bucket representing a light receiver's collection area. When the bucket is near the nozzle it would fill much faster than when it is positioned farther away. The inverse square law predicts that if the distance between the bucket and the nozzle is doubled, the bucket will fill 4 times slower. If it is moved 4 times farther away it will fill 16 times slower. Such a reduction rate
would continue as the bucket is moved away from the nozzle. Conversely, if the bucket is moved, so it halved the distance, it would fill four times faster. By knowing the flow of water from the nozzle (light intensity) and the spray pattern (divergence angle) you can predict how fast the bucket would be filled (light collected) at any position (range) within the spray. Such a prediction is described by the "optical range equation" that combines the inverse square law with some simple trigonometry.

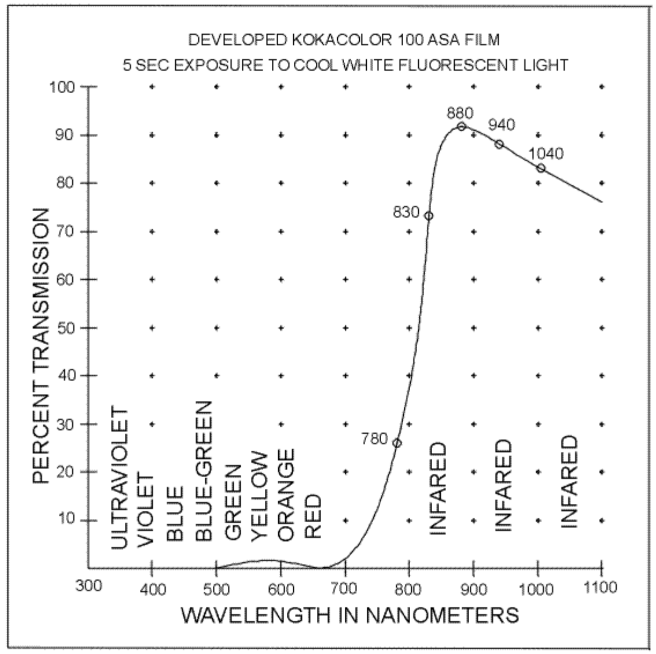

Figure 5h-1

Range Equation

The equation shown in ***Figure 5i*** combines the inverse square law with some other known information. You can use the equation to calculate a number of factors for a typical through-the-air communications system. As in any algebraic equation, you can solve for any unknown factor if the other factors are known. As an example, the equation can tell you how large a light collector you

RANGE EQUATIONS

$$D = \sqrt{\frac{(P)(A)(E)}{(\mathrm{Tan}^2\Theta)(32N)}}$$

$$P = \frac{(32N)(D^2)(\mathrm{Tan}^2\Theta)}{(A)(E)}$$

D = MAXIMUM RANGE IN FEET
P = TRANSMITTER POWER IN WATTS
A = RECEIVER LENS AREA IN SQ FEET
Θ = TRANSMITTER DIVERGENCE HALF ANGLE
N = PIN DETECTOR NOISE FLOOR IN WATTS
E = PIN CONVERSION EFFICIENCY (TYP 0.5)

Figure 5i

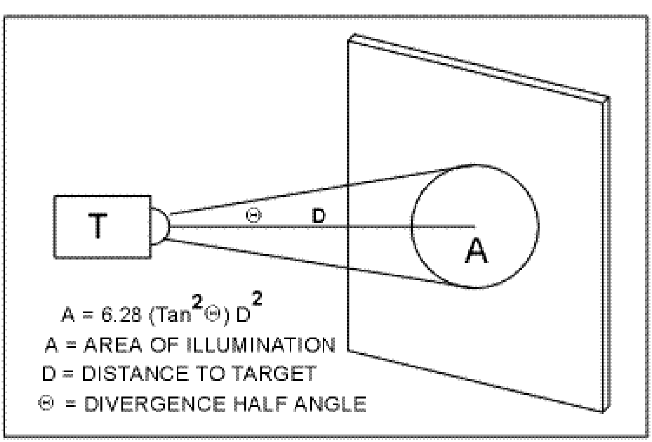

Figure 5j

will need at the receiver or the maximum distance you can position the light receiver from the transmitter. Of course, the equation does not take into account any other losses that may exist within the link, such as poor air quality. ***Figure 5j*** illustrates how the divergence angle effects the illumination area from a light source.

