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A Novel Method to Prove the Visibility Distance of Candlelight and the Milky Way's Vega Star and Apply this Knowledge to Outdoor Lighting Applications

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Abstract

Understanding the human visual system's night-time performance is essential for designing safe lighting for night-time travel. Visibility is a complex assessment process, but our current understanding of how the eye receives and processes light and how well the eye can distinguish objects in different lighting levels and distances are low. The current approach for calculating outdoor lighting level requirements is complicated and limited to illuminance and luminance measurements and does not allow designers to evaluate visibility. This paper aims to develop a simple outdoor lighting visibility calculation using the photons per second. This novel calculation method is applied to the candlelight's visibility distance and the milky way's Vega star visibility to validate the calculation approach. This paper will help researchers, scientists, engineers, consultants, architects, lighting designers, and government agencies seeking to improve outdoor lighting for safety, health, well-being, and quality of life in the built environment.

Keywords: *Outdoor Lighting, the human eye, visibility, Galaxies, Vega starlight, candlelight*

1. Introduction

The human eye can see objects that emit a certain number of photons. The most-distant luminary visible to the naked eye is the Andromeda galaxy, located 2.6 million light-years from Earth. The galaxy's one trillion stars collectively emit enough light for a few hundred photons to hit each square millimeter of Earth every second [1]. Vega is a bright star located just 25 light-years from Earth, visible in the Northern Hemisphere's summer sky, and hits the earth with a few thousand photons per square millimeter every second [2]. It is more than enough to excite our eyes at night. The brightness of any light source is based on the square of the distance away from it. Vision scientists conclude that one could make out the faint glimmer of a candle flame up to 30 miles (48.28 km) away [1, 3]. Previously published studies showed mixed results for visibility distance for candlelight [4]. This paper aims to prove that humans can see a candle flame more than 50 km away if there is no influence of the earth's curvature and atmospheric effects turbulence scattering due to the atoms and molecules in the atmosphere and obscuration due to dust, pollen, smoke, and particulates. It is essential to establish a suitable calculation process and translate that method to outdoor lighting applications.

Our Eyes Have Limits

Human eyes are complex organs and have fundamental limits. In essence, light particles called photons bounce off these objects and onto the retina. These photons reach approximately 120 million rods and 8 million cones in the retina of our eyes [5]. Our brain translates the photons that hit the retina from different directions and powers into different shapes, colors, and brightness, shaping our technicolor world.

Our vision has certain limitations. We cannot see radio waves emanating from our electronic devices, and we cannot spot the tiny bacteria or coronavirus. Beyond our visible spectrum, electromagnetic radiation has higher energies and shorter wavelengths. We find the ultraviolet band, X-rays, topping off with the gamma rays, whose wavelengths are in the mere trillionths-of-a-meter range. We can examine the fundamental limits of natural vision with advances in physics and biology. Everything you can see has above the lowest threshold for visibility. This paper is trying to establish the lowest threshold value for visibility, and anything more than that, we can see more clearly. Therefore, we have limitations in identifying, understanding, and evaluating electromagnetic radiation. The main problem with the current illuminance and luminance meters is that they cannot measure visibility. Visibility depends on several factors, including the observer's eye condition, atmosphere particles, objects' size, luminance and color contrast, and more [6]. We can only see the human visual response to a light source using a spectrometer that records the spectral distribution of incident light and integrates the human visual sensitivity curve across frequencies. Figure 1 provides the typical human visual system.

