Inverse Square Law

Nvis 6006D

Learning Material

Ver 1.1

An ISO 9001: 2008 company

Designed & Manufactured in India by :

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Inverse Square Law

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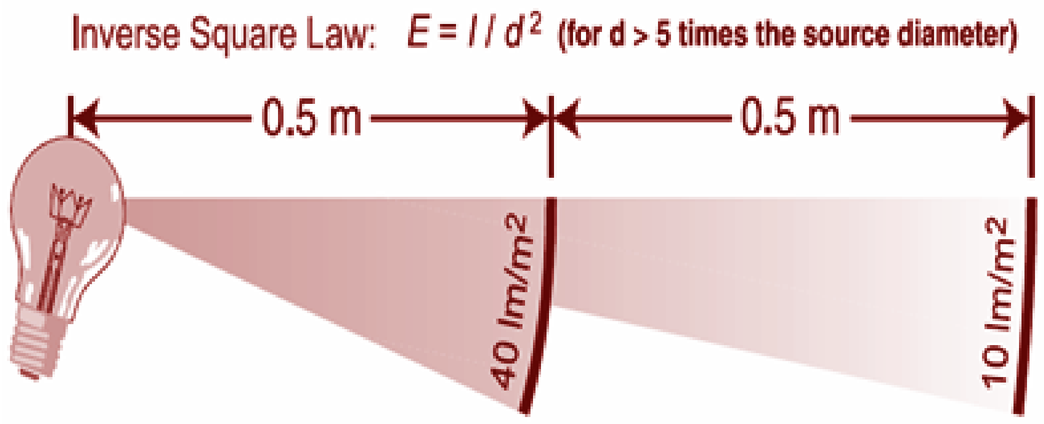
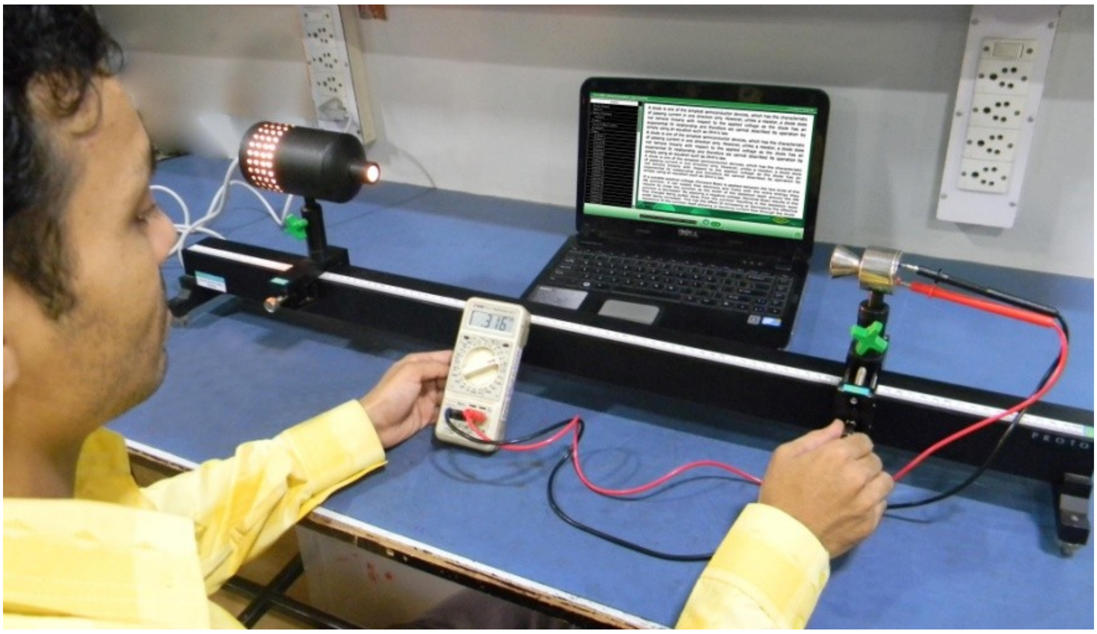
Introduction

Inverse Square Law, Nvis 6006D is an Optical setup for illustrating how light intensity varies with distance. The inverse square law states that the illumination of a surface by a point source is inversely proportional to the square of the distance between the source and surface. Nvis 6006D consists of Optics bench, Light source and Photo detector.



Inverse square law

This experiment investigates the inverse square law and provides a curve for the optical detector with variation of distance. The Phototransistor is a device that converts light into an electrical signal. This signal is monitored and measured using a meter. Photo detector are devices that convert photons into electric current by means of "electron-hole" pair generation subsequent to the absorption of light by a semiconductor material. Presently, the most commonly used material is silicon.



Nvis 6006D Inverse Square Law

Features

- Sliding stand with precise measurement
- Light Source with height adjustment

Technical Specifications

Optics bench

Length : 1 meter

Light Source

Type : Incandescent Lamp

Wattage : 100W

Detector : Phototransistor

Safety Instructions

Read the following safety instructions carefully before operating the instrument. To avoid any personal injury or damage to the instrument or any product connected to the instrument.

Do not operate the instrument if suspect any damage to it.

The instrument should be serviced by qualified personnel only.

For your safety:

Use proper Mains cord : Use only the mains cord designed for this instrument. Ensure that the mains cord is suitable for your country.

Ground the Instrument : This instrument is grounded through the protective earth conductor of the mains cord. To avoid electric shock, the grounding conductor must be connected to the earth ground. Before making connections to the input terminals, ensure that the instrument is properly grounded.

Use in proper Atmosphere : Please refer to operating conditions given in the manual.

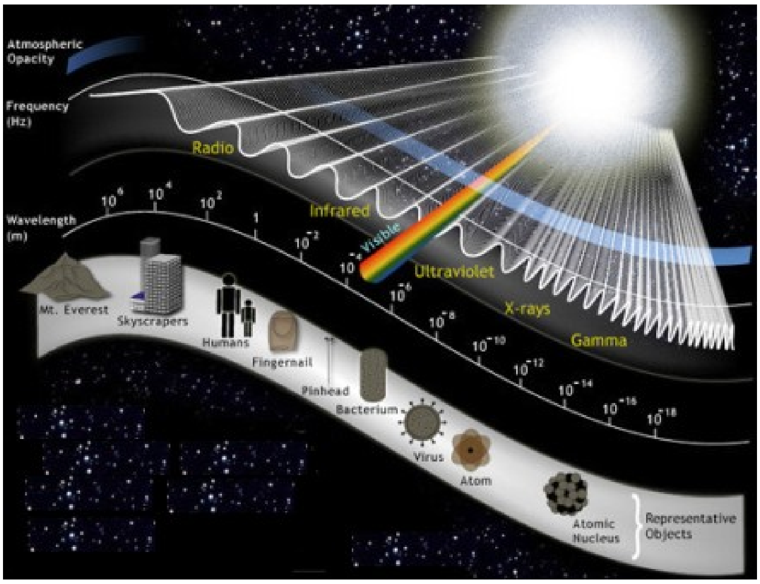
1. **Do not operate in wet / damp conditions.**
2. **Do not operate in an explosive atmosphere.**
3 **Keep the product dust free, clean and dry**

Theory

What is Light?

Light is simply a very small part of the electromagnetic spectrum, sandwiched between ultraviolet and infrared radiation. The visible portion of the electromagnetic spectrum extends from about 380 to about 780 nanometers (nm).

Electromagnetic Wave Theory: Light is just one portion of the various electromagnetic waves flying through space. The electromagnetic spectrum covers an extremely broad range, from radio waves with wavelengths of a meter or more, down to x-rays with wavelengths of less than a billionth of a meter. Optical radiation lies between radio waves and x-rays on the spectrum, exhibiting a unique mix of ray, wave, and quantum properties



Since light can be analyzed as a complex mixture of a huge number of individual electromagnetic waves, the important properties of light and other electromagnetic waves can therefore be understood in terms of the properties of these simple elementary waves.

At any point on the path of a simple harmonic light wave the strengths of the electric and magnetic fields are continually changing. At each point the two fields always change in step, so that the maximum value of the electric field occurs at the same time as the maximum magnetic field.

The electric and magnetic fields point in directions at right angles to each other and also at right angles to the direction in which the wave travels since a complete knowledge of the electric field determines the magnetic field, the wave can be described adequately by specifying the electric field only.

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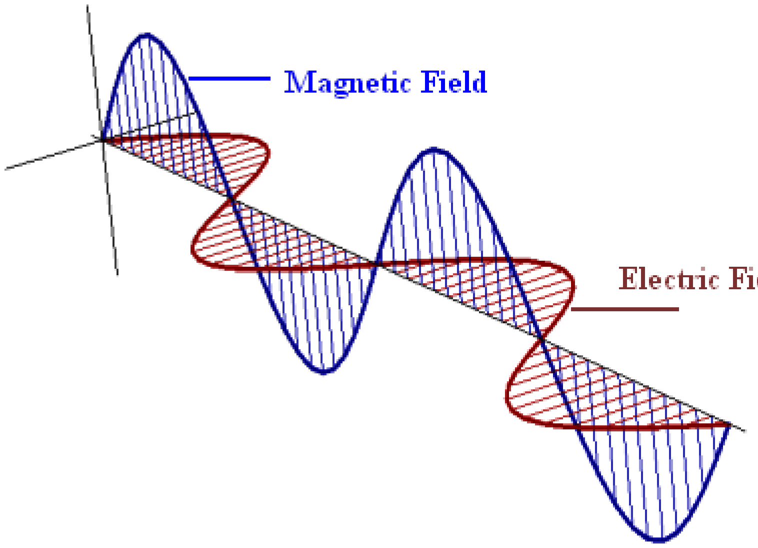
In figure below an instantaneous representation of the fields in part of an elementary electromagnetic wave, Notice that the electric and magnetic fields are in phase, their maxima occur at the same place at the same time. Since both fields are perpendicular to the direction of travel of the wave, the wave is said to be transverse. (A wave in which the direction of the wave property is parallel to the direction of travel is called a longitudinal wave.)



At x-ray and shorter wavelengths, electromagnetic radiation tends to be quite particle like in its behavior, whereas toward the long wavelength end of the spectrum the behavior is mostly wavelike. The visible portion occupies an intermediate position, exhibiting both wave and particle properties in varying degrees.

Like all electromagnetic waves, light waves can interfere with each other, become directionally polarized, and bend slightly when passing an edge. These properties allow light to be filtered by wavelength or amplified coherently as in a laser.