As can be seen, its bandwidth is very narrow and happens to match the emission spectrum of a typical infrared laser diode. If such a filter were used in a communications system, almost all the laser light collected would be allowed to reach the detector, but it would allow only a tiny amount of stray sunlight to pass. Narrow band pass filters can especially be useful when a single light receiver needs to detect light from only one of many different modulated laser sources. Different band pass filters can be moved in front of the detector to reject all sources except one. Such techniques make it possible to have perhaps 10,000 different light receiver bands without interference.

Make Your Own Optical Low Pass Filter

A pretty good optical low pass filter can be made using a photographic film negative. As shown in **Figure 5h-1**, this filter works well at attenuating visible light and is pretty transparent over much of the near infrared wave lengths. However, do note that only light sources with wave lengths longer than 830 nanometers should be used. This filter shouldn't be used for detecting light from many lasers, that operate at 780 nanometers. I found that Kodak Kodacolor film with an ASA of 100 works well. You first remove the unexposed film from the roll and expose it to the light from a cool white fluorescent lamp for about 5 seconds. Then, you wind up the film into roll again and take it to your favorite film developer for processing. Tell them that your not sure if the roll has any images on it and you can usually get them to develop the roll for free. The processed color negatives form the filter material. Keep in mind that the film material is not very robust and should not be used if it can be scratched or exposed to moisture.

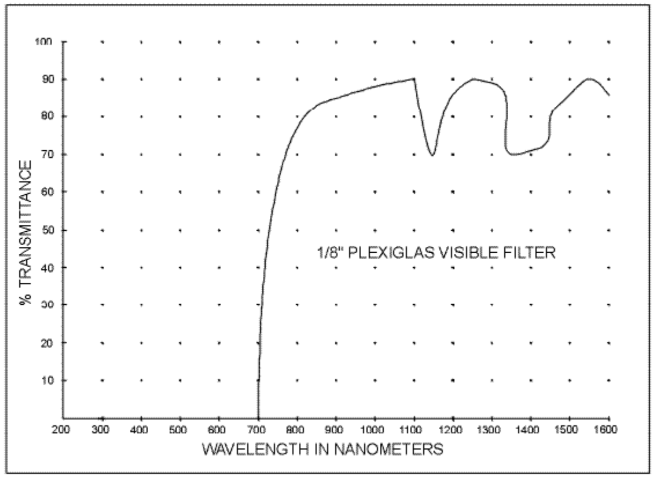

Figure 5g

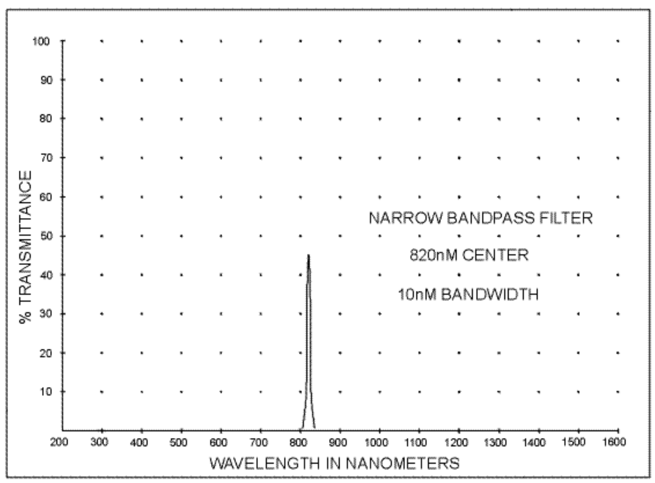

Figure 5h

Inverse Square Law

One of the most important principles you will discover in optics is the inverse square law. The law defines how a light receiver's ability to collect light from a distant emitter will decrease as the receiver is moved away from the source. To help illustrate the concept, let's use a water analogy. Imagine light from a transmitter as a fine spray of water from a small nozzle that produces a cone shaped pattern of water droplets. Also imagine our water source to be in the vacuum of space so that the spray is not effected by air or gravity and will continue to spread out evenly, forever. The gallon per minute rate of water flowing through the nozzle would then represent the intensity of the light source. Now, imagine moving a bucket through the spray at various distances from the nozzle, the

the amount of ambient light that is focused onto a detector is to insert an optical filter between the lens and the detector.