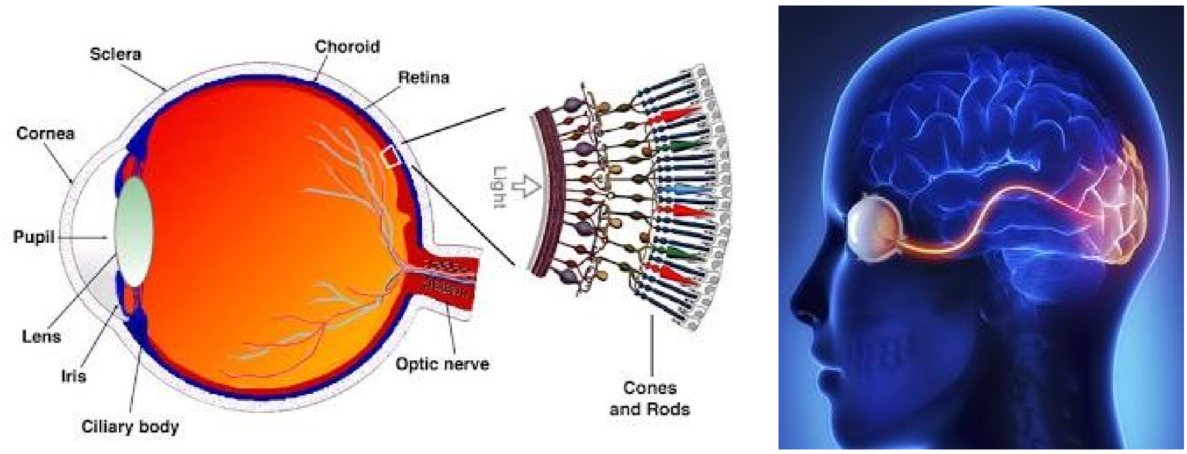

Figure 1. Human Visual System

We have two types of photoreceptors known as rods and cones. The cone cells deal in color, while rod cells allow us to see in grayscale in low-light conditions. The pigment molecules (opsins in retinal cells) absorb the electromagnetic energy from photons and generate an electrical surge. The signal travels via the optic nerve to the brain, where the conscious perception of color and image is formed.

Number of Photons to See

Cone cells yield color vision and typically require more lighting to work with than the rods. In low-light situations, color diminishes as the monochromatic rods take over visual duties. The visual system evolved the ability to encode information from a single-photon response (SPR) arising from the presence of an object of interest in the visual environment. Testing the Limits of Human Vision with a single photon of light is enough to trigger our perception. Several researchers concluded that the photosensors in the human eye could react to a single photon

[7, 8, 9, 10, 11]. The neural filters only pass a signal to the brain to trigger a conscious reply to more than five (5) photons [12, 13]. If we see a single photon consciously, we will feel too much visual "noise" in low light. Therefore, the filter is a necessary adaptation, not a weakness [12].

2. Background

We can assume that all body parts and processes function naturally for clear vision. The limits on how far you can see come down to the object's size, distance, the number of photons from it, luminance, and color contrast. In addition to the above, the Earth's curvature and any line-of-sight obstruction are essential for candlelight. The candle falls below the horizon or is obscured by terrain and other objects, but Vega provides an unobstructed view.

A rapid and complex sequence of actions will occur in the eye and brain when you look at anything. The following Table 1 provides the order of information processed in the visual system using different organs (refer to figure 2) and the corresponding function provided in the description.

Table 1. The Information Processed in the visual system

No.	Organ	Description
1.1	Cornea	Light reflects off an object and passes through the cornea, which is the eye's transparent outer layer.
1.2	Pupil	The cornea bends the light rays to enter the pupil or the dark center of the eye.
1.3	Iris	Simultaneously, the muscles in the iris control the pupil's size, making it smaller in bright light and dilate in a darker setting.
1.4	Lens, Retina	Light rays then pass through the eye lens, which sharpens the image as they reach the retina which contains cells, rods, and cones.
1.5	Roads, Cones, Visual Cortex	The rods and cones convert the light signal into electrical signals and travel through the optic nerve to the visual cortex, which turns them into images.

Distance and Brightness

We cannot pick out individual stars in the Andromeda Galaxy. The limits of our visual resolution or acuity come into play here. Visual acuity is the ability to see fine details, such as a point or a line, as separate from another without them blurring together. We can think of acuity's limits as the number of "pixels" we can discern. Several factors set the boundaries for visual acuities. The spacing between the cones and rods packed onto the retina and the eyeball optics prevent every available photon from landing upon a photoreceptor cell.

