

Sensing Theory Primer

Definitions of Sensing Terms

Like nearly any other technology, photoelectric and ultrasonic sensing have their own sets of "buzzwords". This section introduces the most important terms. Some are not universal, and a few definitions have developed several names. Most of this synonymy is the result of inconsistent use of sensing terminology by various sensor manufacturers. Since it is unlikely that these terms will become standardized in the near future, it is best to be familiar with all of them and to become comfortable with using the synonyms interchangeably.

If you are already familiar with sensing terms, this paper can serve as a quick checklist or refresher for sensing jargon.

Photoelectric Sensor

A **photoelectric sensor** is an electrical device that responds to a change in the intensity of the light falling upon it. The first photoelectric devices used for industrial presence and absence sensing applications took the shape of small metal barrels, with a collimating lens on one end and a cable exiting the opposite end (Figure A.1). The cable connected a photoresistive device to an external vacuum tube type amplifier. A small incandescent bulb, protected inside a matching metal barrel, was the opposing light source. These small, rugged incandescent sensors were the forerunners of today's industrial photoelectric sensors.



Figure A.1. Early photoelectric sensors used an incandescent bulb light source.

LED (Light Emitting Diode)

The 1960s saw the introduction of **light emitting diodes** or **LEDs** which are now part of our daily lives as status indicators on most contemporary electrical and electronic appliances. An LED is a solid-state semiconductor, similar electrically to a diode, except that it emits a small amount of light when current flows through it in the forward direction. LEDs can be built to emit green, blue, blue-green, yellow, red, or infrared light. (Infrared light is invisible to the human eye; see Figure A.2.)

In applications which sense color contrasts, the choice of LED color can be important.

Because LEDs are solid-state, they will last for the entire useful life of a sensor. LED sensors can be totally encapsulated and sealed, making them smaller yet more reliable than their incandescent counterparts.

Unlike incandescent light sources, LEDs are not easily damaged by

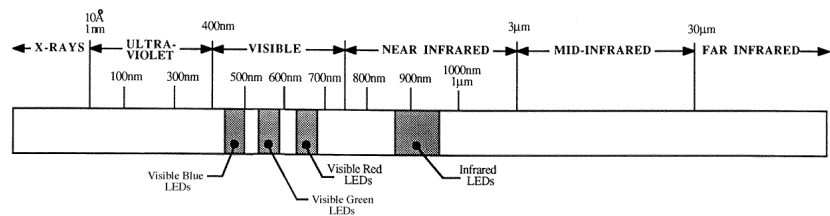
vibration and shock, and worry about filament sag is also eliminated. There is a tradeoff, however, in the area of light intensity: in general, LEDs produce only a small percentage of the light generated by an incandescent bulb of the same size. Laser diodes are a recent exception to this. New sensor designs that incorporate laser diodes can produce many times the light intensity (and sensing range) of ordinary LEDs.

Infrared types are the most efficient LED light generators, and were the only type of LED offered in photoelectric sensors until 1975. However, this invisible infrared light, though ideal for security detection and film processing applications, was initially not well received by those accustomed to visually aligning and checking incandescent emitters.

Phototransistor

The 1960s brought us solidly into the silicon era, and produced photojunction devices including photodiodes, phototransistors, and photodarlington. Of these, the phototransistor has prevailed as the most widely used receiver

Figure A.2. The light spectrum.



optoelement in industrial photoelectric sensor design (Fig. A.3).

Phototransistors offer the best tradeoff between light sensitivity and response speed compared to photoresistive and other photojunction devices.

Photocells are used whenever greater sensitivity to visible wavelengths is required, as in some color mark and ambient light detection applications.

Photodiodes are generally reserved for applications requiring either extremely fast response time or linear response over several magnitudes of light level change.



Figure A.3. Typical photocell (left) and phototransistor (right).

Modulated LED Sensors

By 1970, photoelectric sensor designers had recognized that LEDs had a benefit much more profound than long life. Unlike their incandescent equivalents, LEDs can be turned "on" and "off" (or **modulated**) at a high rate of speed, typically at a frequency of several kilohertz (Figure A.4). This modulating of the LED means that the amplifier of the phototransistor receiver can be "tuned" to the frequency of modulation, and amplify *only* light signals pulsing at that frequency.

This is analogous to the transmission and reception of a radio wave of a particular frequency. A radio receiver tuned to one station ignores other radio signals that may be present in the room. The modulated LED light source of a photoelectric sensor is usually called the transmitter (or **emitter**), and the tuned photodevice is called the **receiver**.

There is a common misconception that because an infrared LED system is invisible, it must therefore be powerful. The apparent high level of optical energy in a modulated photoelectric sensing system has, in itself, little to do with the wavelength of the LED. Remember that an LED emits only a fraction of the light energy of an incandescent bulb of the same size. *It is the modulation of an LED sensing system that accounts for its power.*

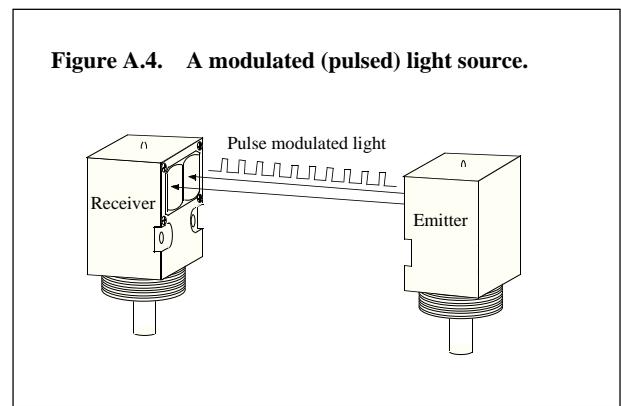


Figure A.4. A modulated (pulsed) light source.

The gain of a non-modulated amplifier is limited to the point at which the receiver recognizes ambient light. A non-modulated sensor may be powerful only if its receiver can be made to "see" only the light from its emitter. This requires the use of lenses with very long focal lengths and/or mechanical shielding of the receiver lens from ambient light. In contrast, a modulated receiver ignores ambient light and responds only to its modulated light source. As a result, the gain of a modulated receiver may be turned up to a very high level. See Figure A.5.

There is, however, a limit to a modulated sensor's immunity to ambient light. Extremely bright ambient light sources may sometimes present problems. No modulated photoelectric receiver will function normally if it is pointed directly into the sunlight. If you have ever focused sunlight through a magnifying glass onto a piece of paper, you know that you can easily focus enough energy to start the paper on fire. Replace the magnifying glass with a sensor lens, and the paper with a phototransistor, and it is easy to understand why the receiver shuts down when the sensor is pointed directly into the sun. This is called *ambient light saturation*.

The concept of the modulated LED caused a major revolution in photoelectric sensor design. Sensing ranges increased, and beam angles widened. Throughout the 1970s, users of modulated devices gradually began to place more trust in this

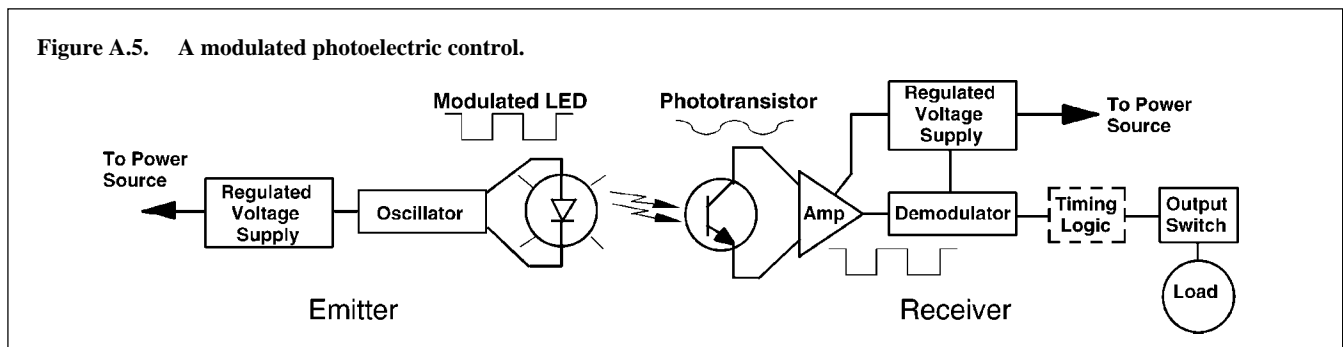


Figure A.5. A modulated photoelectric control.

light beam that they found so dependable and easy to align. By 1980, the non-modulated photoelectric sensor was nearly just a memory. The newer, highly automated processes could not tolerate the interruptions caused by the incandescent bulb burnout common in non-modulated systems.