You may see some optical filters every day without realizing it. As an example, the red clear plastic covers, used on most car taillights, are filters. These filters block most of the unwanted colors emitted by the bulb inside and allow only the red light to pass. These single color band filters are called optical "band pass" filters and are the most valuable type of filter used in through-the-air communications. Other

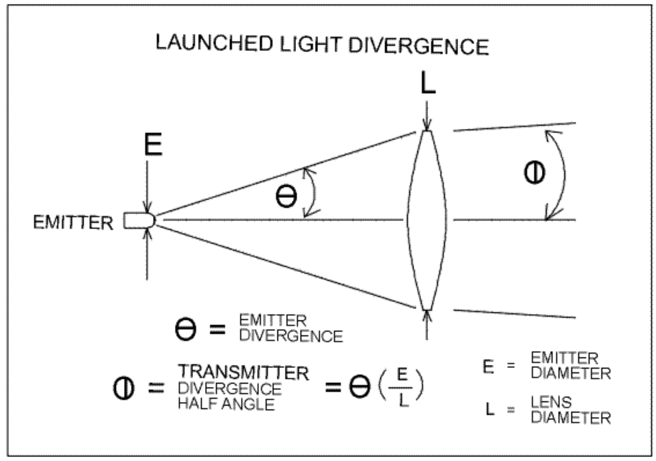

Figure 5e

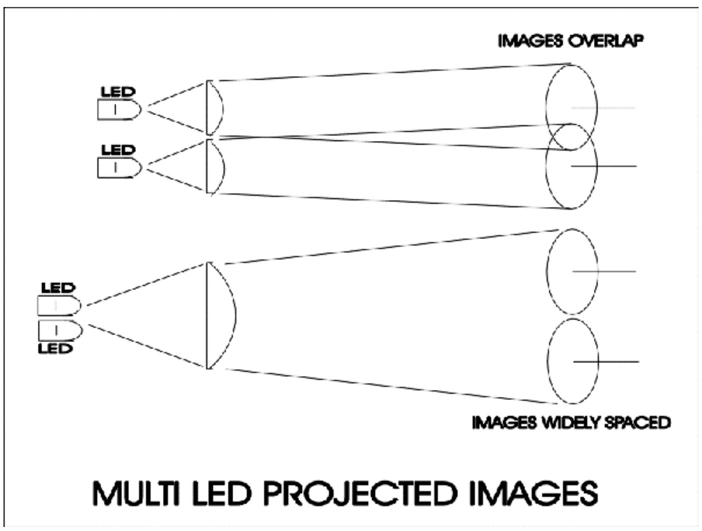

Figure 5f

filters also exist. "High pass" filters are used to block light of long wavelengths and pass shorter wavelengths. Conversely, "low pass" filters block short wavelengths and allow long wavelengths to pass.

Figure 5g shows the transmission spectrum of a low pass filter material. The material has been specifically designed for near infrared use. It is nearly transparent to the near infrared wavelengths but is very dark to most visible light. When placed in front of a silicon detector, the filter will block much of the stray visible ambient light, which may be collected by a lens. But as you will see in the section on light detectors, such a filter will have a minimal effect in the reduction of interference with communications systems that use light emitting diodes (LEDs) as light sources. This occurs because the scattered sunlight, picked

up by the lens, contains a sizable amount of infrared light as well as visible light. The extra light, not blocked by the filter, will still be enough to cause some interference with the signals from the LED source. Even a filter, perfectly matched to an LEDs spectrum, would still cause problems. To filter out most of the unwanted sunlight, a very narrow band pass filter is needed. But to take advantage of a band pass filters they must be used with equally narrow spectrum light emitters, such as semiconductor laser diodes.

One optical band pass filter, that can be made to closely match a laser diode's emission spectrum, is an "interference" filter. Stacking many very thin layers of special materials onto a glass plate makes interference filters. By varying the thickness and the kind of materials deposited, the width of the pass band and the center wavelength can be controlled. ***Figure 5h*** is an example of such a filter.

will only partially use its available diameter and will therefore have a greater overall divergence angle. ***Figure 5e*** illustrates how a lens affects the launched divergence angle from an LED. In a similar way, the size and focal length of the lens used in a light receiver should be selected to insure the light collected is focused properly onto the detector. Fortunately, most light detectors have wide acceptance angles, so you can be use them with a much larger variety of lens shapes, than those required by a light emitter.