Distance affects Brightness. The brightest star, Vega, is about 25 light-years from Earth. We can see the Vega star in the night sky without a telescope or other visual aid. The scientists wondered how far away a person could see the candlelight on Earth. Texas A&M University researchers found that candlelight about 400m away has a brightness similar to Vega [4]. The scientists experimented further to determine the maximum distance you could be from a candle flame. Table 2 provides the approximate visual distances for candle flame, moon face, and from the highest peak and airplane, line of site, and the corresponding description [4].

Table 2. The Visual Distances

No.	Sight distance from	Description
2.1	A candle flame	The scientists concluded that someone with healthy vision could see candlelight up to 30 miles (48.28 km) away [1.3], assuming no fog or other obstructions.
2.2	The Moon's face	The Moon is about 384,400km away, and it is easy to see some of its cavities, gaps, and fields on a cloudless night [4].
2.3	The highest peak	Mount Everest's view in the Himalayas is the world's tallest summit at about 870m above sea level. It offers a view of close to 316km in every direction, according to a user-generated map. Due to the elevation, though, clouds often obscure the view [4].
2.4	The Airplane	If you are in an airplane at an altitude of around 10,500m above the Earth, you can look down and see highways, rivers, farms, and other landmarks easily in daylight. Nothing is blocking your view, and the only real limit to how far you can see depends on your eye health and visual acuity [4].
2.5	Earth Curve	Standing on a flat surface with your eyes about 1.5m above the ground, the farthest edge of the Earth we can see is about 5 kilometers away [4].

We can see an object whatever size, distance, or compactness if it transfers a photon to a retinal cell. The visibility of a source drops off over greater distances. The spatial resolution and the visual obscuration due to our atmosphere change with distance. The luminous intensity is the amount of light that lands on the eye. It is the total number of photons. We can make a light source too tiny, or small, but you can still see it if it has sufficient photons. LED light sources are small but produce High-intensity light. Therefore, we can see LED lights from even farther away.

3. Methodology

A candle flame can be spotted on a clear night from as far away as 48 kilometers. Photons routinely flood our eyes, so stray photons are lost in the wash from great distances. 11.2 x 1015 photons per second are produced by a one-lumen source from 400 to 700 nm [14]. The number of photons striking per second at any wavelength (λ), 1 Watt of radiant power corresponds to 5.034 × 1015 photons per second by a one-lumen source [15]. However, the Peterborough Astronomical Association indicated 4 x 1015 photons per second produced by a one-lumen source [2]. There is a disagreement in the values. Therefore, if the lower number of photons per second satisfies the visibility calculation about to present, it will fulfill all the others. Thus, the author intends to use the Peterborough Astronomical Association photons per second produced value for the analysis. From the definition of the lumen, 1 Watt of radiant power also equals 683 lumens at 555 nm (photopic) and 1,700 lumens at 507 nm (scotopic). Candlelight is an isotropic light source that covers a solid angle of 4π steradians, so the luminous intensity (I) in any direction of the Candle is one (1) Candela (cd). Therefore, the total lumens of a candle in a particular direction would be 12.57, calculated as follows:

$$\text{Intensity (I) [cd]} = \frac{\text{Lumens [lm]}}{\text{Steradian [Sr]}} \tag{1}$$

Swiss scientist Johann Heinrich Lambert (1728-1777) defined two critical laws relating to Illuminance. The first law is known as the inverse square law. It affirms that the illumination on a surface due to a point light source is inversely proportional to the square distance between the light source and the surface area. The second law is Lambert's cosine law, which states that the illumination on the surface changes as the cosine of the angle of incidence [16, 17]. Using a combination of these laws, we can express the illuminance Ev at a point on a surface as follows [17]:

$$\text{Illuminance (Ev) [Lux]} = \frac{\text{Intensity (I)} * \cos(\theta)\ \text{[cd]}}{\text{square of the distance } (d^2)[m^2]} \tag{2}$$

where:

Ev is the illuminance in lux (lx)

Iv is the luminous intensity of the light source in candela (cd)

θ is the angle of incidence (the angle between the light and the normal to the illuminated surface)

d is the distance from the light source to the target point in meters (m)

We declared above that illuminance is the total luminous flux incident on a surface (4πd 2) in lumens per square meter. Since one candela represents one lumen per steradian (Φv (lm) =I (cd)* 4π (Sr)), we can also express the illuminance Ev at a point on a surface as [18]:

$$\text{Illuminance (Ev) [Lux]} = \frac{\text{Lumens } (\Phi_v) * \cos(\theta) \text{ [lm]}}{\text{square of the distance } (d^2)[m^2]} \tag{3}$$

where:

Φv is the luminous flux in lumens (lm)

Note that the above formula only applies if the light source can be a point isotropic light source. For a Star or Candle, we can use the intensity (cd) of the light source divided by the square of the distance between the light source and the observer or the total lumens (Φv (lm) =I (cd)* 4π (Sr)) divided by the surface area of the giant sphere (4πr2). Both calculations yield the same results since the observer looks at the light source cos θ equal to one (1). The calculations required for an extended light source are somewhat more involved and beyond this paper's scope. The light beam hits our eyes and needs to be detected, which seems possible with a threshold of more than five (5) photons per second [12, 13].

3.1 Quantitative Evaluation Method

Using the above equations, we can prove the number of photons required to see the candlelight and star Vega and the corresponding distance requirement. As discussed earlier, in this calculation, we can use 4 x 1015 photons per second for a one-lumen source. The author has undertaken the calculations using the above-noted formulas to prove the Candlelight's visibility distance without any external obstruction. We can express the Candlelight Visibility for Eyes (CV_E) as follows:

$$\text{Candlelight Visibility for Eyes } (CV_E) = \frac{\text{Visibility } (V_A) * \text{ Eye Area } (A_E)}{\text{Area } (A)} \quad (4)$$

Table 3 provides the input data, and the calculation results for the assumed 50 km Candlelight visibility distance.

Table 3. The Candlelight Visibility Distance Calculation

Variable	Variable name	Input data
I	Candlelight Intensity	1 CD
d	Observer distance from the candlelight	50 Km
E_v	**Using formula 2, Illuminance = 4.0 x 10^{-10} Lum/Sq. m. (Lux)**	
Φv	One-lumen source	4 x 10^{15} photons/s
V_A	**Visibility per square meter at 50km = 1.6 x 10^{6} Photons/s/sq. m**	
A_E	Observer Eye-opening area (radius=0.001m)	3.14 x 10^{-6} Sq. m.
CV_E	**Using formula 4, The Candlelight Visibility of one eye = 5.024 Photons/s**	

The research indicates that our photosensors in the eyes can respond to even one photon per second [9, 19, 20], but consciously reply to more than five (5) photons [12, 13]. One eye receives 5.024 photons/s from the Candle located 50km away. Therefore, we can see candlelight clearly from more than 50km away if there is no other external obstruction or absorption of Photons.

The visibility of candlelight indicates that we should not consider the visibility of artificial lighting coming from far away for trespass lighting or obtrusive lighting evaluation because we can see the glow of the light even though the light meter indicates zero lux at eye level. From above Table 3, the human eye can see 4.0 x 10-10 lux (40 nano lux) light level. No meter or sensor is available to measure this lower level of light. Therefore, it is essential to evaluate how much light suppresses the melatonin than how much light we can see from the source or reflected light. It is easier to control entirely if a total cut-off or shield is used to block the glow of light from the high mast lighting, facade lighting, or digital display. It is hard to shield or block the ray of light when the high mast lighting or digital display is visible and close to the residence.