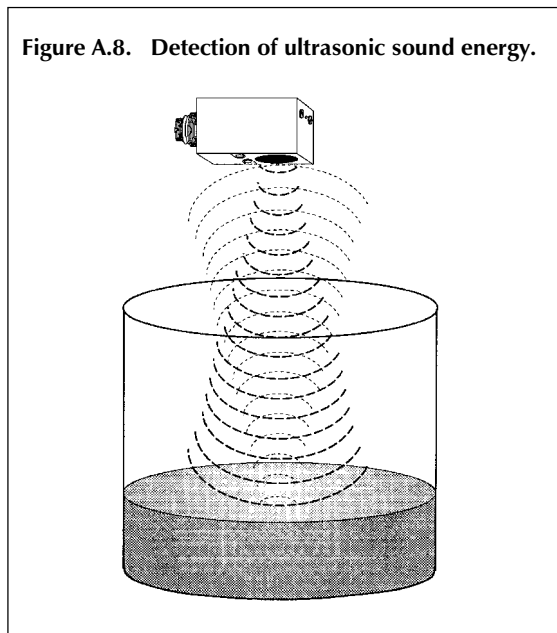
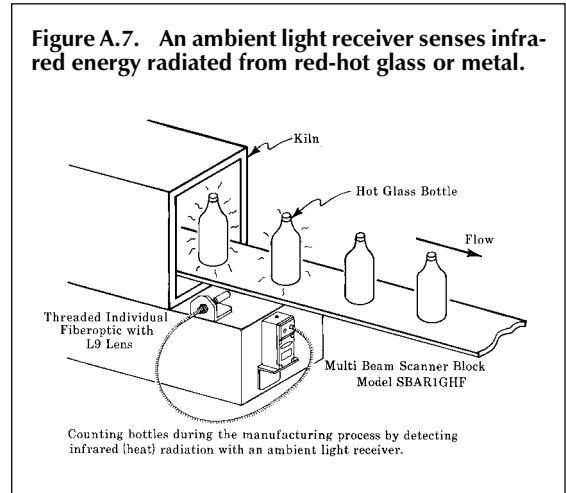
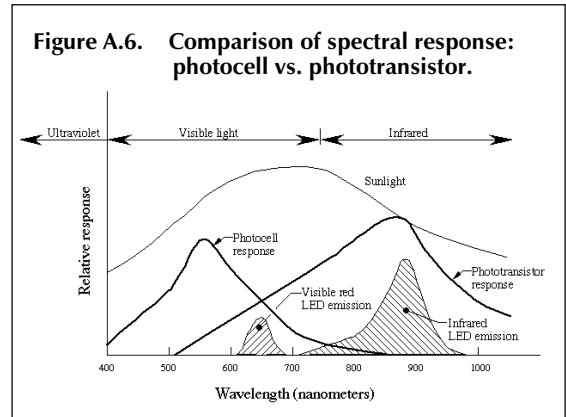
Infrared LEDs were found to be the most efficient types, and were also the best spectral match to phototransistors (Figure A.6). However, photoelectric sensors used to detect *color differences* (as in color mark sensing applications) require a *visible* light source. As a result, color mark sensors continued to use photocell receivers and incandescent lamps while sensor designers awaited the development of more efficient visible LEDs. Today, with improved visible LEDs, most color mark sensors are modulated and utilize colored LEDs as emitters.

Modulated sensor designs usually trade off speed of response for sensing distance. Because distance is most often the dominant sensing system design criteria, non-modulated sensors using phototransistors and either incandescent or LED emitters continued to be used where response speed was important, as in sensing small parts or object features moving at a high rate of speed. But since the performance of modulated sensors steadily improved through the 1980s, there are now very high speed modulated designs that offer respectable sensing ranges *and* satisfy nearly all response requirements.

Ambient Light Receiver

One type of non-modulated photoelectric device still found in frequent use is the **ambient light receiver**. Products like red-hot metal or glass emit large amounts of infrared light. As long as these materials emit more light than the surrounding light level, they may be reliably detected by an ambient light receiver (Figure A.7).

An ambient receiver might also be used beneath a conveyor, looking up between the rollers toward conventional factory lighting. Any objects passing over the sensor are detected by the shadows they cast upon the receiver. Ambient light receivers are also commonly used for outdoor lighting control.



Ultrasonic Sensors

Ultrasonic sensors emit and receive sound energy at frequencies above the range of human hearing (above about 20kHz). Unlike photoelectric sensing which is based upon an object's opacity or reflectivity to light, ultrasonic sensing depends upon an object's density (it's ability to reflect sound). This makes ultrasonic sensing practical in many applications that are unsuited to photoelectric methods. Ultrasonic sensors are categorized by transducer type: either **electrostatic** or **piezoelectric**. Electrostatic types can sense objects up to several feet away by reflection of ultrasound waves from the object's surface. Piezoelectric types are generally used for sensing at shorter ranges. See Figure A.8.

Remote Photoelectric Sensors

Photoelectric sensors are divided into two basic package styles: *remote* and *self-contained*. **Remote photoelectric sensors** contain only the optical components of the sensing system. The circuitry for system power, amplification, and output switching are all at another location, typically in a control panel. Consequently, remote sensors are generally smaller and more tolerant of hostile sensing environments than are self-contained sensors. Examples of remote sensors

(see Figure A.9) include those designed for use with the Banner MAXI-AMP, MICRO-AMP, and PICO-AMP family amplifiers. These sensing systems, which have the optical elements at one location and the electrical components at another, are called **component systems**.

Self-contained Photoelectric Sensors

Self-contained photoelectric sensors contain the optics along with all of the electronics. Their only requirement is a source of voltage for power. The sensor itself does all of the work, which includes modulation, demodulation, amplification, and output switching. Some self-contained sensors provide options such as built-in control timers or totalizing counters. Banner's OMNI-BEAM, Q45, MULTI-BEAM, MAXI-BEAM, VALU-BEAM, MINI-BEAM, ECONO-BEAM, ULTRA-BEAM, and EZ-BEAM sensors are examples of self-contained sensors (Figure A.10).

Fiber Optics

There are many sensing situations where space is too restricted or the environment too hostile even for remote sensors (component systems). For such applications, photoelectric sensing technology offers fiber optics as a third alternative in sensor "packaging". **Fiber optics** are transparent strands of glass or plastic that are used to conduct light energy into and out of such areas.

Fiber optic "light pipes", used *along with* either remote or self-contained sensors, are purely passive, mechanical components of the sensing system (Figure A.11). Since fiber optics contain no electrical circuitry and have no moving parts, they can safely pipe light into and out of hazardous sensing locations and withstand hostile environmental conditions. Moreover, fiber optics are completely immune to all forms of electrical "noise", and may be used to isolate the electronics of a sensing system from known sources of electrical interference.

An optical fiber consists of a glass or plastic core surrounded by a layer of cladding material. The cladding material is less dense than the core material, and consequently has a lower index of refraction. The optical principle of *total internal reflection* says that any ray of light that hits the boundary between two materials with different densities (in this case, the core and the cladding) will be totally reflected, provided that the angle of incidence is less than a certain critical value (θ).

Figure A.12 illustrates two light rays (inside the angle of acceptance) that are repeatedly reflected along the length of the fiber. The light rays exit the opposite end at approximately the entry angle.

Another light ray (outside the angle of acceptance) is lost into the cladding. Note that the acceptance angle is slightly larger than twice θ . This is because the rays are bent slightly as they pass from the air into the more dense fiber material.

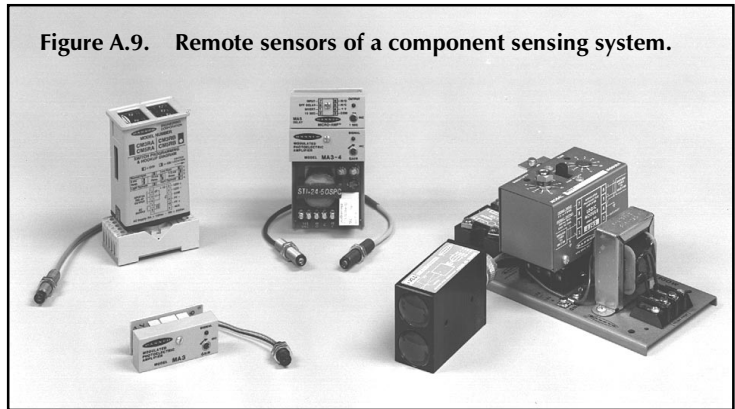


Figure A.9. Remote sensors of a component sensing system.

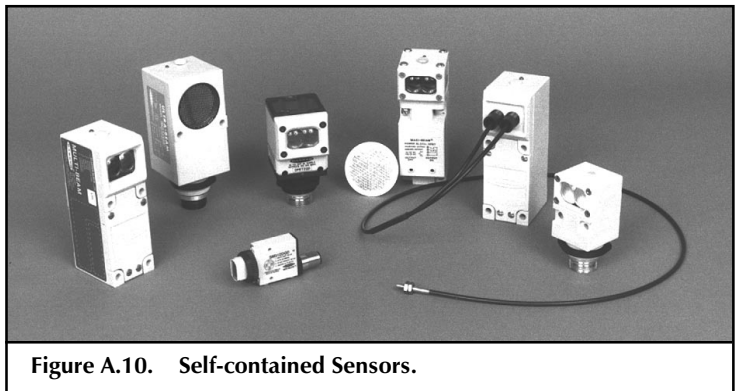


Figure A.10. Self-contained Sensors.