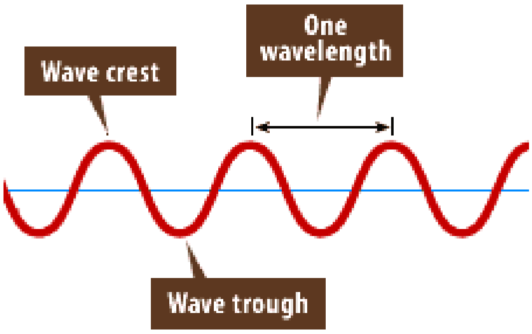
In radiometry, light's propagating wave front is modeled as a ray traveling in a straight line. Lenses and mirrors redirect these rays along predictable paths. Wave effects are insignificant in an incoherent, large scale optical system because the light waves are randomly distributed and there are plenty of photons.

Wavelength and frequency

An important property of electromagnetic waves is that in empty space they all travel at exactly the same speed of about 300 000 kilometers per second (2.99792458 × 108m.s-1 to be more precise) quite independently of their wavelength and frequency.

Light is measured by its wavelength (in nanometers) or frequency (in Hertz).

One wavelength equals the distance between two successive wave crests or troughs.



Frequency (Hertz) equals the number of waves that passes a given point per second.

The distance (measured in the direction of propagation) between two points in the same phase in consecutive cycles of a wave

The quantities which characterize each elementary wave are its amplitude, its frequency and its wavelength. Amplitude and frequency are difficult or impossible to measure directly but there are several kinds of experiment which can be used to measure wavelength. Experiments have yielded values for the wavelengths of visible light which lie roughly in the range, 400 nm to 700nm. The usual unit for light wavelengths, which is consistent with SI, is the nanometer; 1 nm = 1 × 10-9 m.

Frequency f is the number of wavelengths that pass any point in space per second. The unit of frequency is the inverse second (s"1), a unit also called the hertz (Hz).

Since the speed of light in vacuum is fixed, each wavelength corresponds to a different frequency. The range of frequencies for visible light is from about 7 × 1014 Hz (at 400 nm wavelength) to about 4 × 1014 Hz (at 700 nm).

When the wave theory of light is extended to take account of light's interaction with matter, it turns out that when an elementary light wave goes from one material into another its frequency is unchanged but the speed and the wavelength are altered.

So the property which really distinguishes each elementary wave is its frequency, rather than its wavelength. The common practice of describing light in terms of wavelengths is related to the fact that wavelengths can be measured reasonably directly but frequencies are to hard to measure.

Since wavelength changes what does it mean to quote values for wavelength?

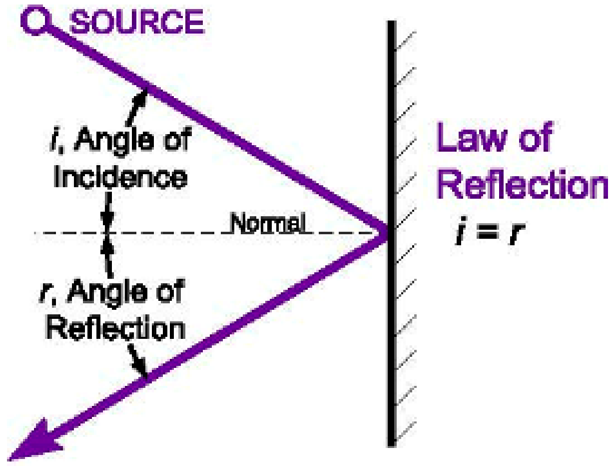
The answer is that

Unqualified references to wavelength are understood to mean wavelength in vacuum, or possibly air.(Fortunately wavelengths of the same wave in air and vacuum are almost equal.)

Light which contains a relatively narrow range of wavelengths looks coloured. The colours correspond to those in the rainbow, ranging from violet (upwards of 400 nm) through blue, green (around 550 nm) and yellow, to red (up to about 700 nm). Normal sunlight, which contains the whole range, is usually described as white light.

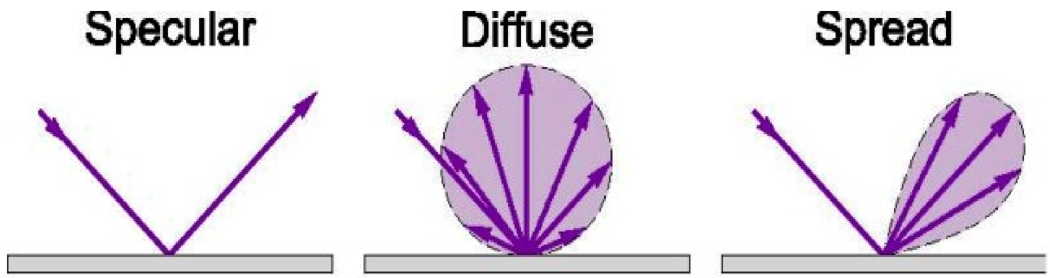
How Light Behaves

Light reflecting off of a polished or mirrored surface obeys the law of reflection: the angle between the incident ray and the normal to the surface is equal to the angle between the reflected ray and the normal.



Law of reflection

Precision optical systems use first surface mirrors that are aluminized on the outer surface to avoid refraction, absorption, and scatter from light passing through the transparent substrate found in second surface mirrors.



When light obeys the law of reflection, it is termed a specular reflection. Most hard polished (shiny) surfaces are primarily specular in nature. Even transparent glass specularly reflects a portion of incoming light.

Diffuse reflection is typical of particulate substances like powders. If you shine a light on baking flour, for example, you will not see a directionally shiny component. The powder will appear uniformly bright from every direction.

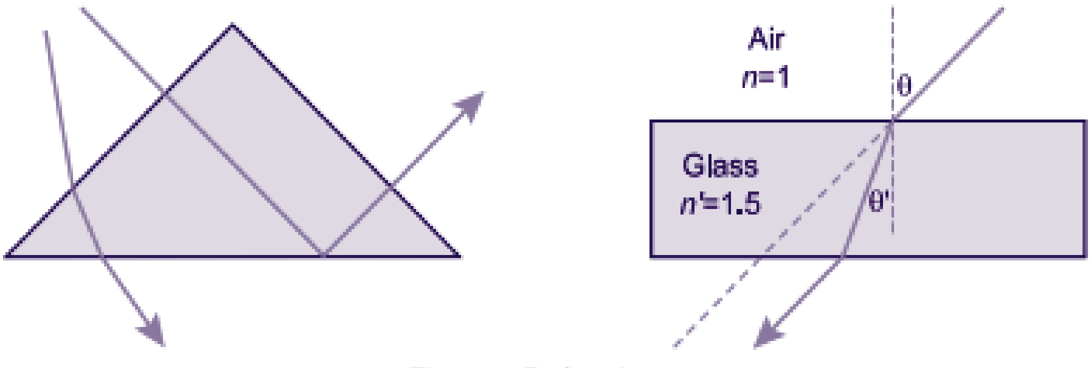
Many reflections are a combination of both diffuse and specular components. One manifestation of this is a spread reflection, which has a dominant directional component that is partially diffused by surface irregularities.

Refraction

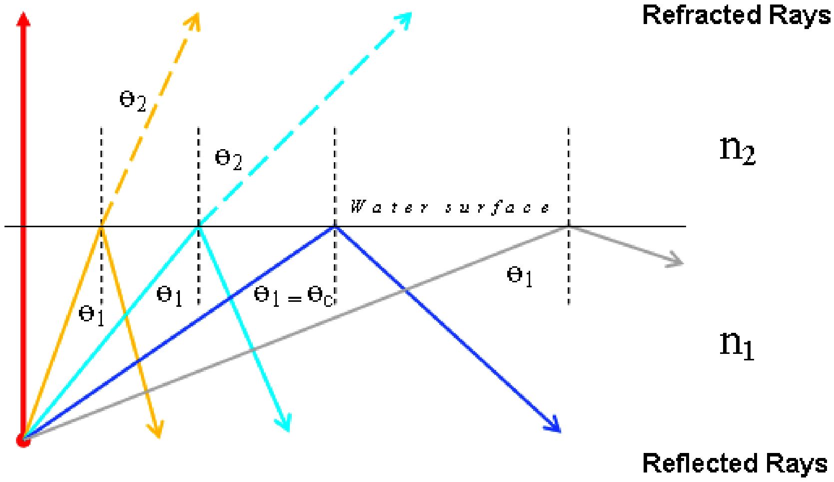
Snell's Law

When light passes between dissimilar materials, the rays bend and change velocity slightly, an effect called refraction. Refraction is dependent on two factors: the incident angle, θ, and the refractive index, n of the material, as given by Snell's law of refraction

n sin(q) = n' sin(q')

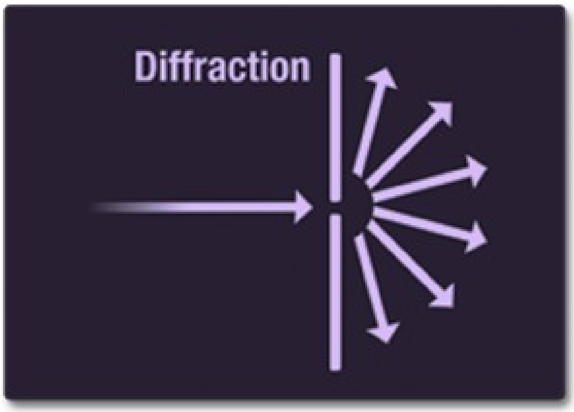


For a typical air-glass boundary, (air n = 1, glass n' = 1.5), a light ray entering the glass at 30° from normal travels though the glass at 19.5° and straightens out to 30° when it exits out the parallel side.



Diffraction

Diffraction is another wave phenomenon that is dependent on wavelength. Light waves bend as they pass by the edge of a narrow aperture or slit.

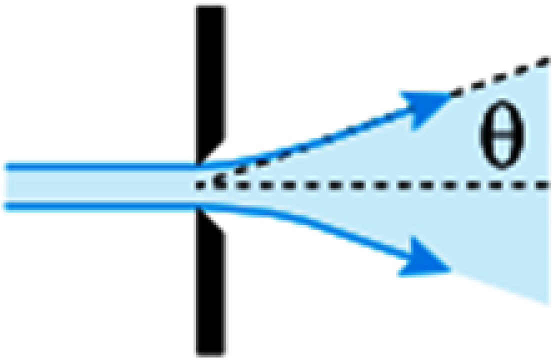


This effect is approximated by

q = l / D

where θ is the diffraction angle, λ the wavelength of radiant energy, and D the aperture diameter. This effect is negligible in most optical systems, but is exploited in mono chromators.

A diffraction grating uses the interference of waves caused by diffraction to separate light angularly by wavelength. Narrow slits then select the portion of the spectrum to be measured. Narrower the slit, narrower the bandwidth that can be measured However, diffraction in the slit itself limits the resolution that can ultimately be achieved.



Interference

The superposition of two or more waves propagating through a given region, depending on how the peaks and troughs of the interacting waves coincide with each other, the resulting wave amplitude can be higher or smaller than the amplitudes of the individual waves.