If Earth were flat or standing atop a mountain surveying a larger-than-usual patch of the planet, you could perceive bright lights hundreds of km distant. The brightness of a candle flame and the way a glowing object dims according to the square of the distance away from it. Researchers have several visibility distances for candlelight, but all are less than 48 km. One study's results indicate the maximum visibility distance, which is close to the author's finding - you could even see a candle flame flickering up to 30 miles (48 km) away at night [1]. Therefore, the author's calculation is correct without experimenting with the field observation. The following comparative evaluation method was introduced as another way to validate the visibility distance with the new calculation method.

3.2 Comparative Evaluation Method

The comparative evaluation method is to verify the candlelight visibility distance calculation. Humans can see and witness the visibility of the Vega star from the earth's surface. Vega star visibility distance can be examined using the same method to verify or justify this calculation method. We can express the Vega star Visibility for Eyes (CVE) as follows:

$$\text{Vega Visibility for Eyes } (VV_E) = \frac{\text{Visibility } (V_A) * \text{ Eye Area } (A_E)}{\text{Area } (A)} \tag{5}$$

The following Table 4 provides the Vega Star Light visibility calculation from the ground:

Table 4. The Vega Star Visibility Distance Calculation from the earth

Variable	Variable name	Input data
I	Vega Star Light Intensity	1.4×10^{29} CD [2]
d	Observer distance from the earth to Vega Star	2.37×10^{17} m [2]
E_v	**Using formula 2, Illuminance = 2.49×10^{-6} lum/Sq. m. (Lux)**	
Φv	One-lumen source	4×10^{15} photons/s
V_A	**Visibility per square meter at 25 light years = 9.97×10^{9} Photons/s/sq. m.**	
A_E	Observer Eye-opening area (radius=0.001m)	3.14×10^{-6} Sq. m.
CV_E	**Using formula 5, The Vega Star Visibility of one eye = 3.13×10^{4} Photons/s**	

According to this calculation method, human eyes receive 3.13 x 104 Photons/s from the Vega Star located 2.37 x 1014 km away (25 Light Year). It is way bigger than one photon/s.

There is always an external obstruction or absorption of Photons. Therefore, according to the calculation, we can see the Vega starlight very clearly if there is no other external obstruction or absorption of Photons. It proves that the calculation method works and reflects the reality that humans can see the Vega Star from the earth.

4. Results

The quantitative and comparative assessments were conducted, and the corresponding results are shown below. The quantitative evaluations were completed to calculate the visibility distance without field measurements, and comparative assessments were used to confirm the calculation evaluation.

4.1. Quantitative Assessment

Table 5 provides the results obtained from the quantitative assessment for the visibility distance from tables 3 and 4 and delivers the corresponding number of photons per second reach to the retina of the eyes. We can evaluate any source or object's visibility distance from these findings and conclusions and control the light intruding into the human eyes. The Vega star and candlelight have different luminous fluxes and location distances. In each case, the radiant flux of the object produces sufficient photons to make it visible at a stated distance. Figure 2 presents visibility distances for the candlelight and Vega star, where the Vega star is in a fixed location. Candlelight and artificial light location vary.

Table 5. The Quantitative Assessment

No.	Description	Distance	Visibility Results
5.1	The Candlelight Visibility of one eye (CVE)	50 km	5.024 Photons/s
5.2	The Vega Star Visibility of one eye (VVE)	25 Light Years	3.13×10^4 Photons/s

