensity" is used

f. When the flashes are continuously repeated at a frequency above the critical flicker frequency, and hence are not seen as separate, the "effective intensity" is then determined by the duty factor (DF), being that fraction of the fixed intensity where (DF) is the ratio of the flash width t to the flash period T. Since the inverse of the flash period T is the frequency f in Hertz, then, on the basis of Talbot's Law:[14]

$$I_e = (DF)I = \frac{tI}{T} = ftI \qquad \text{(Eq. 17)}$$

When this value of "effective intensity" is used in a, b, and c, then the statements hold true for such cases.

This summary provides a basis for optimizing both the navigation and anticollision lights, either from the standpoint of the lights used, or the method of operation, or both.

4.4.4 Estimation of Closure Times to Collision

Having estimated the threshold visibility range of the navigation and anticollision lights, it is next useful to consider two typical velocities of aircraft: fast at 560 mph (902 km/h), and slow at 120 mph (193 km/h). The "closure times to collision," and "just seeing" the respective lights, are thereby able to be estimated. To simplify the analysis, it is assumed that two aircraft are moving perpendicular to each other, at the same velocity, and over the same distance. Table 4 summarizes this data. If the other aircraft is flying head-on at the same velocity toward the observer, the closure time would be reduced to half. All other cases can be estimated accordingly. Also, when flying solely with VFR capability, it is required that the minimum visibility range be 3 miles (4.8 km). This is indicated in Table 4 by the solid horizontal lines in each column. The dashed line cases are discussed below.

Careful study of Table 4 leads to several recommendations for safer flight when the flight must be made solely with VFR. As is seen from the "closure time" columns, sighting, deciding, and taking appropriate evasive action are critically dependent on the closure times available. Contingent upon one's personal reaction time in such a situation, typically on the order of 200 ms and more, conditions that dictate changing to safer flight alternatives can be determined. Fortunately, in the range of the smallest closure times, there are relatively small closure time differences between the 40 cd navigation lights and the 4000 cd anticollision lights for the worst atmospheric conditions and both velocities. This eliminates the need to know the effective intensity of the lights of the other aircraft in order to exercise proper practical judgment.

Also most important in considering potential collision factors is the response time of the aircraft to initiation of an emergency evasive maneuver. In an excellent study of this factor, Mr. Ted Linnert, Director of the Engineering and Air Safety Department of the Air Line Pilots Association summarized valuable information on this matter in his presentation to the National Transportation Safety Board regarding the mid-air collision problem.[15]

> The key statements are: (1) most of the "near misses" occur in the terminal area; (2) most of the mid-air collisions occur at low altitudes and at low closure speeds; (3) approximately 10 second warning time is sufficient for a pilot to maneuver his aircraft into collision avoidance during VFR conditions.

The detailed data from 105 mid-air collisions over the five years from 1964 through 1968 corroborate his statements. Of these, 5% were head-on type collisions, 35% were overtaking-type collisions, and 60% were convergence-type collisions. Therefore, using a minimum pilot-aircraft reaction time of 10 seconds for collision avoidance, the dashed lines drawn in Table 4 establish the 10 second closure time limits for the various cases of velocity, weather conditions and visibility summarized in Table 4.

Bearing in mind each atmospheric condition interval is evaluated on the basis of its minimum optical density, closure times progressively deteriorate as the next worse interval is approached.

Knowing one's velocity, the effective intensity of one's navigation and anticollision lights, and the atmospheric conditions of the flight, better judgment can be exercised in ensuring a safe flight in the face of unforeseen eventualities. Also, it is as important to be properly seen as it is to see.

Hence, Table 4 enables one to judge conservatively as to the safety of each condition that arises during flight.

When visibility conditions become very poor, the particular recommendations therefore are:

a. Change the atmospheric condition by either changing altitude or course or both

b. To the extent feasible, fly at a lower velocity

c. If neither is immediately possible, be particularly alert for any sighting requiring immediate evasive action

d. Land safety wherever possible

It is interesting to compare daytime visibility ranges[16] for describing daily flight conditions corresponding to International Visibility Code conditions, with the corresponding threshold visibility ranges of the nighttime navigation and anticollision lights under the same atmospheric conditions. Table 5 summarizes this information. It is the same as Table 3 except for the inclusion of daytime ranges, and all ranges are given instead in statute miles (kilometers). Study of Table 5 shows that daytime visibility ranges are typically poorer for all fog conditions (Code Numbers 0 through 4), but better for all other less adverse atmospheric conditions (Code Numbers 5 through 9), than the nighttime navigation and anticollision lights visibility ranges. The solid line across the table represents the 3-mile (4.8-km) VFR requirement.