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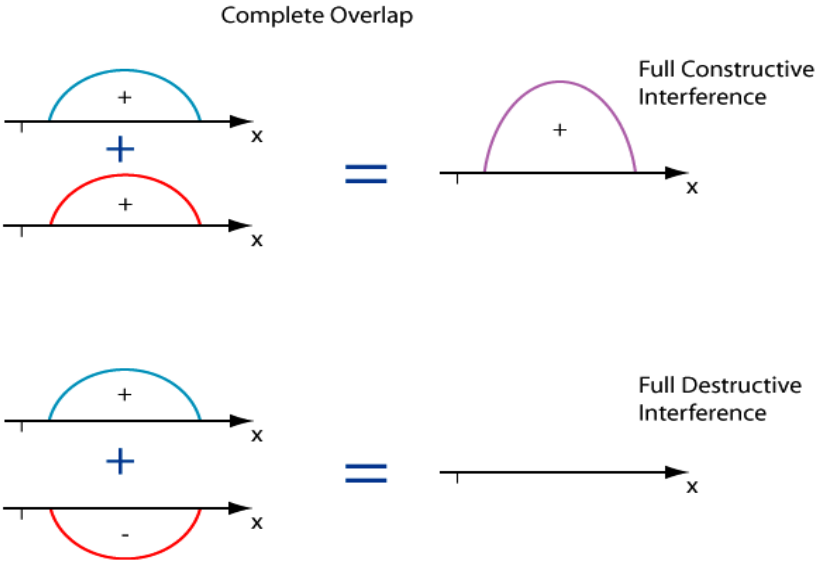


When two waves interact so that they rise and fall together more than half the time, the amplitude of the resulting wave is greater than that of the larger wave. This is called constructive interference.

When two waves interact such that they rise and fall together less than half the time, the resulting amplitude is smaller than the amplitude of the stronger wave. This interference is called destructive interference. It is possible for two waves of the same magnitude to completely cancel out in destructive interference where their sum is always zero, that is, where their peaks and troughs are perfectly opposed.

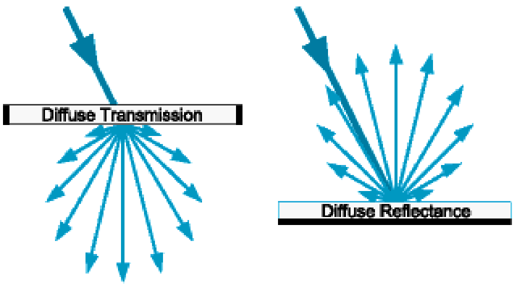
Manipulating Light

Diffusion

"Transmission of electromagnetic or acoustic radiation in all directions by a transmitting body"

It is often necessary to diffuse light, either through transmission or reflection. Diffuse transmission can be accomplished by transmitting light through roughened quartz, flashed

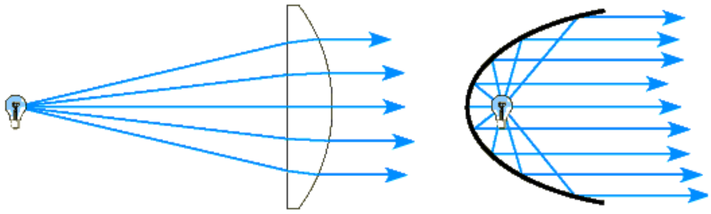
opal, or poly tetrafluoroethylene (PTFE, Teflon). Diffusion can vary with wavelength. Teflon is a poor IR diffuser, but makes an excellent visible / UV diffuser. Quartz is required for UV diffusion.



Diffuse transmission and reflectance.

Collimation

Some lamps use collimating lenses or reflectors to redirect light into a beam of parallel rays. If the lamp filament is placed at the focal point of the lens, all rays entering the lens will become parallel. Similarly, a lamp placed in the focal point of a spherical or parabolic mirror will project a parallel beam.



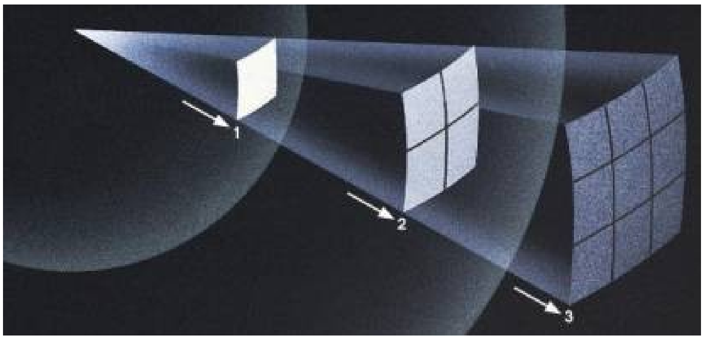
Collimation using a lens and a parabolic reflector

Lenses and reflectors can drastically distort inverse square law approximations, so should be avoided where precision distance calculations are required

Inverse Square Law

In physics, an inverse-square law is any physical law stating that some physical quantity or strength is inversely proportional to the square of the distance from the source of that physical quantity.

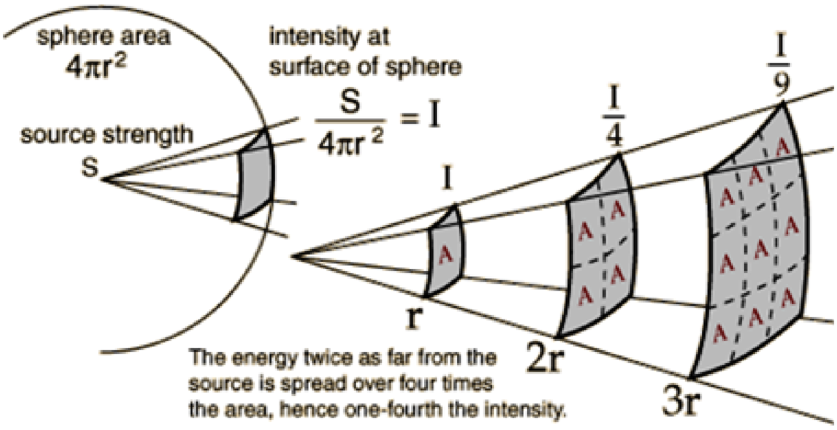
The lines represent the flux emanating from the source. The total number of flux lines depends on the strength of the source and is constant with increasing distance. A greater density of flux lines (lines per unit area) means a stronger field.



The density of flux lines is inversely proportional to the square of the distance from the source because the surface area of a sphere increases with the square of the radius. Thus the strength of the field is inversely proportional to the square of the distance from the source.

Any point source which spreads its influence equally in all directions without a limit to its range will obey the inverse square law. This comes from strictly geometrical considerations. The intensity of the influence at any given radius r is the source strength divided by the area of the sphere. Being strictly geometric in its origin, the inverse square law applies to diverse phenomena. Point sources of gravitational force, electric field, light, sound or radiation obey the inverse square law. It is a subject of continuing debate with a source such as a skunk on top of a flag pole; will it's smell drop off according to the inverse square law?

Nvis 6006D Inverse Square Law



Justification

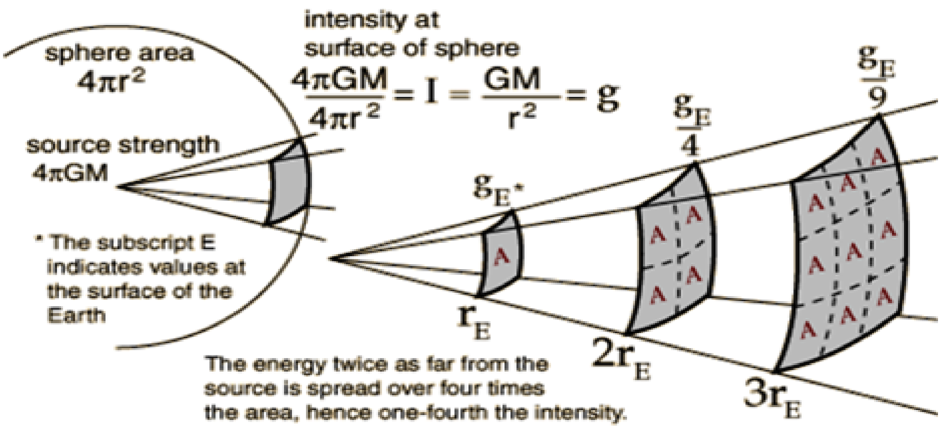
The inverse-square law generally applies when some force, energy, or other conserved quantity is radiated outward radially from a source. Because the surface area of a sphere (which is $4\pi r^2$) is proportional to the square of the radius, as the emitted radiation gets farther from the source, it must spread out over an area that is proportional to the square of the distance from the source. Hence, the radiation passing through any unit area is inversely proportional to the distance from the source.