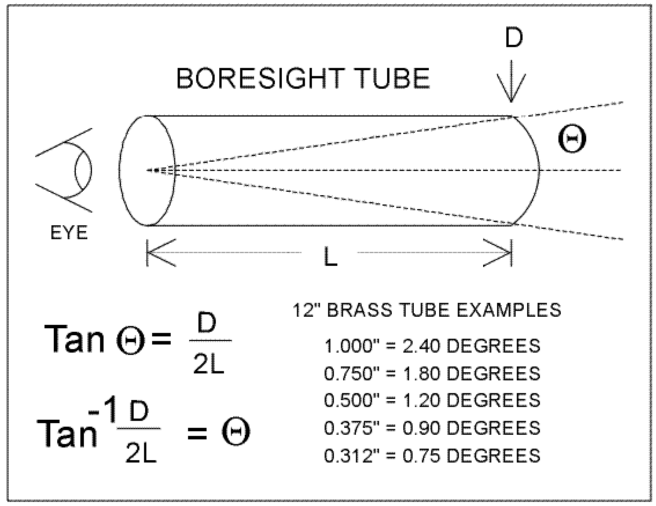

Figure 5c

Multiple Lenses, Multiple Sources

As illustrated in ***Figures 5f***, there are two methods that you can use to collimate light from multiple emitters. If you place a single lens in front an array of light sources, multiple images of the sources will be directed toward the receiver. The individual images will be widely spaced with large blank areas between them. A single receiver will detect only one of the images. This method may be useful if multiple receivers need to receive the transmitted light, but it is not recommended if only one receiver is used. If you want to increase the effective light intensity sent to a distant receiver, from a transmitter that uses multiple emitters, you will need multiple lenses.

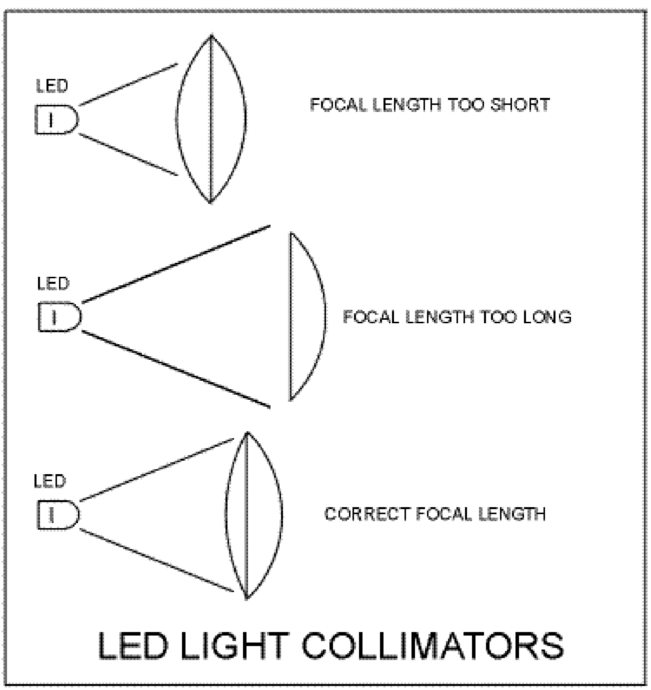

Figure 5d

As illustrated in ***Figure 5f*** an array of lenses, each with its own light source, will appear as one light source, having a higher intensity than a single emitter. This lens array concept is applied in nature by most insects and can be successfully used to produce more powerful light sources that will extend the range of a communications system.

Optical Filters

To increase the separation distance between a light transmitter and a receiver, lenses are often used. A light receiver may use a lens to collect the weak light from the transmitter and focus it onto the receiver's detector for processing. But, the lens will always collect extra light from the environment that is not wanted. Stray light will often interfere with the signals of interest. One method to reduce

Divergence Angle

The outgoing light from an optical transmitter forms a cone shaped area of illumination that spreads out from the end of the transmitter. As illustrated in ***Figure 5a*** the specification that mathematically describes the spreading out of the light is called the "divergence angle". It is almost always described as a half angle or the angle from the center axis of the illumination cone. Often the edge of the illumination cone is defined as the 1/2 power point, relative to the center light intensity. To help illustrate the concept, imagine a flashlight whose beam can be adjusted from a broad flood to a bright spot. The bright spot would have a smaller divergence angle than the flood. Likewise, a red laser pointer would be an example of light source with a very narrow divergence angle. If you have ever had a chance to play with as laser pointer, you would have noticed that the beam does not increase appreciably in size as it strikes a wall across a room. Such divergence angles can be so tight, that keeping the spot on a distant target can be nearly impossible. Most optical communications systems therefore purposely allow the beam to diverge a little so optical alignment can be easily maintained.