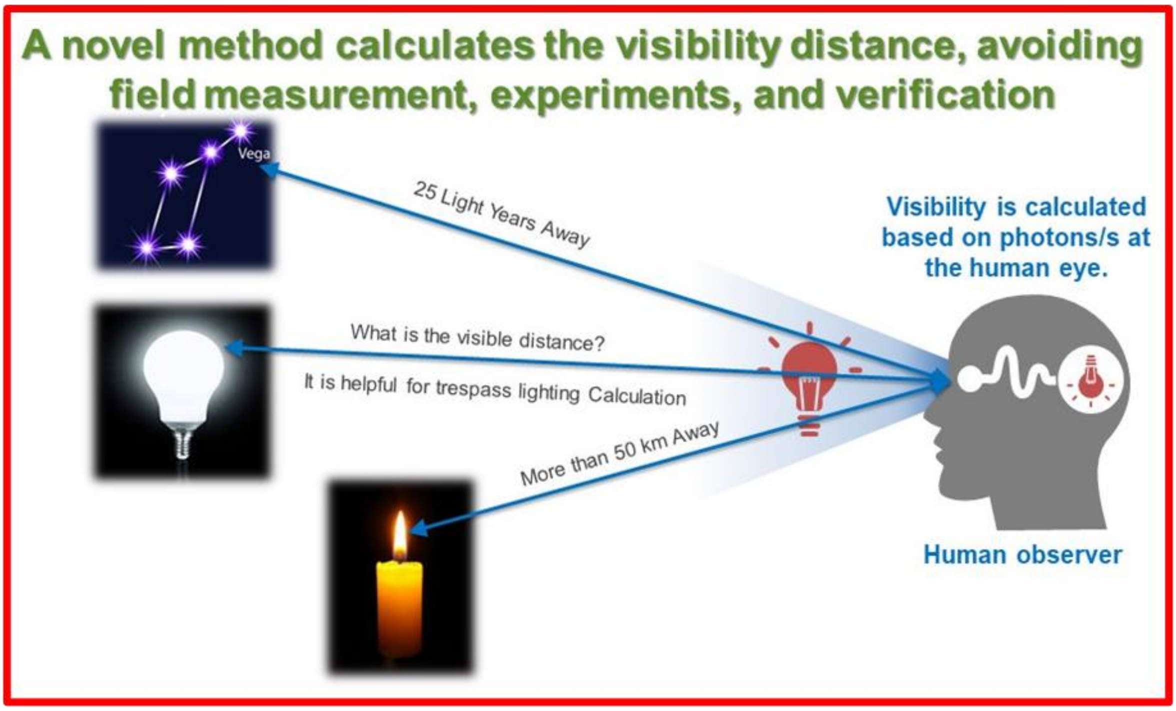

Figure 2. A novel method calculates the visibility distance

This is a novel method to calculate the visibility based on photons/s at the human eye without field measurements. Other research findings indicate the human eye photosensors' reactions and the human brain's conscious responses are used to verify, support, and confirm this novel calculation method.

4.2. Comparative Assessment

It is established evidence that humans can see and witness the visibility of the Vega star from the earth's surface during hours of darkness. The new calculation method justifies the results that meet the theory and requirements. Experimenting and witnessing the candlelight distance is challenging due to the external obstruction and earth curvature. Earth curvature can be solved by placing the source and the observer at a height above the ground. The external obstacle can be solved by locating the candlelight over the seawater. However, It is a very challenging and costly exercise to overcome visual obscuration due to our atmosphere, including dust, mist, fog, rain, snow, and temperature changes.

The comparative evaluation method verifies and confirms the candlelight visibility distance and emphasizes that calculation is the best way to find solutions to the candlelight visibility distance. The following Table 6 provides the results of the comparative assessment for visibility distance calculation methods, for which this method offers accurate results.

Table 6. The Quantitative Assessment

No.	Description	Minimum Required	Achieved	Results
6.1	The Candlelight Visibility	5 Photons/s	5.024 Photons/s	Satisfied
6.2	The Vega Star Visibility	5 Photons/s	3.13×10^4 Photons/s	Satisfied

A novel method calculates the visibility distance, avoiding field measurement, experiments, and verification. This method helps to improve human health, well-being, and Quality of Life in the built environment by calculating the visibility and Melatonin suppression in future lighting design.

5. Discussion

A candle emits an equal number of photons in each direction. The number of photons per square meter gets smaller and smaller if the candlelight is farther away. The number of photons emitted in a particular direction is constant. Therefore, an object far away is hit by much fewer photons. Photons are either reflected or absorbed in all directions. Some photons travel into our eyes. Every light source emits a specific number of photons of a particular wavelength. But to illuminate the whole area, what is essential is the luminous intensity (cd) of the source [18]. A light source emits more photons at a solid angle at a given time if the light source has a high luminous intensity.