Occurrences

1. Gravitation
2. Electrostatics
3. Light and other electromagnetic radiation

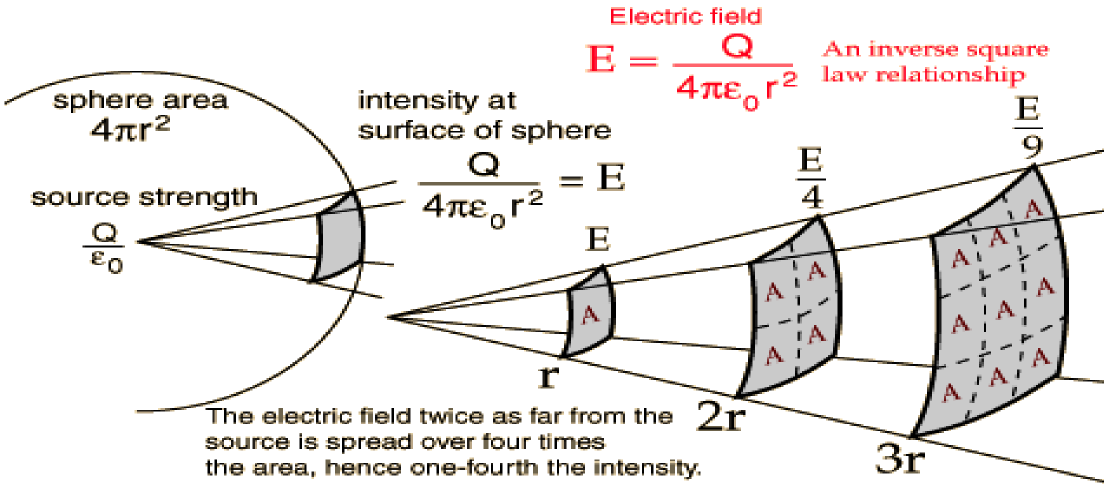
1. Inverse Square Law, Gravity

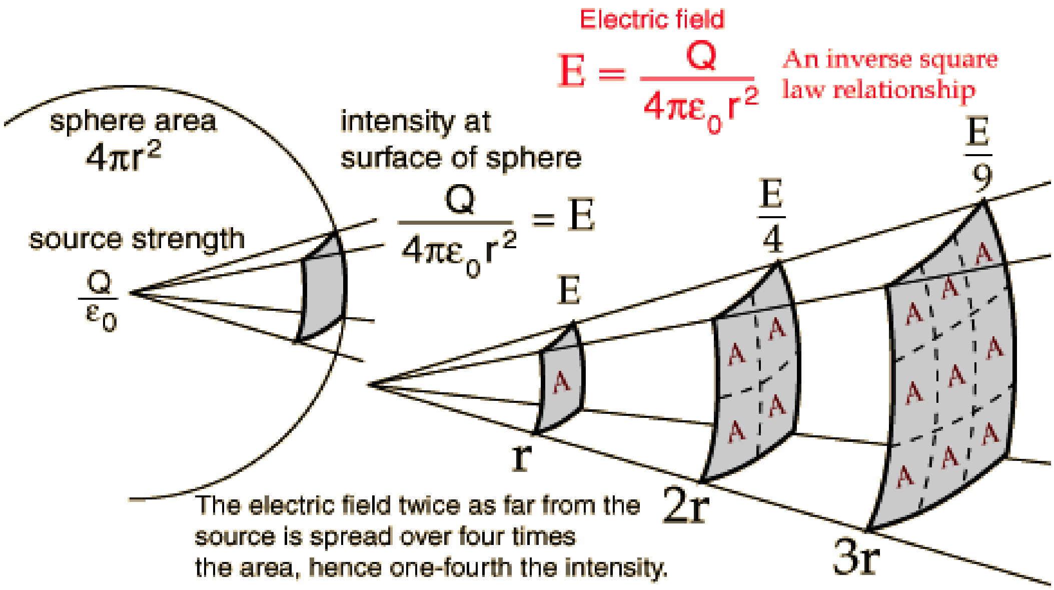
As one of the fields which obey the general inverse square law, the gravity field can be put in the form shown below, showing that the acceleration of gravity, g, is an expression of the intensity of the gravity field.



2. Inverse Square Law, Electric

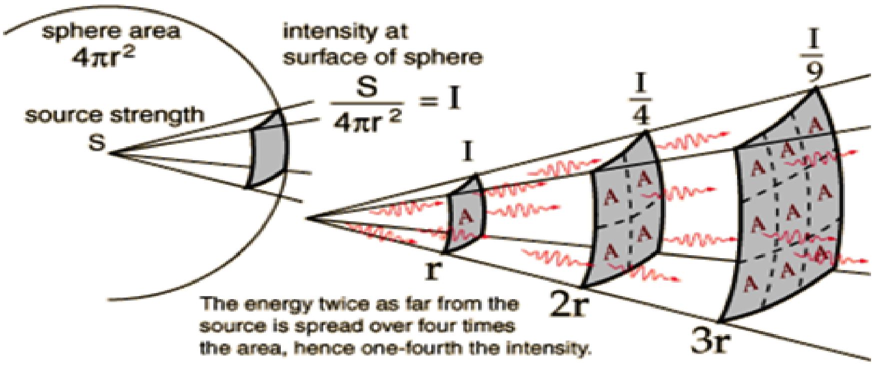
As one of the fields which obey the general inverse square law, the electric field of a point charge can be put in the form shown below where point charge Q is the source of the field. The electric force in Coulomb's law follows the inverse square law.





3 Inverse Square Law, Radiation

As one of the fields which obey the general inverse square law, a point radiation source can be characterized by the relationship below whether you are talking about Roentgens, rads . All measures of exposure will drop off by inverse square law.



The source is described by a general "source strength" S because there are many ways to characterize a radiation source - by grams of a radioactive isotope, source strength in Curies, etc. For any such description of the source, if you have determined the amount of radiation per unit area reaching 1 meter, then it will be one fourth as much at 2 meters.

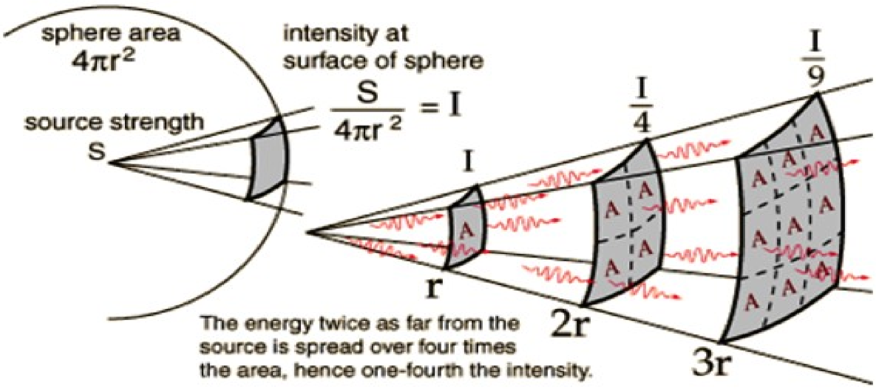
4 Inverse Square Law of Light

As one of the fields which obey the general inverse square law, the light from a point source can be put in the form

Where E is called luminance and I is called pointance.

The source is described by a general "source strength" S because there are many ways to characterize a light source - by power in watts, power in the visible range, power factored by the eye's sensitivity, etc. For any such description of the source, if you have

determined the amount of light per unit area reaching 1 meter, then it will be one fourth as much at 2 meters.



Nvis 6006D Inverse Square Law

More generally, the irradiance, *i.e.,* the intensity (or power per unit area in the direction of propagation), of a spherical wave front varies inversely with the square of the distance from the source (assuming there are no losses caused by absorption or scattering).

For example, the intensity of radiation from the Sun is 9140 watts per square meter at the distance of Mercury (0.387AU); but only 1370 watts per square meter at the distance of Earth (1AU)—a threefold increase in distance results in a nine fold decrease in intensity of radiation.

Photographers and theatrical lighting professionals use the inverse-square law to determine optimal location of the light source for proper illumination of the subject. The inverse-square law can be used only on point source light, a fluorescent lamp is not a point source and therefore one can not use the inverse-square law, as is possible with most other light sources, with a fluorescent lamp.

For an infinite linear-source the equation is: E = I / d

For an infinite planar-source the equation is: E = I (E is invariant with d).

A Plasma Light Bulb is as close to a point source as is practical for most lamps. See here

(Way Back link to "Point Source Approximation") that a "point source" (subject to 1% error) is obtained from a "pseudo-point-source" (not LED or Laser) at a distance 10 times the source radius (5 times the diameter). A four foot fluorescent lamp is (almost) a point source (subject to 1% error) **at a distance of 20 feet**. Similarly, as you get closer to a fluorescent lamp it will get brighter up to a certain distance (because the viewing angle (sampled area) remains constant and close-up (1 foot away) the entire fluorescent tube can not be viewed), after which the intensity will not continue to increase (as it would with a (pseudo) point source).

The fractional reduction in electromagnetic fluence (Φ) for indirectly ionizing radiation with increasing distance from a point source can be calculated using the inverse-square law. Since emissions from a point source have radial directions, they intercept at a perpendicular incidence. The area of such a shell is $4\pi \mathbf{r}^2$ where **r** is the radial distance from the center.

The law is particularly important in diagnostic radiography and radiotherapy treatment planning, though this proportionality does not hold in practical situations unless source dimensions are much smaller than the distance **r**.

The inverse square law in radiography is:

$$\frac{I_1}{I_2} = \left(\frac{D_2}{D_1}\right)^2$$

Where I is intensity and *D* is distance.

Nvis 6006D Inverse Square Law

Example

Let the total power radiated from a point source, *e.g.,* an omnidirectional isotropic antenna, be P. At large distances from the source (compared to the size of the source), this power is distributed over larger and larger spherical surfaces as the distance from the source increases. Since the surface area of a sphere of radius is $A = 4\pi r^2$, then intensity I of radiation at distance is r

$$I = \frac{P}{A} = \frac{P}{4\pi r^2}.$$

$$I \propto \frac{1}{r^2}$$

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

$$I_1 = I_2 r_2^2 \frac{1}{r_1^2}$$

The energy or intensity decreases by a factor of ¼ as the distance *r* is doubled, or measured in dB it would decrease by 6.02 dB. This is the fundamental reason why intensity of radiation, whether it is electromagnetic or acoustic radiation, follows the inverse-square behavior (assuming it originates from a point-source), at least in the ideal

3 dimensional context (propagation in 2 dimensions would just follow an inverse-proportional distance behavior and propagation in one dimension, the plane wave, remains constant in amplitude even as distance from the source changes).

Luminous Flux

The radiant power is the total radiated power in watts, also called radiant flux. This power must be factored by the sensitivity of the human eye to determine luminous flux in lumens. The standard definition is as follows

Lumens = (Radiant Power in watts)(683 lumens/watt) X
(luminous efficiency for the specific light)

Efficacy = lumens /watt

(Typical: 1700 lumens for 100 watt light bulb gives efficacy of 17 lumens /watt)

Luminous efficiency = equivalent light power / electric power for typical incandescent bulb

$$\frac{1700\ lumens}{683\ {}^{lumens}/_{watt}} = 2.49\ watt$$

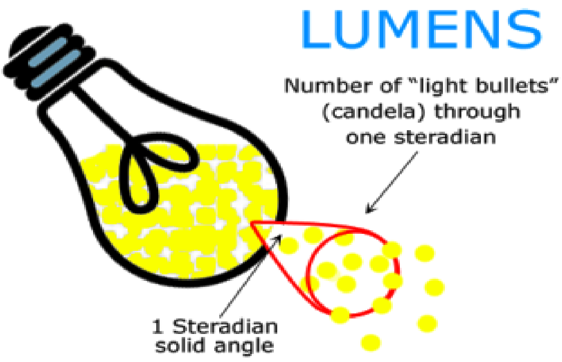
Luminous Efficiency =

$$\frac{2.49\ "\ light\ watts\ "}{100\ watts} = 2.49\ \%$$

The Lumen

The lumen is the standard unit for the luminous flux of a light source. It is an SI derived unit based on the candela. It can be defined as the luminous flux emitted into unit solid angle (1 sr) by an isotropic point source having a luminous intensity of 1 candela. The unit lumen is then equal to cd x sr. The abbreviation is lm and the symbol is Φ_V. In terms of radiant power (also called radiant flux) it can be expressed as

Luminous flux in lumens = Radiant power (watts) x 683 lumens/watt x luminous efficacy



The luminous flux is the part of the power which is perceived as light by the human eye, and the figure 683 lumens/watt is based upon the sensitivity of the eye at 555 nm, the peak efficiency of the photopic (daylight) vision curve. The luminous efficacy is 1 at that frequency.

A typical 100 watt incandescent bulb has a luminous flux of about 1700 lumens. Units for other quantities in photometry contain the lumen, such as the lux(lumens/meter^2)

Luminous Flux

Luminous Flux (Φ_V) is energy per unit time (dQ/dt) that is radiated from a source over visible wavelengths. More specifically, it is energy radiated over wavelengths sensitive to the human eye, from about 330 nm to 780 nm. Thus, luminous flux is a weighted average of the Radiant Flux in the visible spectrum. It is a weighted average because the human eye does not respond equally to all visible wavelengths.