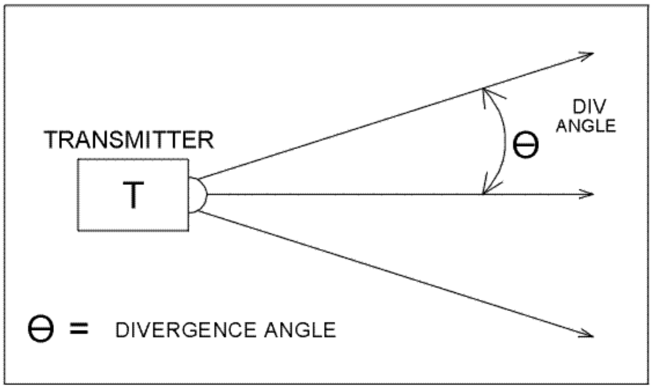

Figure 5a

Acceptance Angle

The incoming light, focused onto a light detector, also has a restricted cone shaped area of collection. Light striking the lens, outside the cone area, will not be focused onto the detector. As illustrated in ***Figure 5b***, the incoming angle is called the "acceptance angle" that is also defined as a half angle. To help illustrate this concept, imagine looking through a long and a short section of pipe. Even if the two pipes have the same diameter the long pipe will restrict the field of view more than the shorter pipe. Pipes that are specially made to restrict the field of view are often used to help aim an optical system and are referred to as "bore sights" (see ***Figure 5c***.) As in divergence angles that are too small, an acceptance angle should also not be too narrow or you will have problems in maintaining alignment with the distant transmitter.

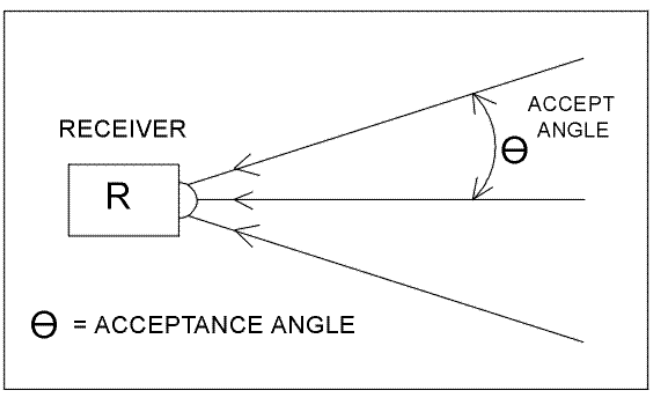

Figure 5b

Light Collimators and Collectors

The light, bent by a lens as it leaves a transmitter, is said to be "collimated". As illustrated by ***Figure 5d***, lenses used to collimate the emitted light from sources such as LEDs, should be carefully selected for their diameter and focal length. A lens with a focal length that is too long will not capture all of the light being emitted. Conversely, a lens that has a focal length that is too short

Chapter Five
LIGHT PROCESSING THEORY

Lenses as Antennas

There is a reoccurring analogy between optical communications and radio. Both systems use similar components that, although made from completely different materials, perform similar functions. As an example, a radio system will always use some kind of antenna to capture the diffuse and often weak signals from the air. Optical systems use similar devices in the form of lenses or mirrors to gather the weak light signals for processing. Large antennas or lenses will allow weaker signals to be detected.

In microwave radio communications, such as satellite receivers, the antenna is often a specially dish shaped metal reflector. The microwave signals are bounced off the dish surface and are concentrated at its focal point, where they can be more efficiently amplified. Similarly, mirrors can be used in optical telescopes or some optical communications systems to collect light and focus it onto special light detectors.

In much the same way that the incoming radio or light signals are processed, the outgoing signals can also benefit from specially shaped antennas or lenses. The radio or light source, when positioned at the focal point of a reflector, can shape the outgoing signal into a narrow beam. The larger the antenna or lens, the narrower the beam becomes. A narrow light beam insures that more of the desired signal is directed toward the distant receiver for better efficiency.

Mirrors and Lenses

Although you can use mirrors in through-the-air communications, lenses are more often used. Lenses are usually much cheaper, readily available and much easier to align than mirrors. Useful lenses can be found in hardware stores, bookstores, office supply stores and even grocery stores. All of the discussions in this book will center on the use of lenses, although some of the techniques used for lenses can also be applied to mirrors.