The light must be reflected from the surface and hit our eye with the required wavelength and intensity so that our eye receptors receive it. The reflection drains the energy from the beam, and irregular surfaces require many reflections until the light beam ejects at an angle that aims toward our eye. Some photons will get absorbed by the surface area, and some will get reflected, but typical pavement or floor would be a diffuse reflection in multiple directions. To see only part of the reflected light, which gets into the observer's direction. Before hitting the receptors, we need to consider the light absorption in the eyes.

The night sky offers startling long-distance vision with its dark setting punctured by stars. Stars are enormous; many we see in the night sky are millions of kilometers in diameter. Even the Vega star is more than 236 trillion kilometers away and is so diminished in size that our eye cannot resolve them. We can still see stars as a sharp, gleaming points. The individual star in the night sky is in our Milky Way. We can see the farthest object with our naked eye is the Andromeda Galaxy, located 2.5 million light-years from us, and Vega Star, 25 Light Years from us. In terms of its apparent size, the Andromeda galaxy is six times the full moon's diameter. Few of its photons reach our eyes. The diameter and the distance of stars influence photon flux and visibility.

People often use the term "sightline" to describe the line of sight from an audience member's seat to the stage. But a sightline is a person's eye's visual angle to see an object or things. The curvature of the Earth is the primary factor that can decrease the sightline apart from typical visual obstructions such as trees, buildings, and clouds. The Earth is curved around 150mm per kilometer [21]. As a result, the farthest edge you can see is about 5 kilometers. The roadway visibility at night is not only lighting but also the line of sight in the roadway based on the geometric design and the external obstructions. Therefore, outdoor lighting applications require both sightline and visibility. The visibility depends on the number of photons per second received by the eyes. It can be reflected lighting from any object or light source, including the Milky Way stars, candlelight, and artificial light on the ground.

Outdoor lighting is required for vehicular and pedestrian visibility and safety. Outdoor lighting light sources can positively or negatively affect visibility. The author uses this knowledge to mitigate the negative visibility of light sources. Figure 3 shows the direct light coming from the luminaire, the changeable message display, and reflected light from the trees, signs, and the ground.