Figure A.11. Glass and plastic fiber optics.

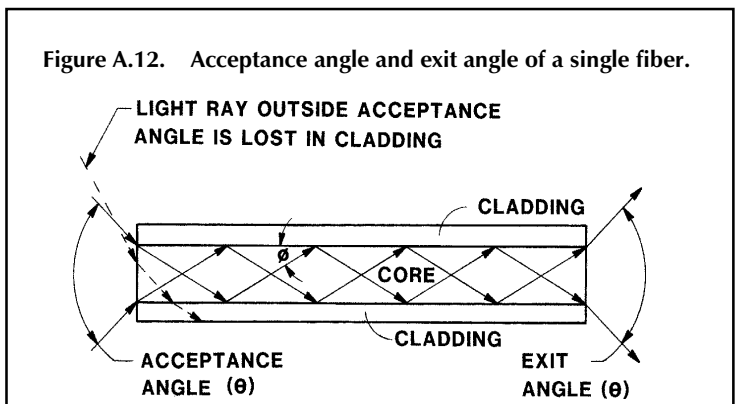


Figure A.12. Acceptance angle and exit angle of a single fiber.

The principle of total internal reflection works regardless of whether the fiber is straight or bent (within a defined minimum bend radius). Most fiber optic assemblies are flexible and allow easy routing through tight areas to the sensing location. In addition, fiber optic sensing heads (and therefore the sensing beams they produce) can be optimally "shaped" to the physical and optical requirements of specific applications (see figures A.11 and A.15).

Glass Fiber optics

Glass fiber optics used for photoelectric light pipes are made up of a bundle of very small (usually about .002 inch diameter) glass fiber strands. A typical glass fiber optic assembly consists of several hundred cladded glass fibers protected by a sheathing material, usually a flexible armored cable. The cable terminates in an end tip that is partially filled with rigid clear epoxy. The sensing face is optically polished so that the end of each fiber is perfectly flat. The degree of care taken in the polishing process dramatically affects the light coupling efficiency of the fiber bundle (see Figure A.13).

There are two types of glass fiber optic bundles. One type, the **coherent bundle**, is used in medical instruments and in borescopes. Coherent fiber optic assemblies have each fiber carefully lined up from one end to the other in such a way that an image at one end may be viewed at the opposite end. Coherent bundles are expensive to manufacture. Because the production of a clear image is irrelevant in most fiber optic sensing applications, almost all glass fiber optic assemblies use the much less costly **randomized bundles**, in which no special care is taken to line up corresponding fiber ends.

It is relatively easy, fast, and inexpensive to create a glass fiber optic assembly to fit a specific space or sensing environment. These are called **special fiber optic assemblies**. The bundle may even be shaped at the sensing end to create a beam to "match" the profile of the object to be sensed (Figure A.14).

The outer sheath of a glass fiber optic assembly is usually stainless steel flexible conduit, but may be PVC or some other type of flexible plastic tubing. Even when a non-armored outer covering is used, a protective steel coil is usually retained beneath the sheath to protect the fiber bundle.

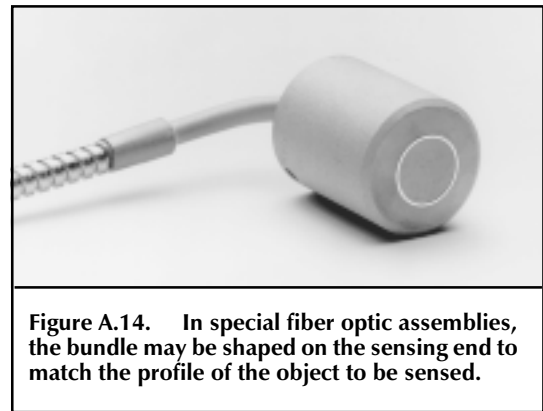
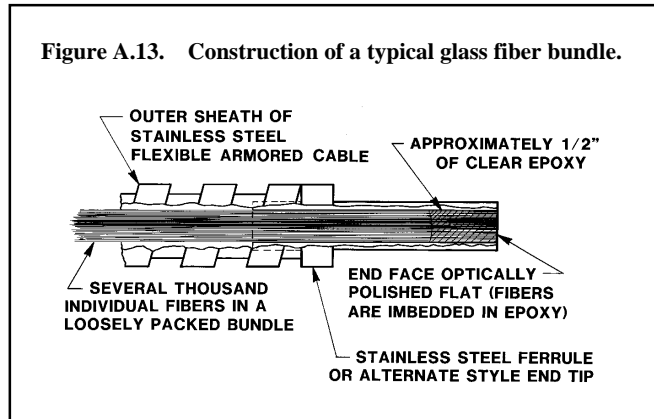


Figure A.14. In special fiber optic assemblies, the bundle may be shaped on the sensing end to match the profile of the object to be sensed.



Figure A.15. Plastic fiber optic assemblies.

Most glass fiber optic assemblies are very rugged and perform reliably in extreme temperatures. The most common problem experienced with glass fibers is breakage of the individual strands resulting from sharp bending or continued flexing, as occurs on reciprocating mechanisms.

Plastic Fiber optics

Plastic fiber optics (Figure A.15) are usually *single* strands of fiber optic material (typically .01 to .06 inch in diameter). They can be routed into extremely tight areas.

Most plastic fiber optic assemblies are terminated on the sensing end with a probe and/or a threaded mounting tip. The control (sensor) end of most plastic fiber optic assemblies is left unterminated so that it may be easily cut by the user to the proper length. Most Banner plastic fiber assemblies are supplied with a cutting device for this purpose.

Unlike glass fiber optics, plastic fibers survive well under repeated flexing. Pre-coiled plastic fiber optics are available for sensing applications on reciprocating mechanisms.

Plastic, however, does absorb certain bands of light wavelengths, including the light from most infrared LEDs (see Figure A.16). Consequently, plastic fiber optics require a *visible* light source, such as a visible red LED, for effective sensing. Also, in their

simplest form, plastic fiber optics are less tolerant of temperature extremes, and are sensitive to many chemicals and solvents. However, sheathing materials such as polypropylene, Teflon®, and nylon are used to shield plastic fiber optic assemblies in harsh environments.

Individual and Bifurcated Fiber Optics

Both glass and plastic fiber optic assemblies are manufactured in two styles. **Individual** fiber optics (Figure A.17) simply guide light from an emitter to a sensing location, or from the sensing location back to a receiver.

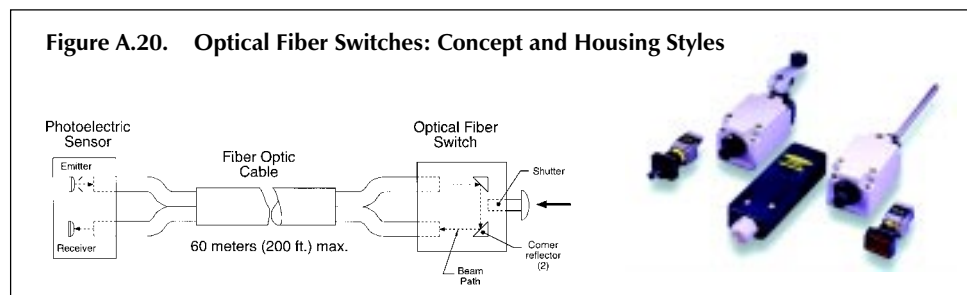
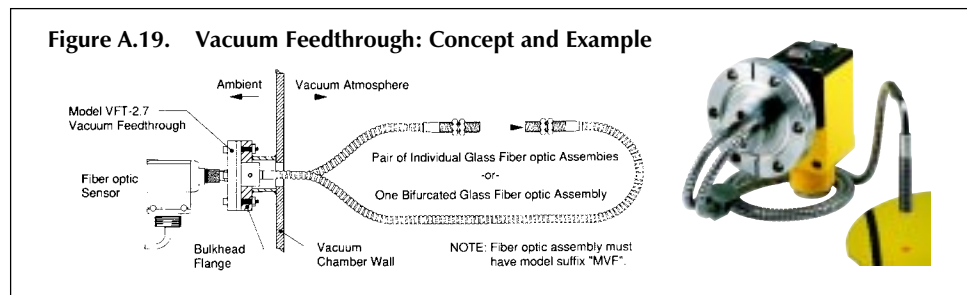
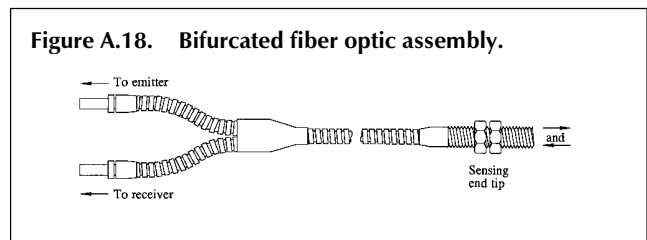
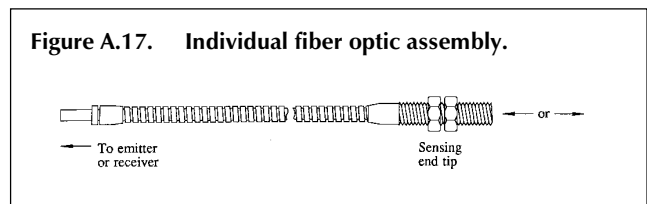
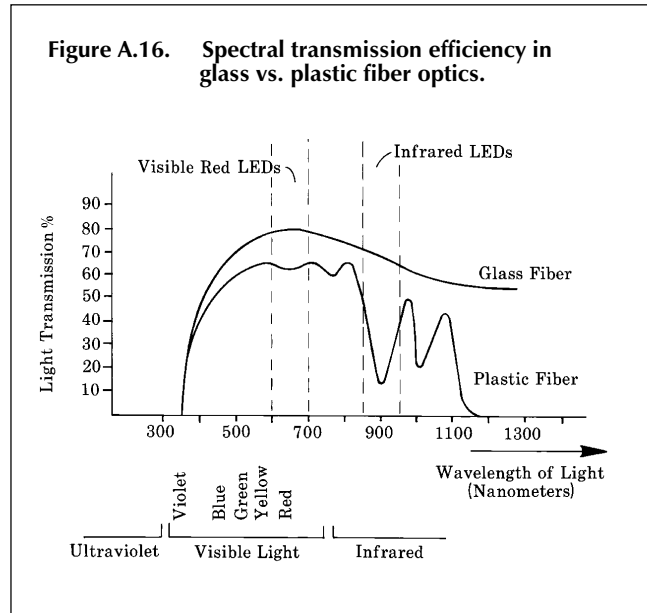
Bifurcated fiber optics (Figure A.18) conduct the emitted light together with the received light (via two branches consisting of different fibers) within one fiber optic assembly. This allows a single sensor to both illuminate and view an object through the same fiber optic assembly. If an object appears in front of the sensing end of a bifurcated fiber optic, light from one branch will be reflected off the object and back to the receiver through the other branch.