Types of Lenses

Most of the lenses used in through-the-air communications have one or two outwardly curved surfaces. Such lenses are called "convex" lenses. Small glass or plastic lenses are great for short-range applications. However, glass lenses larger than about 3 inches become too heavy and expensive to be practical. Beyond the 3-inch size it is best to use a flat or "Fresnel" lens. Fresnel lenses can be purchased with diameters ranging from one to more than 36 inches. These lenses are made from molded plastic sheets that have small concentric grooves on one side. When viewed close-up, they look like the grooves in a phonograph record. These lenses are very carefully designed to bend the light just as a convex lens would. When using a Fresnel lens always remember to keep the grooves pointing toward the outside, away from its focal point. Using the lens in reverse will result in lost light and a poor image.

Some alarm systems also use the retro-reflective technique. Pulsed light is bounced off a distant plastic reflector and is collected by a nearby light receiver. Objects moving between the light transmitter and the reflector break the established light path, setting off the alarm. Some industrial systems also use the technique to monitor products moving down a production line.

Figure 4d-1

You can increase the effective corner cube size by placing a fresnel lens in front of the corner cube as shown in ***figure 4d-2.*** Using the technique, you can make a one inch diameter glass corner cube appear to be several feet in diameter. This technique can dramatically lower the overall cost.

When using the retro reflective technique you have to treat the reflector as a distant light source with its own emitting area and divergence angle. The amount of light sent back by the reflector will depend on the ratio of the illuminated area and the reflector's area. A typical plastic reflector has an equivalent divergence angle of about 0.5 degrees. For long-range applications a large reflector will be needed.

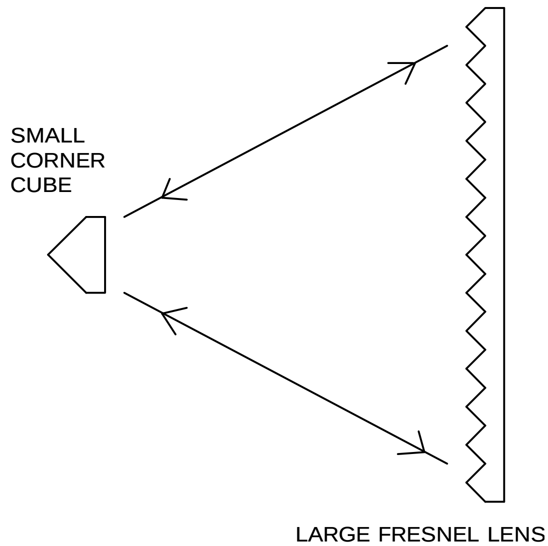

Figure 4d-2

Figure 4d-3 shows a large corner cube reflector you can make yourself. Gluing three glass tile mirrors together makes it. A sturdy cardboard box will help position the mirrors. One mirror is positioned at the bottom of the box and the other two converge at the box sides. You would align such an assembly so the light would enter at a 30-degree angle relative to the bottom. The target for such an assembly would be the point where the three mirrors converge. I have used such a simple mirror for some experiments and was able to detect reflections over a distance of 10 miles. Larger mirror assemblies or even multi-reflector arrays are also possible to increase the effective range. Perhaps you might experiment with your own large reflector to see if a long range distant measuring systems could be devised. Using two such reflectors it might be possible to pinpoint your location using triangulation techniques.

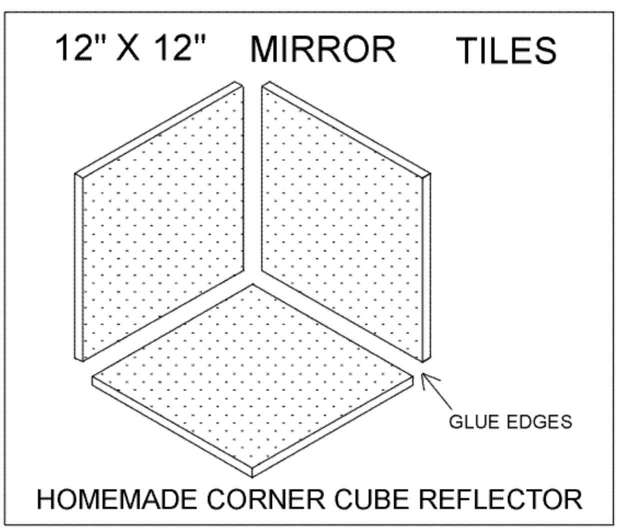

Figure 4d-3

if a transmitter, using a narrow light beam, launches sufficient light power and an equally efficient light receiver with a large light collector is used. Such a method may be very useful in allowing one powerful transmitter to be received by multiple light receivers that do not have a direct line-of-sight path to the transmitter. The imagined scheme might resemble the bright search lights often used to attract people to some gala event. Even the tiny amount of light reflected off dust particles in the air allow you to see the search light beam moving up toward the clouds many miles away. This concept would be a great area for an experimenter to try to see if such a system could actually be made to work.