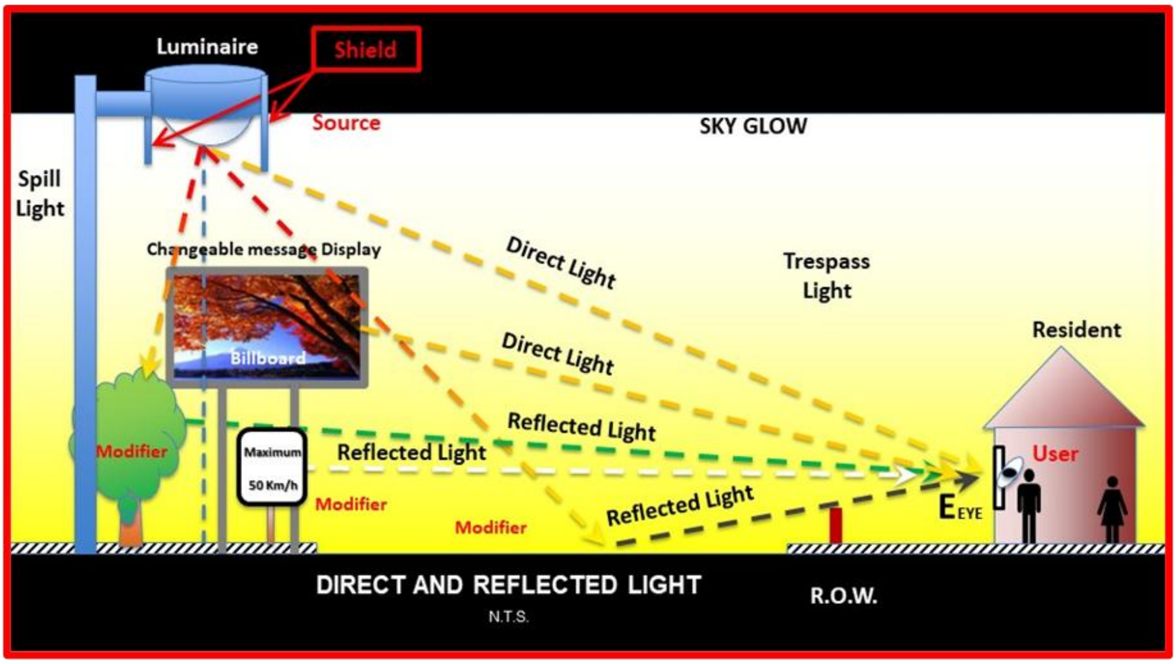

Figure 3. Sample outdoor lighting application

The billboard sign can be relocated or reoriented to avoid direct light coming to the windows. The luminaire can be changed and shielded without compromising the light level on the roadway. It is impossible in some situations where the right of way and house are very close to the highway. The reflected light from the trees, signs, and the ground cannot be controlled. In this case, a mitigation strategy can be possible in consultation with the residents to either increase the height of the fence or use the window cover during the hours of darkness.

The luminance calculation has many shortcomings and assumptions, including the fixed observer position and viewing angle, and the results do not correlate with reality. It is complex and difficult to assess or reach a consensus since millions of colors and luminances contrast we can witness in the environment. In addition, Brightness is the human sensation of luminance, which varies from person to person [17]. The luminance or illuminance meter cannot provide the lowest threshold for visibility. Luminance and luminance contrast can work in theory but not in reality. Therefore, the photons per second method offer the lowest threshold for visibility. Anything above the threshold value provides visibility and not visible acuity.

6. Conclusion

This paper discusses the challenges of human vision and perception during the night and how they can perceive galaxies and outdoor lighting applications. Understanding the human visual system is essential for lighting design. Visibility and safety are crucial during night-time traveling and health, well-being, and quality of life in the built environment. This understanding and the implementation of lighting design will benefit society and the profession. The current approach to outdoor lighting and the required calculation method to achieve the lighting requirement are based on the space's application and function. It does not consider the amount of light intruding on the human eye and its impact on human health and well-being.

The photocell controls most outdoor lighting applications. Therefore, the trespass or obtrusive lighting from the outdoor applications cannot be dimmed or turned on or off by the public. This study's novel calculation method is validated using the photons/s visibility number and the candlelight and Vega star visibility distance from others' findings. This knowledge can be easily used for outdoor lighting applications to find the visibility and the corresponding health and well-being impact on humans in the built environment. It is important to note that we could see the glow of light even though the lux meter light measurement is zero lux at eye level. This paper achieved the following conclusion or objective:

1. The current illuminance lighting meter cannot measure the lowest threshold value for visibility. This novel calculation method is validated by comparing the experimental findings of other studies.

2. The proposed novel calculation method provides the capacity to measure and understand the visibility of the light even if the lighting meter reading shows a zero-lux level.

3. A lighting designer must understand the need for photons per second for visibility and can calculate the required photons per second to suppress melatonin at night.

4. This paper clarifies to the public that the glow of the light from the light source can be seen many kilometers away and cannot be controlled unless luminaire shields are used. Therefore, the flow of the light cannot be considered intrusive or trespass lighting.

5. It has opened up many areas of application to find the lower threshold of visibility, good visibility, suppression of melatonin and sleep disturbance, visibility for pedestrian and vehicular traffic at night, and more.

6. The method can be applied to any lighting situation to find visibility using photons per second. Therefore, it can be called the Uthayan method of visibility calculation.

This paper discusses only the needed photons per second for visibility and proves this by sample calculations for the candlelight and Vega starlight. Vega starlight provides over 30 thousand photons per second and is one of the brightest stars in the sky. Candlelight provides a lower threshold of human visual perception. Both satisfy the novel calculation method. Therefore, this knowledge can be used for outdoor lighting applications. A separate paper will discuss the required photons per second to suppress melatonin at night.

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