A bifurcated *glass* fiber optic assembly usually randomly mixes the emitter and receiver fibers together in the sensing end tip. Bifurcated *plastic* fiber strands are joined side-by-side along the length of the cable, and so may be thought of as two individual fibers joined together at the sensing end.

Fiber Optic Variations

Vacuum feedthrough fiber optic assemblies (VFTs) enable the use of fiber optics in vacuum environments where out-gassing of the materials used in the fiber is unacceptable. Special stainless steel and copper components are used (in place of epoxy) to bond the strands within the sensing tip. Such "VFT compatible" fibers are used with a flanged feedthrough to couple fibers inside the vacuum environment to a photoelectric sensor on the outside. Fibers and feedthroughs are available in various sizes and designs. Figure A.19 shows a VFT with a sensor and fiber optic assembly attached.

Optical fiber switches (Figure A.20) use a mechanical switch to activate a photoelectric sensor via a length of plastic fiber optic cable. Electrical switching takes place remotely at the sensor. The mechanical switch simply passes or blocks the sensor's light signal. These intrinsically safe switches are useful in hazardous environments, and are immune to electrical "noise". Several "package" types (with a variety of actuators) are available (figure A.20).



Sensing Modes

The optical system of any photoelectric sensor is designed for one of three basic sensing modes: *opposed*, *retroreflective*, or *proximity*. The photoelectric proximity mode is further divided into four submodes: *diffuse proximity*, *divergent-beam proximity*, *convergent-beam proximity*, and *fixed-field* or *adjustable-field proximity*. Ultrasonic sensors are designed for either opposed or proximity mode sensing. Following is a description of each sensing mode.

Opposed mode

Opposed mode sensing is often referred to as "direct scanning", and is sometimes called the "beam-break" mode. In the opposed mode, the emitter and receiver are positioned opposite each other so that the sensing energy from the emitter is aimed directly at the receiver. An object is detected when it interrupts the sensing path established between the two sensing components. See Figure A.21.

Opposed sensing was historically the first photoelectric sensing mode. In the early days of non-modulated photoelectrics, problems of difficult emitter-receiver alignment gave the opposed mode a bad reputation. With today's high-powered modulated designs and alignment systems, however, it is extremely easy to align most opposed mode photoelectric sensors.

Alignment of a sensor means positioning the sensor(s) so that the maximum amount of emitted energy reaches the receive sensing element. In opposed sensing, this means that the emitter and the receiver are positioned relative to each other so that the radiated energy from the emitter is centered on the field of view of the receiver.

Sensing range is specified for all sensors. For opposed mode sensors, range is the maximum operating distance between the emitter and the receiver. A sensor's **effective beam** is the "working" part of the beam: it is the portion of the beam that must be completely interrupted in order for an object to be reliably sensed. The effective beam of an opposed mode sensor pair may be pictured as a rod that connects the emitter lens (or ultrasonic transducer) to the receiver lens (or transducer). See Figure A.22. This rod will be tapered if the two lenses (or transducers) are of different sizes (Figure A.23). The effective beam should not be confused with the actual radiation pattern of the emitter, or with the field of view of the receiver.

The effective beam size of a standard opposed mode photoelectric sensor pair may be too large to detect small parts or inspect small profiles, or for very accurate position sensing. In such cases, opposed mode photoelectric sensor lenses can usually be **apertured** to reduce the size of the effective beam (Figure A.24). Some sensors, like the S18, SP12, SM30, and MINI-BEAM opposed mode sensors, have optional aperture assemblies that mechanically attach to the sensor lens. Creating an aperture can be as easy as drilling a hole or milling a slot in a thin metal plate and locating the plate directly in front of the lens, with the opening on the lens centerline. When selecting an aperture material, it is important to remember that the powerful beam of modulated opposed mode photoelectric sensors can actually penetrate many non-metallic materials to varying degrees.

Apertures reduce the amount of light energy that can pass through a lens by an amount equal to the lens area reduction. For example, if a one inch diameter lens is apertured down to 1/4-inch diameter, the amount of optical energy passing through the apertured lens is equal to $(1/4)^2 = 1/16$ th the

Figure A.21. Opposed sensing mode.

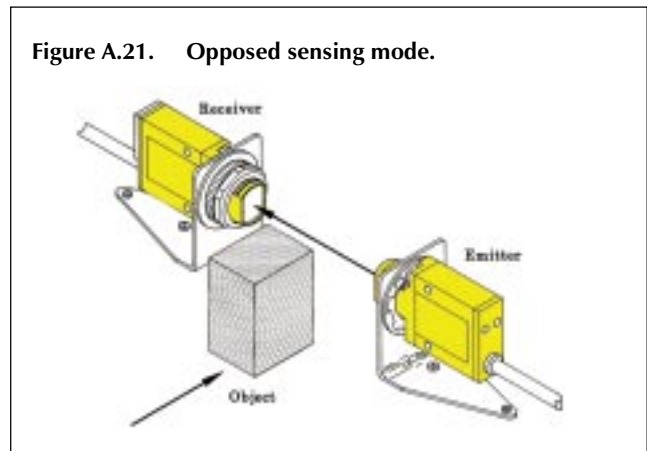


Figure A.22. Effective beam.

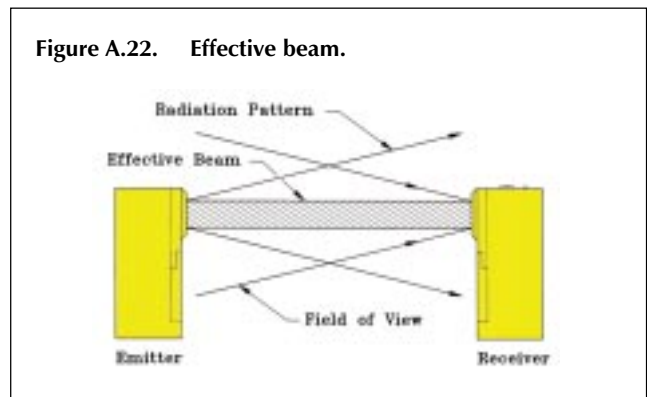
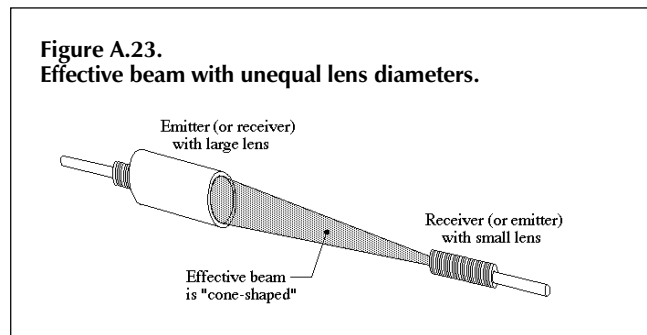


Figure A.23. Effective beam with unequal lens diameters.



amount of energy through the one-inch lens. *This energy loss is doubled if apertures are used on both the emitter and the receiver.*

A rectangular aperture of any given width covers much less light gathering lens area as does a round aperture of the same width (diameter). For this reason, rectangular apertures (also called "slit apertures") should be used whenever possible. Rectangular apertures are reliable whenever an object travels into the beam with a predictable orientation to the effective beam (as in edge detection, for example). Whenever objects with small profiles move through the beam with random orientation, round apertures are required.