Retro Reflective Configuration

As illustrated in ***Figure 4c*** if a special mirror reflector, called a "corner cube" reflector, is used to bounce light from a transmitter to a nearby light receiver, the light transmitter and receiver are said to be linked using a "retro reflective" configuration. A corner cube reflector can be made from a specially ground piece of glass, as shown in ***figure 4d*** or from positioning three mirrors at right angles to each other as shown in ***figure 4d-3***. Some plastic reflectors often used on bicycles and roadside indicators are actually large arrays of miniature molded corner cube reflectors (see ***figure 4d-1***). A corner cube has the unique characteristic that will return much of the light striking the assembly directly backs to the light source in a parallel path, independent of the position of the emitter. However, because of the parallel path, the light transmitter and receiver must positioned very close to each other. Some very accurately made corner cube reflectors send the light back in a path that is so parallel that the light receiver must actually be placed inside the light transmitter to properly detect the light being returned.

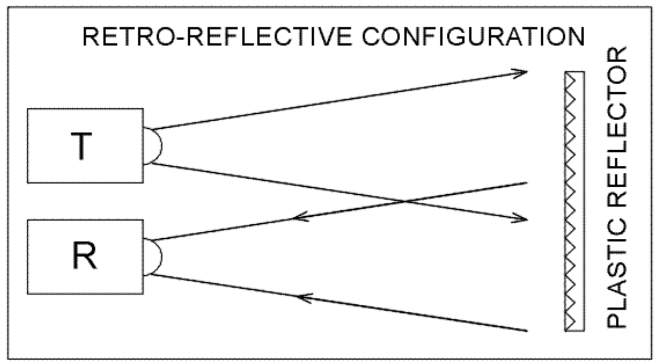

Figure 4c

Corner cube reflectors have a wide variety of applications. Several highly accurate corner cube arrays were left on the moon during some of the Apollo moon missions in the early 1970s. Scientists have been using powerful lasers and specially modified telescopes to bounce light off of the reflectors. By measuring the time the light pulses take to make the round trip from the earth, to the moon and back, the distance can be measured down to inches. Electronic distance measurement devices (EDMs), used by survey crews, also use corner cubes and "time of flight" techniques to measure distances accurate to inches. Some systems have effective ranges of several miles. Remember, light travels about one foot in one nanosecond, so for a round trip of 10,000 feet would cause a pulse delay of 10,000 nanoseconds or 10 microseconds.

Figure 4d

Diffuse Reflective Configuration

When you look at the stars at night, car headlights or at the sun, your eyes collect the light that is coming directly from the light source. When you look at the moon, a movie screen or when you look at the light reflected off walls from a table lamp, you don't see the source of the light, but the light that happens to reflect off the object being illuminated by the source. Unless the object has a mirrored surface, the light that strikes the object spreads out in all directions. The light that you see is only a very small portion of the total light that actually illuminates the object. This "diffuse reflective" configuration, as shown in ***Figure 4b*** is a technique that is very useful in some communications systems. It is especially good for short distances when multiple reflections allow the light receiver to be aimed, not at the light source directly, but at objects being illuminated by the source. Some cordless stereo headsets use such a method to give a person some freedom of movement as he listens to music. These systems bounce the light off the walls, ceilings and floors with sufficient power that enough light finds its way to a light detector attached to the headset, no matter how the headset detector is oriented.

