



AEROSPACE INFORMATION REPORT

AIR1106™

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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.

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Documents

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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 Lights²⁻⁴

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.

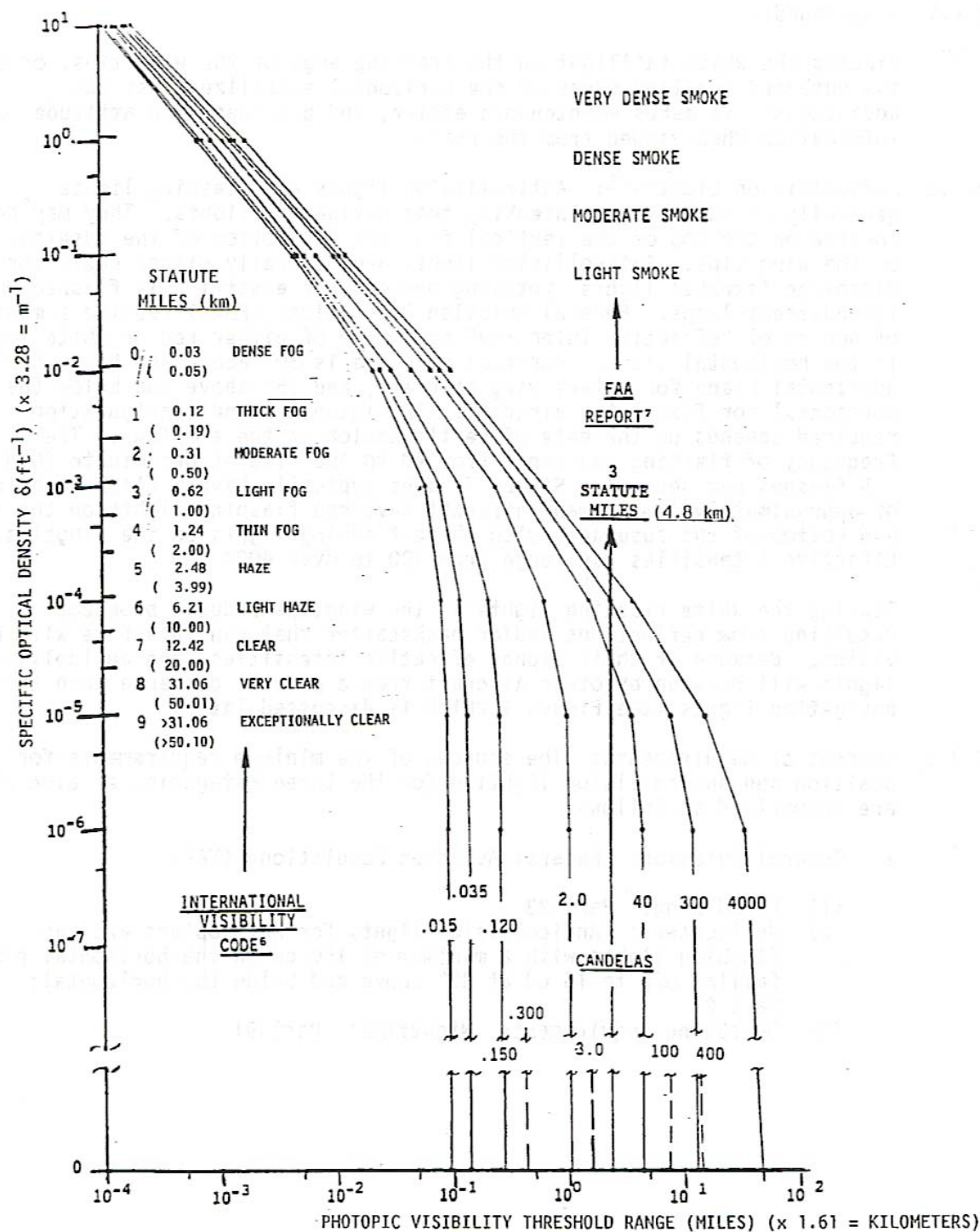


FIGURE 1 - SPECIFIC OPTICAL DENSITY VERSUS PHOTOPIC VISIBILITY THRESHOLD RANGE FOR FULLY DARK ADAPTED EYE

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/ft² (646 cd/m²). A 40 W frosted bulb has a luminance of about 58 cd/ft² (624 cd/m²). 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/ft² (646 cd/m²). 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/ft² (430 lm/m²). However, at a distance of 1000 feet (305 m), the illuminance would be 4.00×10^{-5} lm/ft² (4.3×10^{-4} lm/m²), 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:

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

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

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:

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

Therefore:

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

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

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

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

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

then:

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

For an example, see Figure 1. Consider an aircraft navigation light intensity of 40 cd, but as seen through a light fog. Let $\delta = 1.0 \times 10^{-3}/\text{foot}$ ($3.28 \times 10^{-3}/\text{m}$), 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
1×10^{-3} (3.28×10^{-3})	1 (0.305)	0.99	39.60
1×10^{-3} (3.28×10^{-3})	1000 (305)	0.10	4.00
1×10^{-3} (3.28×10^{-3})	5280 (1610)	5.25×10^{-6}	2.10×10^{-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):

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

or

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

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 $3.59 \times 10^{-10} \text{ lm/ft}^2$ ($3.86 \times 10^{-9} \text{ lm/m}^2$). Considering the normal eye pupil aperture diameter to be about 4 mm,¹⁴ this would correspond to an eye pupil aperture area of $1.35 \times 10^{-4} \text{ ft}^2$ ($1.255 \times 10^{-5} \text{ m}^2$). Hence, 0.01 mile candles (0.0039 km candles) would correspond to $4.85 \times 10^{-14} \text{ lm}$ 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."