The sensitivity of the eye peaks at 555 nm and falls off to approximately 10-4 at 380 and 750 nm. This constitutes the range of daylight sensitivity, or photopic vision. The eye's nighttime sensitivity, called scotopic vision, shifts toward the blue end of the visible, peaking at 507 nm and falling to 10-4 at 340 and 670 nm, this weighting factor, or luminous efficacy ($V\lambda$), allows for conversion of Radiant Flux to Luminous Flux at any wavelength. In the photopic region, the peak at 555 nm is assigned a conversion value of 683 lumens per Watt. The lumen is the unit of luminous flux, and is defined in terms of the candela, an SI base unit like the meter or second. 1 lumen is defined to be $1/4\pi$ candela, the SI base unit of Luminous Intensity.

Since the eye does not see all wavelengths equally well, the efficacy curve is a very important way to determine the Luminous Flux from a source. The Luminous Flux from a monochromatic source producing light at a single wavelength is easiest to determine.

$$\Phi_V = \Phi * V_\lambda * (683 \text{ lm/W})$$

For instance, a 5 mW laser pointer using at a wavelength of 680 nm produces .005 W * .017 * 683 lm/W = .058 lm

While a 5 mW laser pointer at 630 nm produces.005 W * .265 * 683 lm/W = .905 lm, a significantly greater luminous flux. Determining the Luminous Flux from a source radiating over a spectrum is more difficult.

It is necessary to determine the Spectral Power Distribution for the particular source.

Once that is done, it is necessary to calculate the Luminous Flux at each wavelength, or at regular intervals for continuous spectra. Adding up the flux at each wavelength gives a total flux produced by a source in the visible spectrum.

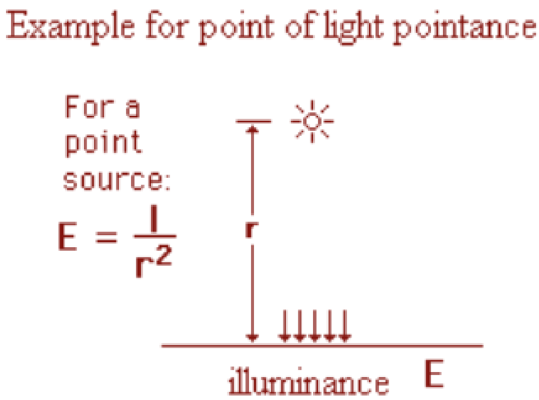
Some sources are easier to do this with than others. A standard incandescent lamp produces a continuous spectrum in the visible, and various intervals must be used to determine the Luminous Flux. For sources like a mercury vapor lamp, however, it is slightly easier. Mercury emits light primarily in a line spectrum. It emits radiant flux at 6 primary wavelengths. This makes it easier to determine the Luminous Flux of this lamp versus the incandescent.

Generally, it is not necessary to determine the luminous flux for yourself. It is commonly given for a lamp based on laboratory testing during manufacture. For instance, the Luminous Flux for a 100W incandescent lamp is approximately 1700 lm. We can use this information to extrapolate to similar lamps. Thus the average luminous efficacy for an incandescent lamp is about 17 lm/W, We can now use this as an approximation for similar incandescent sources at various wattages. Often times, the manufacturer will list 'initial lumens' in its data for a lamp, this is the Luminous Flux for that lamp. It is listed in this manner because as a lamp ages, its power distribution shifts slightly and no longer radiates at precisely the wavelengths it did at the time it was new. However, for all intents and purposes, 'initial lumens' may be used for Luminous Flux for any necessary calculation.

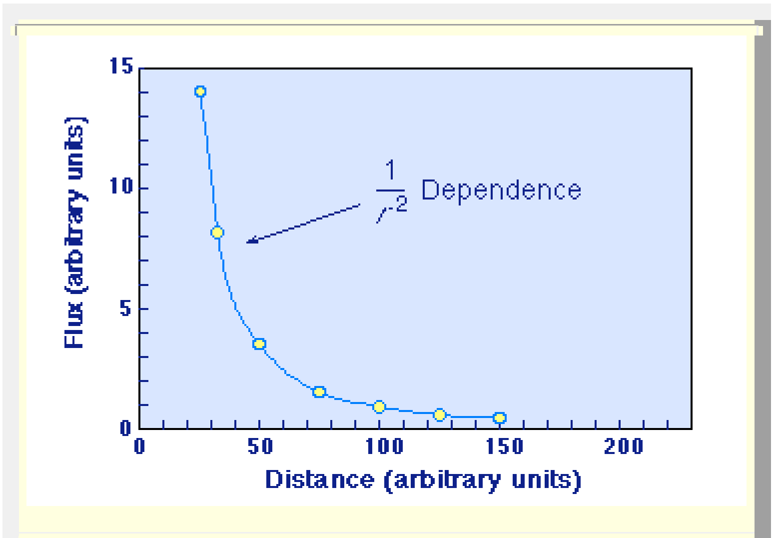
Power Per Unit Area of Surface

The power per unit area on an illuminated surface, sometimes called arcane, is distinguished from the similar quantity for the source. In radiometry the surface arcane may be called irradiance and luminous arcane may be called illuminance. This is the quantity of practical importance in judging whether an area is lighted well enough for reading or other activities. The illuminance is measured in lux, but the older unit foot-candle is still encountered.

Nvis 6006D Inverse Square Law



The intensity of light observed from a source of constant intrinsic luminosity falls off as the square of the distance from the object. This is known as the inverse square law for light intensity.

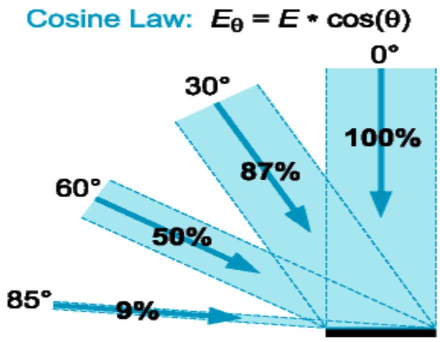


The inverse square law for intensity

Thus, if I double the distance to a light source the observed intensity is decreased to $(1/2)^2$ = 1/4 of its original value. Generally, the ratio of intensities at distances d_1 and d_2 are

$$\frac{l_1}{l_2} = \frac{d_2^2}{d_1^2}$$

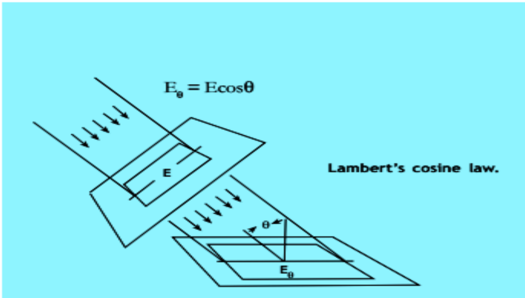
Lambert's Cosine Law



Lambert's cosine law.

Lambert's cosine law states that the luminance falling on any surface depends on the cosine of the light's angle of incidence, θ. "Reflection," that the angle of incidence is measured from a line normal to the surface.

$$E_\theta = E\cos\theta$$



Lambertian Emission and Reflection

A Lambertian surface reflects or emits equal (isotropic) luminance in every direction. For example, an evenly illuminated diffuse flat surface such as a piece of paper is approximately Lambertian, because the reflected light is the same in every direction from which you can see the surface of the paper. However, it does not have isotropic intensity, because the intensity varies according to the cosine law.

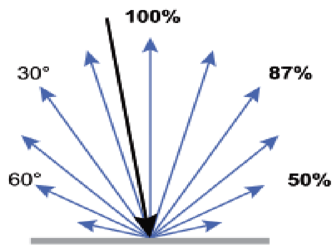


Figure shows a Lambertian reflection from a surface. Notice that the reflection follows the cosine law — the amount of reflected energy in a particular direction (the intensity) is proportional to the cosine of the reflected angle.

Nvis 6006D Inverse Square Law

Remember that luminance is intensity per unit area. Because both intensity and apparent area follow the cosine law, they remain in proportion to each other as the viewing angle changes. Therefore, luminance remains constant while luminous intensity does not.

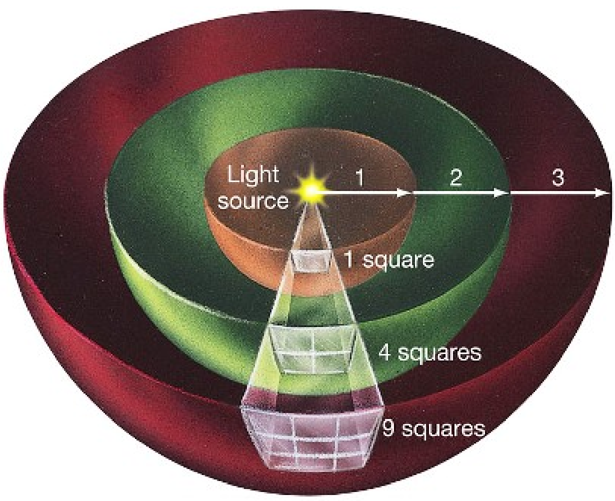
The Inverse-Square Law

The intensity of a star's light falls off with distance according to a simple mathematical law. We will test that law in the lab, and illustrate its key applications in astronomy.

In everyday life we describe light subjectively; for example, light is `good' if it enables us to do what we want to do, and `bad' if it doesn't. But light can be measured and described numerically. In particular, we can measure the intensity of light; if a given source produces one unit of light, two such sources will produce twice as much light, and ten sources will produce ten times as much, and so on.

In this class we will need to measure the intensity of light in two different ways. First, we must consider the total amount of light a source - say, a star, or a light-bulb - gives off. Second, we must consider the amount of light from a source which reaches our location. The difference between these two kinds of intensity is part of everyday experience. For example, a 100 watt light-bulb is a fairly powerful source of light; placed a few feet from your desk, it provides plenty of reading light. But even a 1000 watt light-bulb won't provide enough light to read by if it's located a few hundred feet away.

It helps to give different names to these two ways of measuring intensity. The total amount of light a source emits is called its luminosity. A light-bulb's luminosity is roughly proportional to the number of watts it consumes. (This is not an exact relationship because light-bulbs are not 100% efficient: in addition to light, they also give off lots of heat.) The amount of light we receive from a source is called its brightness. Brightness is amount of light per unit area. The brightness of a source depends on how far away it happens to be, while the luminosity of a source does not.



Nvis 6006D Inverse Square Law

L = luminosity (power output) of a source which emits light in all directions

d = distance from the source to the point where we want to calculate the apparent brightness.