If the object to be detected will always pass very close to either the emitter or the receiver, an aperture may be required on only one side of the process. In this case, the size of the effective beam is equal to the size of the aperture on the apertured side and uniformly expands to the size of the lens on the unapertured side. The effective beam is therefore "cone-shaped". See Figure A.23.

The goal in any application requiring the detection of small parts in an opposed beam is to size and shape the effective beam to be smaller than the smallest profile that will ever need to be detected, while retaining as much lens area as possible. Often the easiest way to size and shape an effective beam to match a part profile is to use a glass fiber optic assembly that has its sensing end terminated in the desired shape. See Figure A.14.

The very high power of some modulated LED opposed sensor pairs (especially when used at close range) can create a "flooding" effect of light energy around an object that is equal to or even slightly larger than the effective beam. This is another reason to ensure that the size of the effective beam is always smaller than the profile of the object to be detected.

Laser diode emitters can present a practical alternative to apertured conventional opposed mode sensors. Opposed mode laser diode sensors can produce narrow effective beams over extended ranges, and are very useful in applications such as small object detection and precise position control.

It is possible to shape an opposed *ultrasonic* beam by using *waveguides*. Waveguides attach to the transducer of the ultrasonic receiver (and sometimes to the emitter). With waveguides attached, the receiver is less likely to respond to sound echoes that approach from the side. This makes for more reliable detection of small objects that interrupt the ultrasonic beam.

Retroreflective mode

The photoelectric *retroreflective sensing mode* is also called the "reflex" mode, or simply the "retro" mode (Figure A.25). A retroreflective sensor contains both emitter and receiver circuitry. A light beam is established between the emitter, the retroreflective target, and the receiver. Just as in opposed mode sensing, an object is sensed when it interrupts the beam.

Retroreflective range is defined as the distance from the sensor to its retroreflective target. The effective beam is usually cone-shaped and connects the periphery of the retro sensor lens (or lens pair) to that of the retroreflective target. See Figure A.26. The exception to this is at close range, where the size of the retro beam has not expanded enough to at least fill the target.

Retroreflective targets are also called "retroreflectors" or "retro targets". Most retroreflective targets are made up of many small corner-cube prisms, each of which has three mutually perpendicular surfaces and a hypotenuse face. A light beam that enters a corner-cube prism through its hypotenuse face is reflected from the three surfaces and emerges back through the hypotenuse face parallel to the entering beam (Figure A.27). In this way, the retroreflective target returns the light beam to its source.

Most corner-cube retroreflectors are molded using clear acrylic plastic, and are manufactured in various sizes, shapes, and colors. Corner-cube plastic retroreflectors are commonly used for highway markers and vehicle safety reflectors. Retroreflectors appear brightly

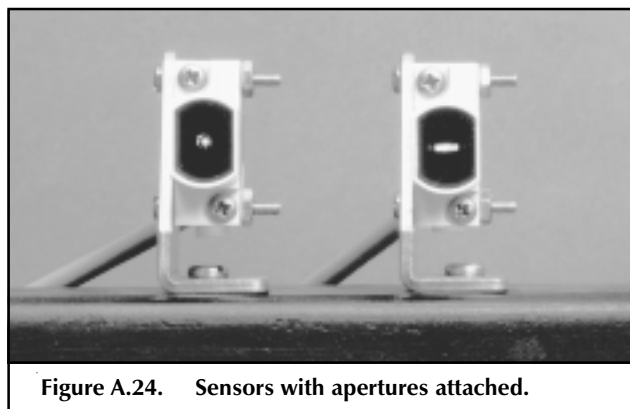


Figure A.24. Sensors with apertures attached.

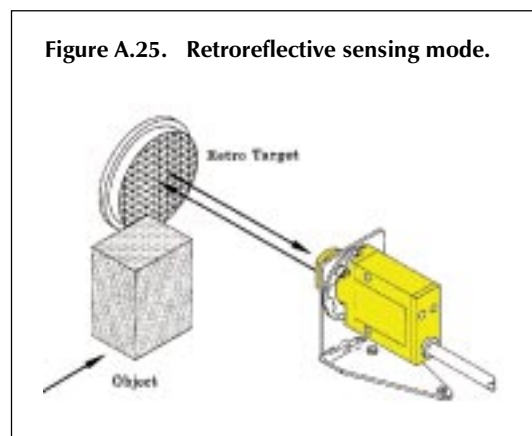
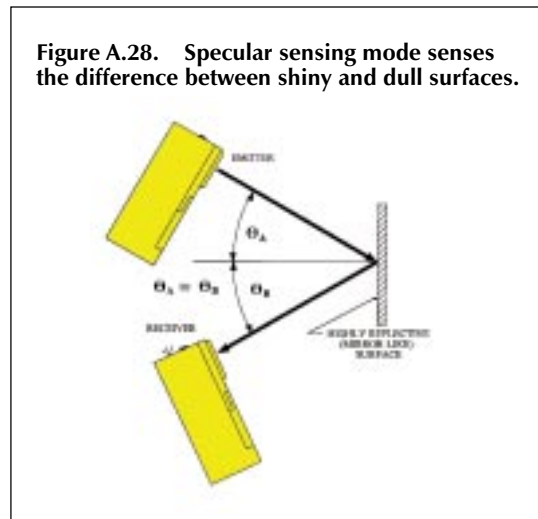
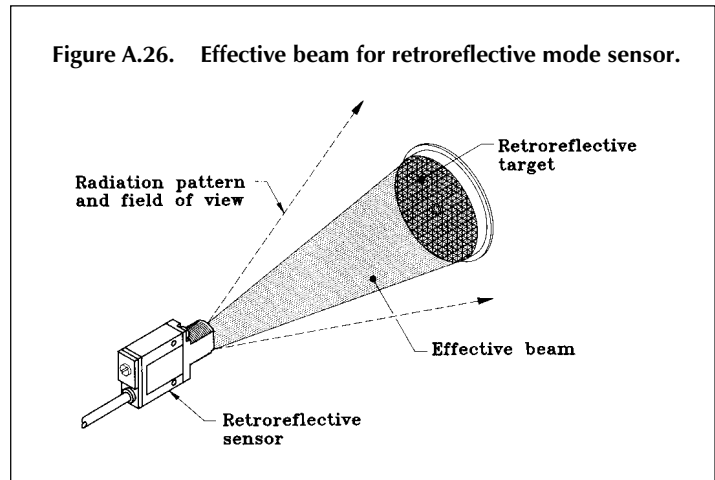


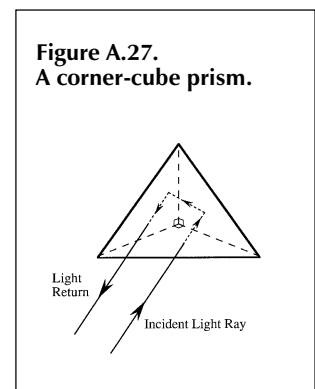
Figure A.25. Retroreflective sensing mode.

illuminated to a driver whenever light from a vehicle's headlamps is returned by the array of corner cubes. Highway markers are often wrapped in retroreflective tape, which has a covering of either many microscopic molded corner-cube reflectors or microscopic glass beads. A clear glass sphere also has the ability to return a light beam back to its source, but a coating of glass beads is not as efficient a reflector as is a molded array of corner-cubes.

A single mirrored surface may also be used with a retroreflective sensor. Light striking a flat mirror surface, however, is reflected at an angle that is equal and opposite to the angle of incidence (Figure A.28). This is called **specular reflection**. In order for a retroreflective sensor to "see" its light reflected from a flat mirrored surface, it must be positioned so that its emitted beam strikes the mirror exactly perpendicular to its surface. A retroreflector, on the other hand, has the ability to forgivingly return incident light back to its source at angles up to about 20 degrees from the perpendicular. This property makes retroreflective sensors easy to align to their retro targets.



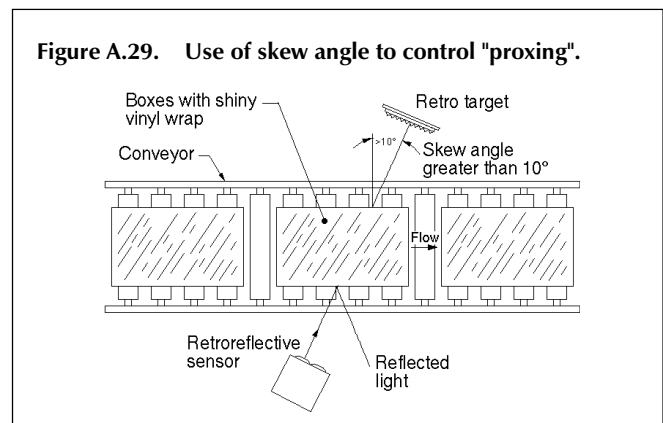
A good retroreflector returns about 3,000 times as much light to its sensor as does a piece of white typing paper. This is why it is easy for a retroreflective sensor to recognize only the light returned from its retroreflector. If the object that is to interrupt a retroreflective beam is *itself* highly reflective, however, it is possible for the object to slip through the retroreflective beam without being detected. This retroreflective sensing problem is called **proxing**, and relatively simple methods exist to deal with it.