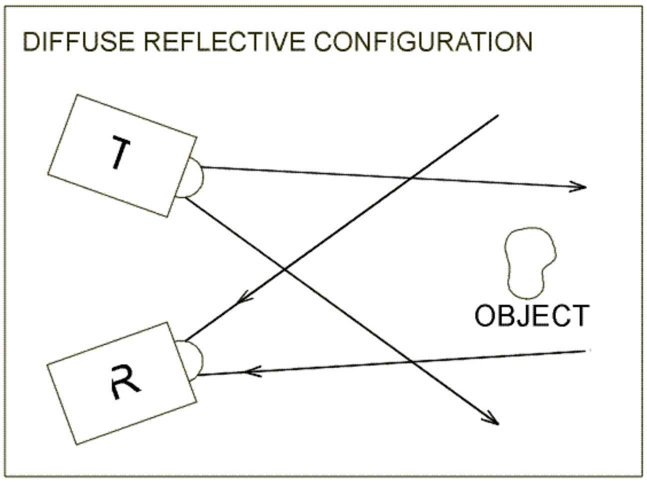

Figure 4b

The amount of light detected by the receiver is very dependent on the nature of object's surface that reflects the light. As an example, walls painted with white paint will reflect more light than those painted with dark paint. Also, rough surfaces will tend to reflect less light than smooth surfaces. Most surfaces reflect the light in a hemispherical pattern with more light being bounced straight back toward the light source then off to the sides. When you are trying to predict the behavior of such reflections it is best to think of the area of illumination as an independent light source that has a 90-degree half-angle divergence pattern. Then, if you know the acceptance angle of the light receiver and its collection area, you can use the range equation to calculate how much of the total light reflected will be collected by the light receiver.

If a single surface reflection is to be used, it is best to try to illuminate the smallest area possible. This concept can be illustrated by imagining how your eyes respond better to a brightly lit spot reflected off a wall than to a broad floodlight. By concentrating most of the light onto a small area more light will be reflected back to a nearby receiver that is aimed at the illuminated area. However, when multiple reflections are desired, such as done with the stereo headsets, a small or large illuminated area will work just about the same. In detecting light from single reflections you should plan to use a large collection area, with a small acceptance angle. The receiver would be aimed directly at the illuminated spot. However, for multiple reflection applications it is best to use a detector with a very wide acceptance angle. Detectors using large lens collectors will have little effect in multiple reflection cases, since they would have narrow acceptance angles.

As food for thought, it may be possible to use fluffy white clouds as diffuse reflectors to link two distant light transceivers. Some preliminary test results indicate that such a scheme may be possible

Chapter Four
LIGHT SYSTEM CONFIGURATIONS

Whether you are sending a simple on and off signal or high-speed computer data, some kind of light path must be establish between the light transmitter and the distant receiver. The three basic ways the information can be transferred are: "Opposed", "diffused reflective" and "retro reflective". Every communications system will use one or more of these methods.

Opposed Configuration

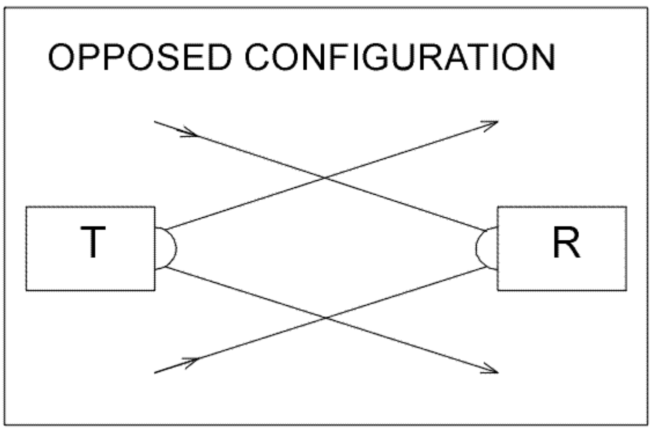

Figure 4a

As illustrated in ***Figure 4a*** an "opposed" or "through beam" configuration points the light transmitter and the receiver directly at each other. Although much of the light launched by the transmitter may never reach the distant receiver assembly, sufficient light is detected to pass information. Since there is only air between the transmitter and receiver, it is the most commonly used configuration to transmit information over long distances. Most optical communications systems rely on this configuration. Remote controllers for televisions, VCRs, audio systems and computers all rely on this direct light link method, since it makes the most efficient use of the transmitted light.

As the light emerges from the end of the transmitter it immediately begins spreading out. The light forms a cone shaped pattern of illumination. The spreading out of the light beam means the area being illuminated at the distant receiver will always exceed the receiver's light collecting area. The light that does not actually strike the receiver assembly is therefore lost. If you tried to design a system so all the launched light hit the receiver, you would soon discover that it would be impossible to maintain proper alignment. Small vibrations, building sway and even air disturbances could bend the light beam enough to miss the receiver assembly altogether. An intentional over-illumination scheme works the best, since it allows for some misalignment without the complete loss of the light signal. When designing a system using an opposed configuration you can use the range equation discussed in the last section as a way of predicting how much light will strike the receiver, how much light power needs to be launched and what kind of divergence angle is needed to establish a communications link over a specified distance.