B = apparent brightness (power received per unit area)

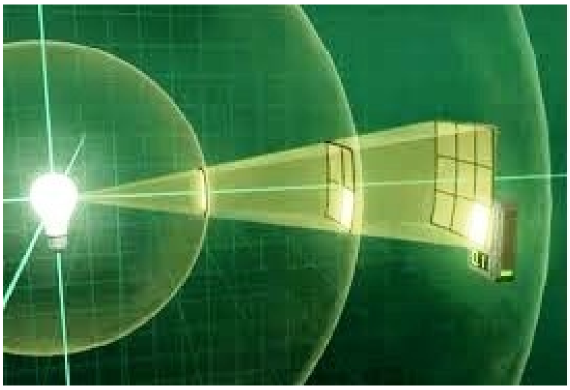
$$B = \frac{L}{4\pi d^2}$$

All this formula says is that brightness is the luminosity divided by the area which is illuminated. Because the area of a sphere increases as the square of its radius, it's the square of D which appears in the denominator

Geometry of the inverse-square law

A simple experiment illuminates (pun intended) the relationship between luminosity, brightness, and distance. As shown in the diagram below, we will set up a light-bulb, and on one side of the bulb we will set up a wall with a small hole. The light from the bulb spreads out in all directions. A certain amount of light passes through the hole and falls on a movable screen which is parallel to the wall. The total amount of light passing through the hole and falling on the screen does not depend on where we put the screen. But as we move the screen further away, this fixed amount of light must cover a larger area, and the brightness on the screen decreases.

To be specific, suppose we are using a 200 watt light-bulb. According to the manufacturer, this bulb has a light output of about 4000 lumens (A **lumen** is a unit of luminosity). Let's put the wall 1 foot away from the center of the light-bulb, and make the hole a square 1 inch on a side. Imagine a sphere with a radius of 1 foot = 12 inches centered on the light-bulb. This sphere has a surface area of 1,810 square inches; in other words, it would take 1,810 squares, each 1 inch on a side, to cover the entire sphere. The 4000 lumens put out by the light-bulb spreads evenly over the entire surface of the sphere, so each square inch gets just 4000 / 1810 = 2.2 lumens, which is also the amount of light passing through the 1 inch hole we've cut in the wall.



Nvis 6006D Inverse Square Law

The inverse-square law in action, a certain amount of light passes through the hole at a distance of 1 foot from the light-bulb. At distances of 2 feet, 3 feet, and 4 feet from the bulb, the same amount of light spreads out to cover 4, 9, and 16 times the hole's area, respectively.

Now consider the light passing through the hole and falling on the screen. If we put the screen up right next to the hole, this light falls on a square 1 inch on a side. This square receives a total of 2.2 lumens, spread over 1 square inch, so the brightness of the light on the screen is 2.2 lumens / 1 square inch = 2.2 lumens per square inch. If we move the screen to a distance of 2 feet from the light-bulb, the light passing through the hole now falls on a square which is 2 inches on a side. The area of this square is 2 inches × 2 inches= 4 square inches, so the brightness on the screen is now 2.2 lumens / 4 square inch =0.55 lumens per square inch. Moving the screen even further away spreads the light out more and reduces the brightness of the light even further. The numerical results for this simple experiment are summarized in the table below. In every case, the last column is just 2.2 lumens divided by the area of the illuminated square.

We're now ready for the last step, which is to take away the wall between the light-bulb and the screen! When we do this, the brightness of the light falling on the screen does not change. The wall with its central hole helped us define the amount of light falling on the screen, and the bright outline of the hole helped us to see how that fixed amount of light spreads over a greater area as the screen is moved further from the bulb.

Distance from bulb to screen	Size of square on screen	Area of square on screen	Brightness in square
1 foot (12 inches)	1 inch × 1 inch	1 square inch	2.20 lumens per square inch
2 feet (24 inches)	2 inches × 2 inches	4 square inches	0.55 lumens per square inch
3 feet (36 inches)	3 inches × 3 inches	9 square inches	0.244 lumens per square inch
4 feet (48 inches)	4 inches × 4 inches	16 square inches	0.138 lumens per square inch

But the light passing through the hole on its way to the screen `had no idea' that the wall was there, so it produces the same brightness on the screen no matter what. When we take away the wall, more of the screen is illuminated, but the brightness remains the same. The brightness depends on only two things: the luminosity of the light-bulb, and the distance from the bulb to the screen.

We can express the relationship between luminosity, brightness, and distance with a simple formula. Let L be the luminosity of a source which emits light in all directions, and D be the distance from the source to the point where we want to calculate the source's brightness. Then the brightness is

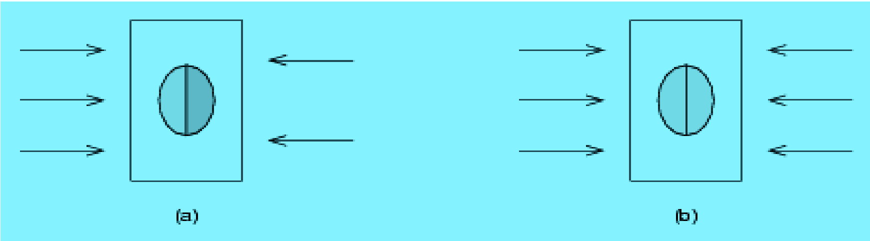
$$B = \frac{L}{4\pi D^2}$$

Here the denominator is just the area of a sphere of radius D. All that this formula says is that brightness is the luminosity divided by the area which is illuminated. Because the area of a sphere increases as the square of its radius, it's the square of D which appears in the denominator. That's why this is called the inverse-square law; brightness is inversely proportional to the square of the distance.

Comparing brightness with a null-photometer

To test the inverse-square law, we need a way of measuring brightness. With modern technology, brightness can be measured electronically. Unfortunately, it's not easy to explain how this technology works; we would have to discuss the nature of electricity, some mysteries of quantum mechanics, and the physics of electromagnetic fields. So we will fall back on an earlier technology which can be understood at an intuitive level without a lot of extra explanation.

A null-photometer is a device for comparing the brightness of two light sources. It can't provide a direct measurement of brightness, but it can tell you when two sources have the same brightness. In practical terms, the null-photometer we will use is just a sheet of aluminum foil sandwiched between two slabs of wax; a band of foil is wrapped around the edge, with a window allowing you to view the sandwich edge-on. The operation of a null-photometer is illustrated in the diagram below. To begin with, you orient the photometer so each side is pointing directly at one to the two light sources you want to compare; the light must strike the wax slabs squarely, and not at an angle. Thus one side is illuminated by one source, and the other side is illuminated by the other source. You then look through the window. If both sources have the same brightness, both halves of the sandwich will be equally bright; this is called a `null' reading (hence the term null-photometer). If one source is brighter than the other, the corresponding side of the sandwich will be brighter than the other side. You eyes are pretty good at judging relative brightness; with a little care, you can determine a null reading quite accurately.



A null-photometer in operation **(a)** with more light (arrows) coming from the left than from the right, the left half of the photometer's window is brighter. **(b)** With equal amounts of light coming from both sides, the two halves of the window have the same brightness.

The inverse-square law in the lab

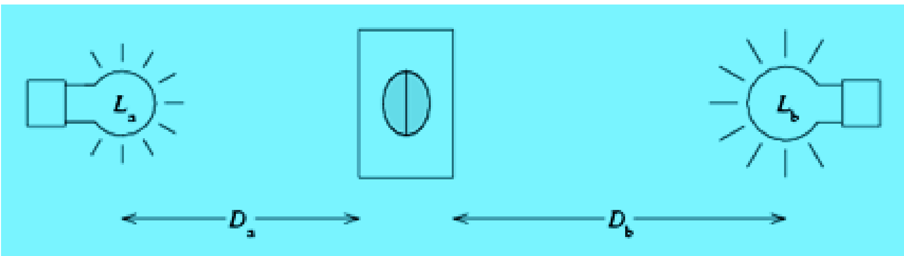
To test the inverse-square law using a null-photometer, we need to express the law in a slightly different way. A null-photometer tells you if two light sources provide equal brightness; in mathematical terms, that is $B_a = B_b$, where B_a is the brightness produced by light source `a' and $B_b$ is the brightness produced by light source `b'. Let's say that source `a' has luminosity $L_a$ and is at distance $D_a$, while source `b' has luminosity L_b and is at distance D_b. Then if $B_a = B_b$, we must have

$$\frac{L_a}{L_b} = \left[\frac{D_b}{D_a}\right]^2$$

$$\frac{L_a}{D_a^2} = \frac{L_b}{D_b^2}$$

The equation on the left is derived by using our original formula for brightness, and canceling out the common factors. The equation on the right is derived from the one on the left by rearranging the terms; this form is convenient for an experimental test of the inverse-square law.

The basic procedure for our laboratory test of the inverse-square law is shown in the diagram below. We will set up two lights of known luminosities. The null-photometer is placed between the lights, and moved to the point where both halves of the window are equally bright. The distances from the photometer to the lights are then measured. Finally, the luminosities and distances are substituted into the equation just derived; if the law is correct, the two sides should be equal, or nearly equal if we allow for experimental error.



Experimental measurement, the null-photometer is placed between the two lights and moved until both halves of the window have the same brightness.

Testing the inverse law

To test the law properly, we will set up several pairs of lights, with each pair separated from the others to avoid confusion. You will find this experiment easier if you work with a partner; one person can hold the photometer in position, while the other measures the distances to the lights. However, you and your partner should switch roles so that everyone gets a chance to do every measurement.

When you make measurement, hold the null-photometer between the lights, and move it back and forth along an imaginary line between them until both halves of the photometer's window appear the same. Your partner can check to make sure the photometer really is on a line between the two lights, and then measure the distances D_a and D_b. Ideally, these distances should be measured from the center of each light-bulb to the nearest side of the photometer, as shown in the diagram. Once both distances have been recorded, flip the photometer over so the left face is now the right face, and vice versa. Re-position the photometer between the lights, move it so both halves appear the same, and again measure the distances. Repeat two more times, again flipping the photometer each time. You should now have four separate measurements of the two distances. Each set of four measurements can be averaged to get a more precise value; you can also look at the range of values for each measurement to get some idea of the accuracy of your work.

Before moving on to the next pair of lights, be sure to record the luminosities L_a and L_b. Now compute averages for your measurements of D_a and D_b for each pair of lights. Summarize your results in a table, with a separate row for each pair of lights, and separate columns for your average values of D_a, D_b, L_a / L_b, and $(D_b / D_a)^2$. If the last two columns of each row are equal, allowing for experimental error, then the inverse-square law passes the test.

Measuring luminosity

The same procedure can be used to measure the luminosity of a light-bulb. We will set up a pair of lights and tell you the luminosity of one light; your job is to calculate the luminosity of the other. Follow the same procedure you used when testing the law: position the photometer so both halves appear the same, measure the distances to the bulbs, repeat another three times, flipping the photometer each time. Record your measurements for D_a and D_b, along with the known luminosity L_a.