If a shiny object has flat sides and passes through a retroreflective beam with a predictable orientation, the cure for proxing is to orient the beam so that the object's specular surface reflects the beam away from the sensor. This is called scanning at a **skew angle** to the object's surface (Figure A.29). The skew angle usually need be only

10 to 15 degrees (or more) to be effective. This solution to proxing may, however, be complicated if the shiny object has a rounded (radiused) surface or if the object presents itself to the beam at an unpredictable angle. In these cases, the best mounting scheme, although less convenient, has the beam striking the object at *both* a vertical and a horizontal skew angle (Figure A.29).

With recent improvements in LED technology, the use of *visible light* LEDs as photoelectric emitters has increased. When equipped with a visible emitter, a retro sensor may be aimed like a flashlight at its retroreflective target. When the reflection of the beam is seen on the retroreflector, correct alignment is assured. This principle is also of benefit when a visible emitter is used in an opposed mode photoelectric system. A retro target is placed directly in front of the lens of the receiver, and the emitter is aligned by sighting the visible beam on the target. The retro target is then removed, and the emitter and receiver orientations are "fine-tuned" for optimum alignment.



Polarizing filters are readily available for use with visible emitters. When used on visible retroreflective sensors, polarizing filters (sometimes called anti-glare filters) can significantly reduce the potential for proxing. A polarizing filter is placed in front of both the emitter lens and the receiver lens. The two filters are oriented so that the planes of polarization are at 90 degrees to one another. When the light is emitted, it is polarized "vertically" (Figure A.32). When the light reflects from a corner-cube retro target, its plane of polarization is rotated 90 degrees, and only the polarized target-reflected light is allowed to pass through the polarized receiver filter and into the receiver. When the polarized emitted light strikes the shiny surface of the object being detected, its plane of polarization is *not* rotated, and the returned non-polarized beam is blocked from entering the receiver.

This scheme is very effective for elimination of proxing. Polarizing filters, however, like a good pair of sunglasses, reduce the amount of optical power available in a retro beam by more than 50%. This is an important consideration whenever the environment is very dirty or where the sensing range is long. Also, polarized retro sensors work only with corner-cube type retroreflective materials. Often, the best insurance against proxing is the skew angle approach. When this is not possible, opposed mode sensors should be considered.

Proximity mode

Proximity mode sensing involves detecting an object that is directly in front of a sensor by detecting the sensor's own transmitted energy reflected back from the object's surface (Figure A.33). For example, an object is sensed when its surface reflects a sound wave back to an ultrasonic proximity sensor. Both the emitter and receiver are on the same side of the object, usually together in the same housing. In proximity sensing modes, an object, when present, actually "makes" (establishes) a beam, rather than interrupts the beam. Photoelectric proximity sensors have several different optical arrangements. They are described under the following headings: diffuse, divergent, convergent beam, fixed-field, and adjustable field.

Diffuse —

Diffuse mode sensors are the most commonly used type of photoelectric proximity sensor. In the diffuse sensing mode, the emitted light strikes the surface of an object at some arbitrary angle. The light is then diffused from that surface at many angles. The receiver can be at some other arbitrary angle, and some small portion of the diffused light will reach it.

Generally speaking, the diffuse mode is an inefficient sensing mode, since the receiver looks for a relatively small amount of light that is bounced back from a surface. Also, the diffuse mode, like the other proximity sensing modes, is dramatically influenced by the reflectivity of the surface being sensed. A bright white surface will be sensed at a greater range than a dull black surface. Most diffuse mode sensors use lenses to **collimate** (make parallel) the emitted light

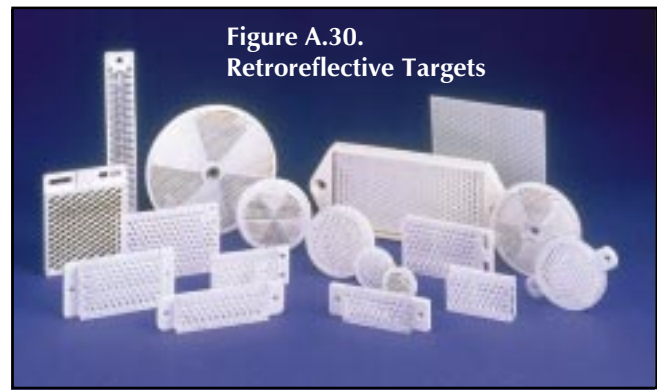


Figure A.31. Retroreflective sensing of radiused shiny objects requires both vertical and horizontal skew angles.

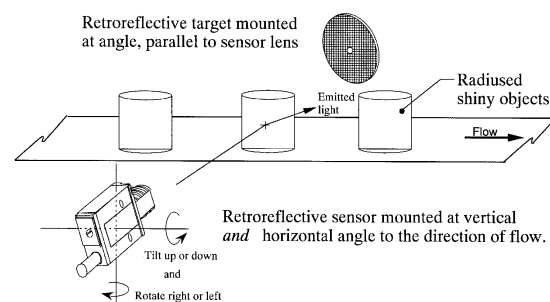


Figure A.32. Polarized light.

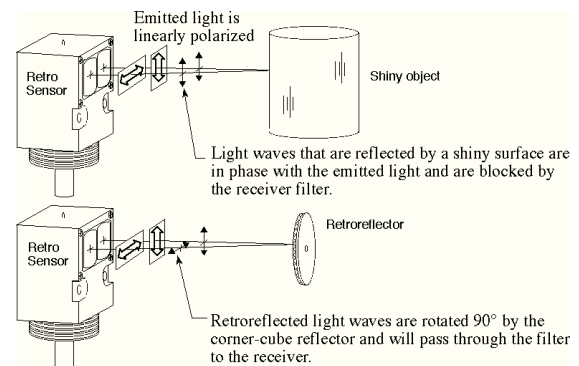
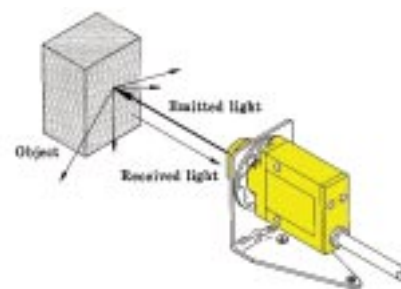
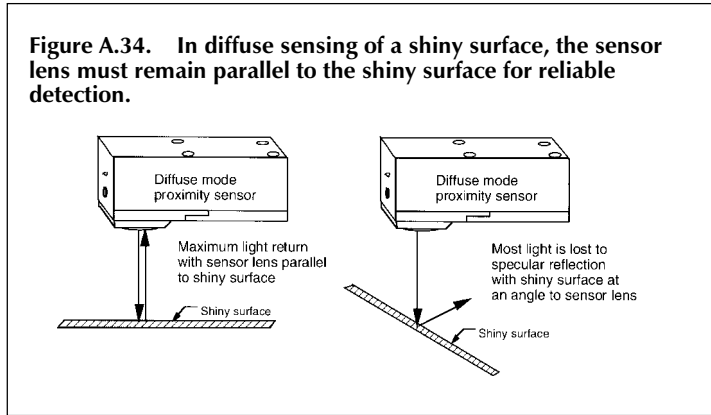


Figure A.33. Diffuse sensing mode.



rays and to gather in more received light. While lenses help a great deal to extend the range of diffuse sensors, they also increase the criticality of the sensing angle to a shiny or glossy surface. Because all such surfaces are mirror-like to some degree, the reflection is more specular than diffuse.

Most diffuse sensors can guarantee a return light signal only if the shiny surface of the material presents itself perfectly parallel to the sensor lens (Figure A.34). This is usually not possible with radiused parts like bottles or shiny cans. It is also a concern when detecting webs of metal foil or poly film where there is any amount of web "flutter".

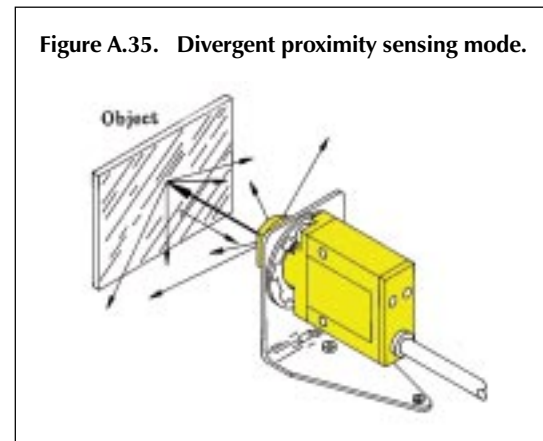


Divergent —

To avoid the effects of signal loss from shiny objects, special short-range, unlensed **divergent mode** sensors should be considered. By eliminating collimating lenses, the sensing range is shortened, but the sensor is also made much less dependent upon the angle of incidence of its light to a shiny surface that falls within its range. See Figure A.35.