Now compute averages for your measurements of D_a and D_b just as you did when testing the law. Then plug your averages and the known luminosity L_a into the equation

$$L_b = \left(\frac{D_a}{D_b}\right)^2 \times L_a .$$

(In astronomy, we sometimes know the distance to a star but not its luminosity. A measurement like this can be used to find the star's luminosity.)

Measuring distance

A similar procedure can be used to measure an unknown distance, given the luminosities of both light-bulbs. We will set up one last pair of lights and tell you both luminosities. This time you will keep the photometer fixed, and move bulb `a' back and forth until both halves of the photometer appear the same; then measure the distance D_a. Once again, repeat another three times, flipping the photometer each time. Record your measurements for D_a, along with the given luminosities L_a and L_b.

Now compute averages for your measurements of D_a, and plug your result into the equation

$$D_b = \sqrt{\frac{L_b}{L_a}} \times D_a .$$

(In astronomy, stars come in a range of luminosities, and we can sometimes figure out the luminosity by measuring the star's color. If we know the luminosity, we can then use this technique to measure the star's distance.)

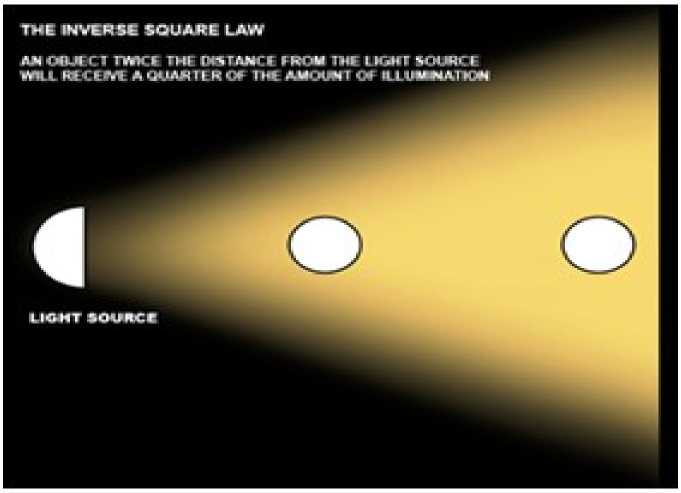
The Inverse Square Law - what it means to Photographers

It's useful to know a little about the inverse square law especially when using flash or studio lights. Basically all the inverse square law says is that an object that is twice the distance from a point source of light will receive a quarter of the illumination. So what it means to us photographers is that if you move your subject from 3 meters away to six meters away, you will need four times the amount of light for the same exposure. This can most easily be achieved by opening the lens aperture two f-stops (see aperture for an explanation) or using a flashgun that is four times as powerful.

What do we mean by a point source of light? Well in Physics there might be a very strict definition but for our purposes any flashgun or lamp can be considered a point source. The other variable to be aware of is that the law works for 'unfocused' light sources. Light from a laser or other highly focused source will not drop off quite so rapidly.

The reason why the power of the light diminishes so rapidly is not because it 'runs out of energy' or anything like that, but because it spreads and so a smaller and smaller proportion of the light hits the object. Here's a little diagram to illustrate the point.

Nvis 6006D Inverse Square Law



As you can see from the diagram the beam of light fans out quite quickly and the object furthest from the light receives only a small proportion of the light, most of the beam misses the target.

The more the beam is focused the higher proportion of the light will fall on the object. With a theatrical spotlight for instance which has a very narrow beam, much light will fall on the object.

In photography though we don't tend to use highly focused beams as they produce a very harsh light, too contrast for our purposes. So the inverse square law, as a rule of thumb, works very well for us.

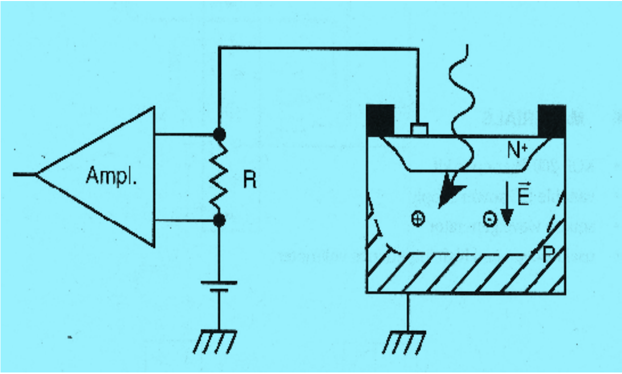
Photo detector

Photo detector is devices that convert photons into electric current by means of “electron-hole” pair generation subsequent to the absorption of light by a semiconductor material. Presently, the most commonly used material is silicon.

Principle of operation

In a semiconductor material, the absorption of light becomes important whenever photon energy is equal or larger than the forbidden band gap energy. In the case of visible and near infrared light, incident photon energy is sufficiently large to create e-h pairs. By this process, carrier density increases in the conduction band.

Figure illustrates the conversion process. Under reverse bias, the semiconductor junction will pass a current that is proportional to the incident photon flux, or optical power. The intense electric field E existing in the depleted region drains off all the carriers created by photon absorption. The current due to carrier collection is sampled by resistor R and thus can be measured as a voltage. That is how optical power is transformed into electric signal.



Basic Structure of a Photodiode and Amplifier Circuit

Characteristics

The principle interesting characteristics of Photo detector are quantum efficiency, sensitivity, linearity, time constant, and leakage current.

Quantum efficiency

Pair generation by photon absorption is a random phenomenon characterized by the mean number of pairs created by each incoming photon. This probability, named quantum efficiency and noted η, depends upon photon wavelength and semiconductor type. For a typical silicon photodiode, for example, quantum efficiencies are

$$\eta = 85\% \text{ at } 0.9\ \mu m$$

$\eta = 20\%$ at 1.06 µm

Sensitivity

By definition, sensitivity (*S*) is the current generated by the Photo detector per watt of incident optical power (P_{op}). For example, silicon photodiodes exhibit values of 0.6 A/W at 900 nm.

For a given detector construction, sensitivity varies as a function of wavelength. At short wavelengths, quantum efficiency is low since absorption occurs very close to the surface. The light-generated photo carriers recombine very quickly in the N^+ region and consequently are not collected. At long wavelengths, the layer thickness is too small for complete absorption.

$$S = \frac{CurrentIntensity}{P_{op}}$$

Once the quantum efficiency is known, the sensitivity can be deduced from the relationship

$$S = \frac{\eta e}{h\nu}$$

Where η is the quantum efficiency, e the electric charge, *h* Planck's constant, and *v* the radiation frequency, Moreover we already know that a proportional current I_0 corresponds to an incident power P_0 so that

$$I_o = SP_0$$

Linearity

Linearity is another very important Photo detector characteristic. In fact, it is most important that the photocurrent varies linearly as a function of the incident energy flux, especially for analog signal reception. Typically, a photodiode exhibits a 100 dB dynamic

Range while keeping linearity within 1%.Under zero illumination conditions, the measured current corresponds to the total noise current including leakage current. This current therefore is named “dark current”.

Time constant

The Photo detector time constant corresponds to the carrier travel time within the collection or depletion region. It depends upon the depletion zone thickness and carrier velocity. With the application of sufficient bias to the diode, we make sure that carriers reach their limiting velocity within this zone. IN principle, the time constant of a typical photodiode is 0.5 ns for 50 µm layer thickness. The actual values are much closer to 1 ns because the carriers crated outside the depletion zone are collected at a much slower rate, due to reduced field intensity in that area.

`Experimental Method

First, we will measure the time constant of a detection system using a photodiode made from the collector-base junction of a phototransistor. Second, we will measure the time constant of a phototransistor in its normal mode of operation. Finally, we will measure the relative sensitivity of both configurations and check the linearity of a PIN photodiode. A Phototransistor can be used as a simple photodiode when using the reverse-biased collector-base junction only. In a phototransistor, the collector-base photodiode generates a photocurrent I_C that is subsequently amplified by the transistor current gain B which gives

$$I_C = \beta I_L$$

The determination of the Photo detector time constants is performed by measuring the output signal in response to a step input of light on the device. In practice, we apply a square wave signal to the input of the transmission module and measure the time interval required for the output signal to rise form 0-63% of its terminal value as shown in figure below. This measured value gives the time constant τ of the detector.

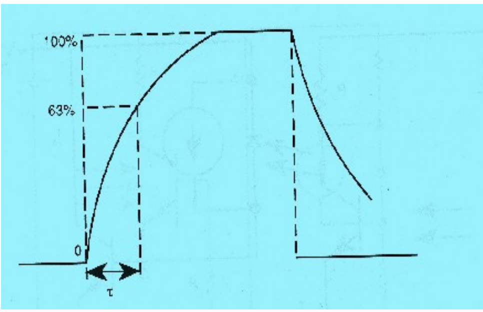


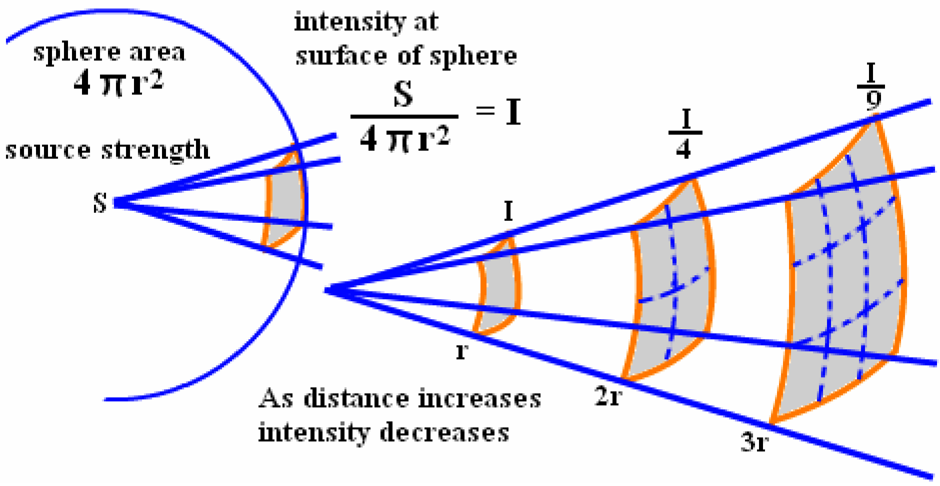
Photo detector Time Constant

Nvis 6006D Inverse Square Law

In order to measure the relative sensitivity of photo detectors, we apply a constant voltage to the input of the transmission module and calculate the transfer ration from the output signal measurements. Photodiode linearity measurement will require the LED with a pigtail fiber. The experiment consists in measuring the signal output of the Photo detector as a function of its separation from the light source. Since the light source used approximates a point source, its illumination varies in a inverse square law. Photodiode linearity then can be evaluated by plotting the amplitude curve on log-log paper. We should then have a straight sloping line.