The range of any proximity mode sensor also may be affected by the size and profile of the object to be detected. A large object that fills the sensor's beam will return more energy to the receiver than a small object that only partially fills the beam.

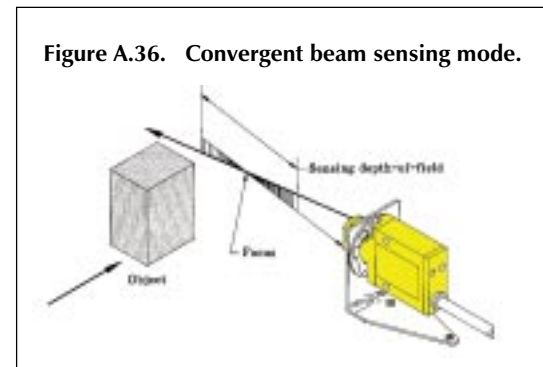
A divergent sensor responds better to objects within about one inch of its sensing elements than does a diffuse mode sensor. As a result, divergent mode sensors can successfully sense objects with very small profiles, like yarn or wire. Remote sensor model LP400WB is a good example of this type of sensor.



Convergent Beam —

Another proximity mode that is effective for sensing small objects is the **convergent beam mode**. Most convergent beam sensors use a lens system that focuses the emitted light to an exact point in front of the sensor, and focuses the receiver element at the same point. This design produces a small, intense, and well-defined sensing area at a fixed distance from the sensor lens (Figure A.36).

This is a very efficient use of reflective sensing energy. Objects with small profiles are reliably sensed. Also, materials of very low reflectivity that cannot be sensed with diffuse or divergent mode sensors can often be sensed reliably using the convergent beam mode.



The range of a convergent beam sensor is defined as its **focus point**, which is fixed. This means that the distance from a convergent beam device to the surface to be sensed must be more or less closely controlled. Every convergent beam sensor will detect an object of a given reflectivity at its focus point, plus and minus some distance. This sensing area, centered on the focus point, is called the sensor's **depth of field**. The size of the depth of field depends upon the sensor design and the reflectivity of the object to be sensed.

Color mark sensing (or **register mark sensing**) is a specialized application of convergent sensing in which a precise focus convergent sensor is used to sense register marks in applications usually involving product positioning. LED color is important in determining the color contrasts that can be sensed. Banner R55 Series color mark sensors use a powerful blue-green LED to sense an extremely wide range of contrasts without the need for the multiple light sources often used in competitive products. Contrasts as slight as 20% yellow on white can be easily sensed.

Laser diode convergent sensors can produce an extremely small, concentrated focus point. Banner PicoDot™ laser diode convergent beam sensors (see figure A.37) produce a focus point only 0.25mm (.01") in diameter at a sensing distance of 100mm (4"). Such sensors are ideal for use in small parts detection applications and as robotic end effectors. Laser convergent sensors, with their high sensing power, are often able to detect objects that are not reflective enough to be sensed with conventional LEDs.

The depth of field of **mechanical convergent beam sensors** is relatively large. As the name suggests, mechanical convergent beam sensors direct a lensed emitter and a separate lensed receiver toward a common point ahead of the sensor. Remote sensor model SP100C is a good example of this type. With the proper bracketing, any opposed mode sensor pair may be configured for the mechanical convergent beam mode (Figure A.38).

One specialized use of mechanical convergence is for the sensing of specular reflections (see Figure A.28). This involves positioning a lensed emitter and receiver at equal and opposite angles (from the perpendicular) to a glossy or mirror-like surface. The distance from the shiny surface to the sensors must remain constant. Specular reflection is useful for sensing the difference between a shiny and a dull surface. It is particularly useful for detecting the presence of materials that do not offer enough height differential from their background to be recognized by a convergent beam or fixed-field sensor. For example, the specular mode may be used to sense the presence of cloth material of any color (a "diffuse material") on a steel sewing machine work surface (a "shiny surface").

It is often necessary to detect objects that pass the sensor within a specified range, while ignoring other stationary or moving objects in the background. One advantage of convergent beam sensors is that objects beyond the far limit of the depth of field are ignored. It is important to remember, however, that the near and far limits of a convergent beam sensor's depth of field are dependent upon the reflectivity of the object in the scan path. Background objects of high reflectivity will be sensed at a greater distance than objects of low reflectivity.

Fixed-field—

Fixed-field sensors (Figure A.39) have a definite limit to their sensing range: they ignore objects that lie beyond their sensing range, regardless of object surface reflectivity.

Fixed-field sensors compare the amount of reflected light that is seen by two differently-aimed receiver optoelements. A target is recognized as long as the amount of light reaching receiver R2 is equal to or greater than the amount "seen" by R1. The sensor's output is cancelled as soon as the amount of light at R1 becomes greater than the amount of light at R2. Banner self-contained sensors with the "FF" model number suffix and remote sensor model SP100FF are good examples of fixed-field sensors.

Adjustable field—

The receiver element of an **adjustable field sensor** produces two currents: I1 and I2 (Figure A.40). In adjustable field sensing, the ratio of the two currents changes as the received light signal moves along the length of the receiver element. The sensing cutoff distance relates directly to this ratio, which is made adjustable via a potentiometer. Even highly reflective objects lying beyond the cutoff distance (example: object B) are ignored. Banner QM42AF Series sensors are adjustable field sensors.

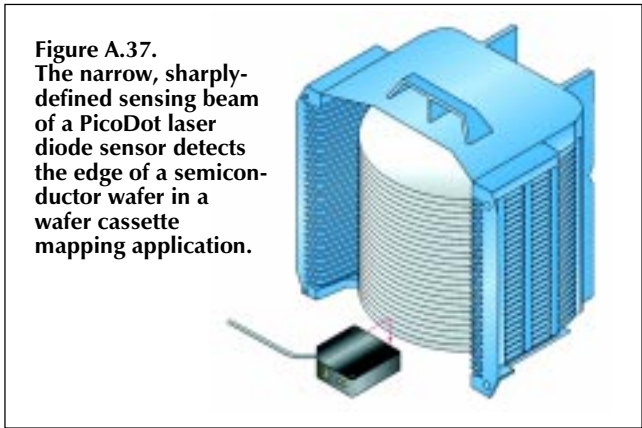


Figure A.37. The narrow, sharply-defined sensing beam of a PicoDot laser diode sensor detects the edge of a semiconductor wafer in a wafer cassette mapping application.

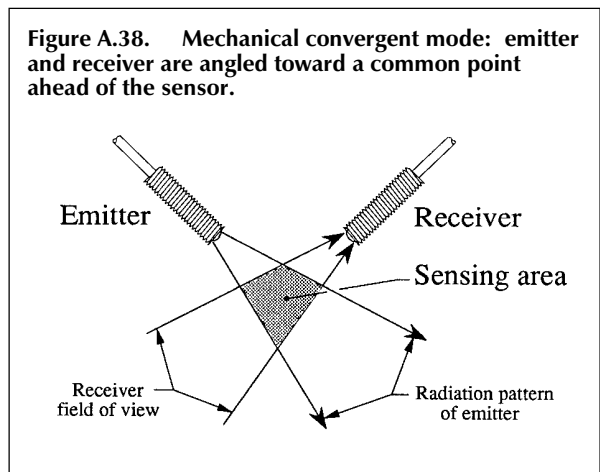


Figure A.38. Mechanical convergent mode: emitter and receiver are angled toward a common point ahead of the sensor.

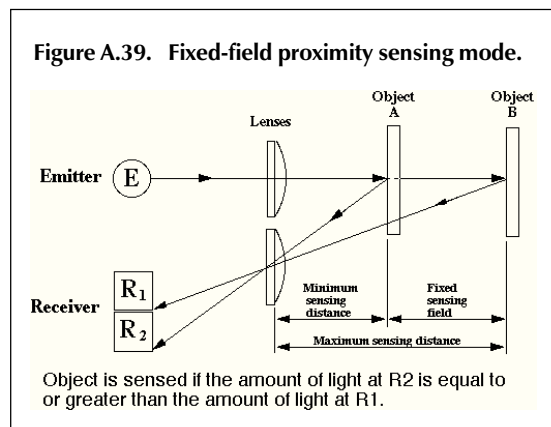


Figure A.39. Fixed-field proximity sensing mode.

Object is sensed if the amount of light at R2 is equal to or greater than the amount of light at R1.

Opposed Mode Beam Patterns

Beam patterns for opposed sensors represent the area within which the receiver will effectively "see" the emitted light beam. The horizontal scale is the separation distance between the emitter and receiver. The vertical scale is the width of the active beam, measured on either side of the optical axis of the emitter or receiver lens.

It is assumed that there is no angular misalignment between the emitter and the receiver. In other words, the optical axis of the emitter lens is kept exactly parallel to the optical axis of the receiver lens while plotting the pattern. Even small amounts of angular misalignment will significantly affect the size of the sensing area of most opposed sensor pairs, except at close range.