Inverse Square Law Formula

Inverse Square Law states that the intensity of light is inversely proportional to the square of the distance.



Inverse Square Law Formula is given by

$$I \propto \frac{1}{d^2}$$

Where I is the intensity of the radiation

d is the distance.

If I_1 and I_2 are intensities of light at distances d_1 and d_2 respectively, Then Inverse square law is given by

$$\frac{I_1}{I_2} \propto \frac{d_2^2}{d_1^2}$$

Inverse square law formula is useful in finding distance or intensity of any given radiation. The intensity is given in Lumen or candela and distance s expressed in meters. It has wide applications in problems based on light.

Experiment

Objective: To verify inverse square law.

Items Required

1. Optics bench
2. Light source
3. Photo detector
4. Fix stand
5. Sliding stand

Procedure

1. Place the optics bench in the dark room adjust the height of the bench with the help of Leveling screw.
2. Fix the light source with a holding rod.
3. Now mount the light source on the fixed stand.
4. Place it on the bench such that its left end coincides with the zero mark of the bench, and fix it with the help of provided screw.
5. Mount the Detector on the sliding stand in front of light source. And place the detector at minimum distance with light source by moving sliding stand.
6. Take multimeter and connect the probe of multimeter to photo detector polarity wise.
7. Now set multimeter at millivolt range and note the reading of multimeter in light of room, it will give intensity of light in dark (I_o) in the form of voltage.
8. Connect light source to the mains and switch it on.
9. Now align the photo detector with the light source. Such that the detector should be properly illuminated by the light coming from a incandescent lamp.
10. The setup is as shown below.

Precaution: Don't touch the light source, it can burn the skin.

11. Note the position of detector from light source (r) and voltage on multimeter (intensity of light) in below table.

12. Now move the detector away from light source by the increment of 10cm and take the reading of voltage, till the 95 cm mark on the scale.

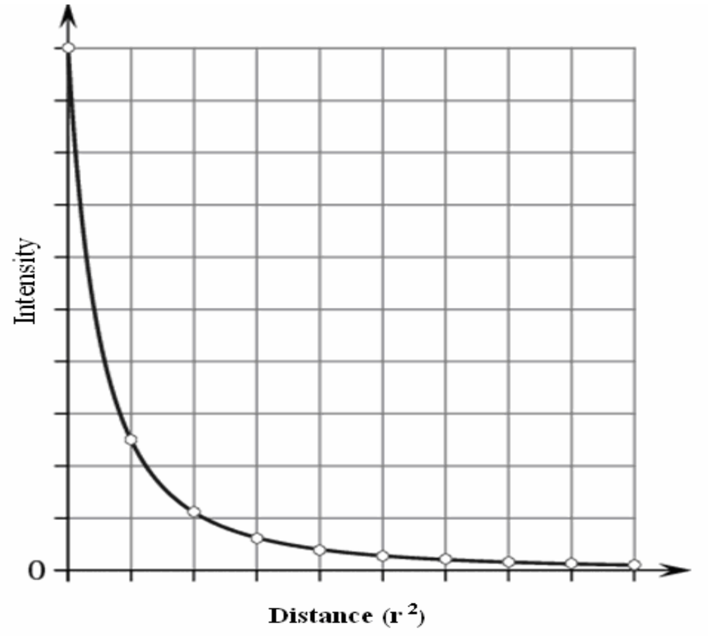
 Note: As photo transistor is device which convert optical light to electrical signals, so we are consider output of photo detector as a intensity of light obtain from light source.

Observation Table

Intensity of light without light source (I_o) = ... mv

S. No.	Distance (in cm.) r		Intensity I_r (in mv)	Actual Intensity $I = I_o - I_r$

Now plot the graph between I and r^2 and it should be like below curve, so we can say that inverse square law is verified.

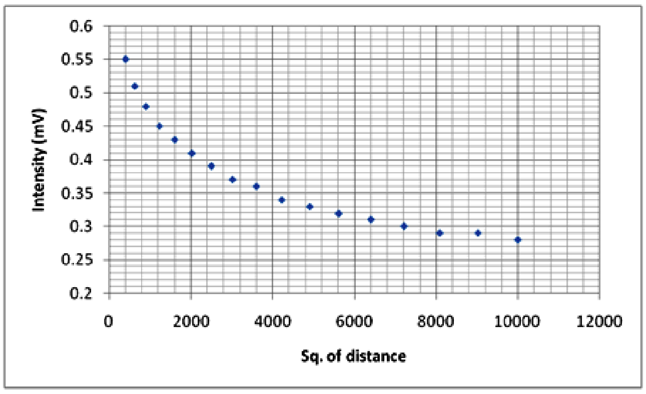


Sample Results

Observation Table

Intensity of light without light source (I_O) = 0 mv

S.No.	Distance r (cm)	Distance Square r^2	Intensity (mV)
1	20	400	0.55
2	25	625	0.51
3	30	900	0.48
4	35	1225	0.45
5	40	1600	0.43
6	45	2025	0.41
7	50	2500	0.39
8	55	3025	0.37
9	60	3600	0.36
10	65	4225	0.34
11	70	4900	0.33
12	75	5625	0.32
13	80	6400	0.31
14	85	7225	0.3
15	90	8100	0.29
16	95	9025	0.29
17	100	10000	0.28



Now plot the graph between I and rand it should be like below curve, so we can say that inverse square law is verified.

Glossary

1. **Absorption:** Transformation of radiant energy to a different form of energy by the interaction with matter, depending on temperature and wavelength
2. **Accessible Emission Level:** The magnitude of accessible laser (or collateral) radiation of a specific wavelength or emission duration at a particular point as measured by appropriate methods and devices. Also means radiation to which human access is possible in accordance with the definitions of the laser's hazard classification.
3. **Acousto- optics:** It is a branch of physics that studies the interactions between sound waves and light waves.
4. **Attenuation:** - The decrease in radiation energy (power) as a beam passes through an absorbing or scattering medium.
5. **Absorption of radiation:** Receiving electromagnetic radiation by interaction with the material, and transforming it to different form, which is usually heat (rise in temperature). The absorption process is dependent on the wavelength of the electromagnetic radiation and on the absorbing material.
6. **Circular polarization:** Circular polarization of an electromagnetic wave is a polarization in which the electric field of the passing wave does not change strength but only changes direction in a rotary manner.
7. **Coherent light:** Coherent light are light waves that are "in phase" with one another.
8. **Collimated:** A beam of radiation or matter whose rays or particles are nearly parallel so that the beam does not converge or diverge appreciably.
9. **Collimation:** Ability of the laser beam to not spread significantly (low divergence) with distance.
10. **Continuous Mode:** The duration of laser exposure is controlled by the user (by foot or hand switch).
11. **Correlated color temperature (CCT):** A specification of the apparent color of a light source relative to the color appearance of a reference source, measured in Kelvin(K). The CCT rating for a lamp is a general indication of the “warmth” or “coolness “of its color. Lamps with a CCT below 3200 K are usually considered warm (more yellow) sources, whereas those with a CCT above 4000 K are usually considered cool (more blue) in appearance.
12. **Isotropic:** The same in all directions.
13. **Light:** Radiant energy that is capable of exciting the retina and producing a visual sensation. Light forms a very small part of the electromagnetic spectrum, from about380 to about 780 nanometers — between ultraviolet and infrared radiation.

14. **Luminance**: It is the physical measure of brightness. The standard unit of luminance is candela per square meter (cd/m2).
15. **Mesopic vision:** Vision with luminance levels between photopic and scotopic.
16. **Nanometer (nm):** One billionth of a meter.
17. **Normal:** Perpendicular.
18. **Photometry:** The measurement of quantities associated with light.
19. **Photopic vision:** Vision when the eye is adapted for bright light (luminance levels generally greater than 3 cd/m2).
20. **Photo detector:** It is an optical detector that converts light signals into electrical signals, which can then be amplified and processed. The photo detector is as essential an element of any fiber optic system as the optical fiber or the light source.
21. **Plasma Radiation:** Black-body radiation generated by luminescence of matter in a laser-generated plume.
22. **Radiometry:** The study of optical radiation — light, ultraviolet radiation, and infrared radiation.
23. **Steradian (sr):** The solid angle subtended at the center .
24. **Radiative:** Emitting or causing the emission of radiation.
25. **Reflection coefficient:** The ratio of the amplitude of the reflected wave and the amplitude of the incident wave.
26. **Resonator:** A part of a laser, consisting of two mirrors, one highly reflective and one partly reflective, placed on either side of a laser pump. Amplified light bounces back and forth between the mirrors, enhancing stimulated emission within the pump, eventually being emitted through the partly reflective mirror.

Frequently Asked Questions

Q1. Define the illuminating power, Intensity of illumination?

Ans. Illumination power is defined as the intensity per unit area. Intensity is defined as no. of photon incident per unit area.

Q2. State Inverse Square Law

Ans. Inverse Square Law states that the intensity of light is inversely proportional to the square of the distance.

Q3. What is meant by monochromatic light?

Ans. Light consisting of only one colour or wave-length

Q4. Can you see all the wave-lengths?

Ans. No, wave lengths from 4000 A^o (violet) to 6000 A^o (Red) are visible only.

Q5. What is Electromagnetic radiation (EM radiation or EMR) ?

Ans. It is a form of energy emitted and absorbed by charged particles which exhibits wave-like behavior as it travels through space.

Q6. What is the electromagnetic spectrum?

Ans. The electromagnetic spectrum consists of all the different wavelengths of electromagnetic radiation, including light, radio waves, and X-rays.

Q7. What is a light wave?

Ans. Light is a disturbance of electric and magnetic fields that travels in the form of a wave.

Q8. How does light carry information about stars, galaxies and other celestial objects?

Ans. Light is a form of electromagnetic radiation. Visible light is a narrow range of wavelengths of the electromagnetic spectrum. By measuring the wavelength or frequency of light coming from objects in the universe, we can learn something about their nature.

Warranty

- We guarantee the product against all manufacturing defects for 12 months from the date of sale by us or through our dealers. Consumables like dry cell etc. are not covered under warranty.
- The guarantee will become void, if
  - The product is not operated as per the instruction given in the learning material.
  - The agreed payment terms and other conditions of sale are not followed.
  - The customer resells the instrument to another party.
  - Any attempt is made to service and modify the instrument.
- The non-working of the product is to be communicated to us immediately giving full details of the complaints and defects noticed specifically mentioning the type, serial number of the product and date of purchase etc.
- The repair work will be carried out, provided the product is dispatched securely packed and insured. The transportation charges shall be borne by the customer.

List of Accessories

- Optics Bench 1 No.
- Fix Stand 1 No.
- Sliding Stand 1 No.
- Light Source 1 No.
- Photo detector 1 No.

References

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- http://irtel.uni-mannheim.de/lehre/seminar-psychophysik/artikel/Alex_Ryer_Light_Measurement_Handbook.pdf
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