Opposed beam patterns predict how closely adjacent to one another parallel opposed sensor pairs may be placed without generating optical crosstalk from one pair to the next. A typical beam pattern for an opposed mode sensor pair is shown in Figure A.43. This pattern predicts that, at an opposed sensing distance of four feet, a receiver that is kept perfectly parallel to its emitter will "see" enough light for operation at up to just over eight inches in any direction from the optical axis of the emitter. This means that adjacent emitter/receiver pairs may be safely placed parallel to each other as close as about ten inches apart (i.e. safely more than eight inches apart) without optical crosstalk from an emitter to the wrong receiver (Figure A.44).

Figure A.44 shows how parallel beam spacing may be cut in half by *alternating* emitter - receiver - emitter - receiver - etc. on each side of the sensing area. Whenever *only two* opposed beams are involved in the sensing scheme, they may be placed in this manner as closely together as the dimensions of the sensors permit without causing direct optical crosstalk. However, whenever emitters and receivers that are on the same side of the sensing area get very close together (typically two inches or less) the potential for reflective crosstalk (i.e. "proxing") increases. Since the receivers in opposed mode sensing are "looking" for dark (i.e. beam blocked) for object detection, the light detected by a receiver due to reflective crosstalk may cause an object in the sensing area to slip past undetected.

Another common way to minimize optical crosstalk between adjacent opposed sensor pairs is to include a slight angle in the emitter or receiver mounting to intentionally misalign the outermost beams of the array. For example, in Figure A.43, Emitter #1 could be rotated to direct its beam slightly "up" and away from the view of Receiver #2. Similarly, Emitter #3 could be rotated slightly "down" and away from Receiver #2.

Yet another way to minimize optical crosstalk is to separate adjacent emitter/receiver pairs both horizontally *and* vertically. The diagonal separation between adjacent beams is determined by the beam pattern. In this way, adjacent beams may be placed on closer centers in one dimension. This is possible whenever the object that is to be sensed is large in crosssection and when available space permits this approach to sensor mounting.

When adjacent opposed beams are placed on very close centers, optical crosstalk can be eliminated by *multiplexing* the sensors in the array (Figure A.45). **Multiplexing** is a scheme in which an electronic

Figure A.43. Spacing for three opposed pairs. A beam pattern indicates the minimum separation required to avoid crosstalk between adjacent opposed mode sensor pairs.

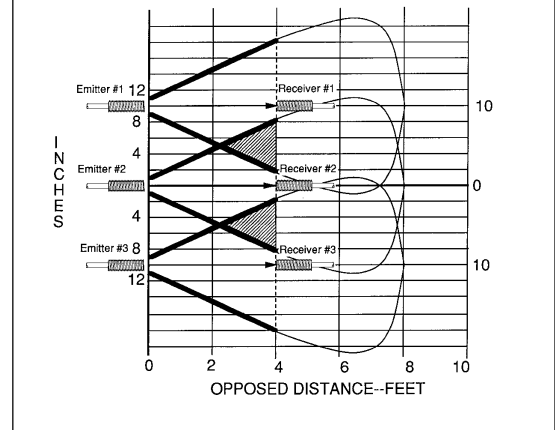


Figure A.44. Spacing for three opposed sensor pairs (staggered). The minimum spacing between adjacent opposed sensor pairs is cut in half if emitters and receivers are alternated on each side.

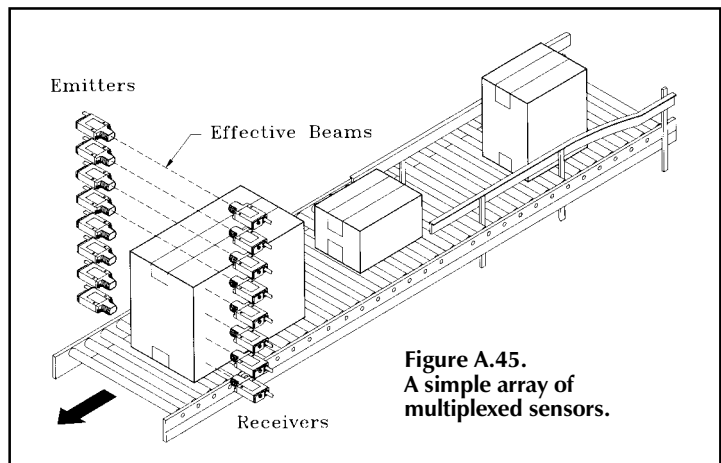
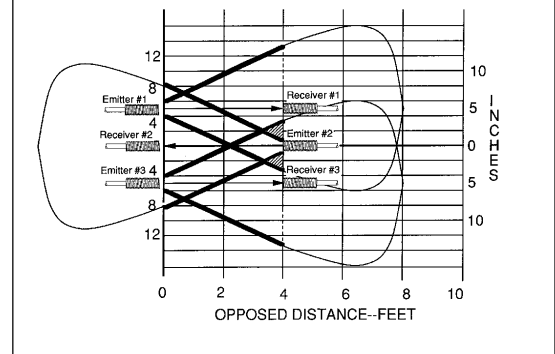
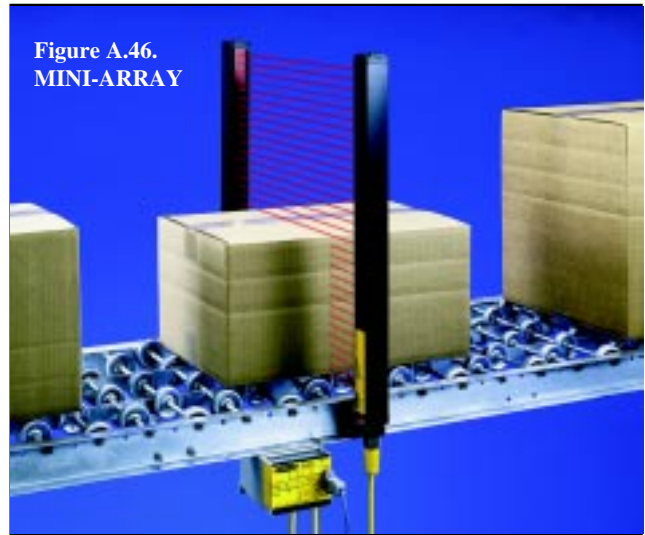


Figure A.45. A simple array of multiplexed sensors.

control circuit interrogates each sensor in the array in sequence. True photoelectric multiplexing enables ("turns on") each modulated emitter only during the time that it samples the output of its associated receiver. The chance of false response of any receiver to the wrong light source is eliminated.

The MINI-ARRAY System (Fig. A.46) is an example of a multiplexed "light curtain" used for on-the-fly parts profiling, part ejection verification, parts counting, and similar applications. The "light curtain" is generated by two linear arrays, one containing a row of emitter LEDs and the other containing a corresponding row of receiver phototransistors. MINI-ARRAY controllers are available with a variety of outputs, including electromechanical, NPN, or NPN and PNP solid-state relays, and serial data for interfacing with a computer or PLC for scan control and data analysis. MINI-ARRAY controllers provide eight measurement modes and four scan modes using the included software. Sensors are available in lengths of six inches through six feet. A GATE input allows control of scan initiation (e.g. by a presence sensor, etc).



Opposed mode beam pattern information is also useful for predicting the area within which an emitter and receiver will align when one is moving relative to the other, as with automatic vehicle guidance systems. The beam pattern represents the largest typical sensing area when sensor sensitivity is adjusted to match range specifications. The boundary of the beam pattern will shrink with decreased sensitivity setting, and may expand with increased sensitivity.

Retroreflective Mode Beam Patterns

Beam patterns for retroreflective sensors are plotted using a model BRT-3 three inch diameter plastic corner-cube type retroreflector. The beam pattern represents the boundary within which the sensor will respond to a BRT-3 target (Figure A.47). The retroreflective target is kept perpendicular to the sensor's optical axis when plotting the pattern.

The horizontal scale is the distance from the retro sensor to the BRT-3 retroreflector. The vertical scale is the farthest distance on either side of the sensor's optical axis where a BRT-3 reflector can establish a retroreflective beam with the sensor.

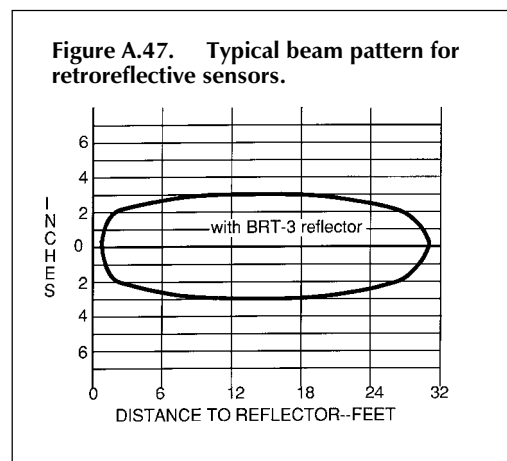
A "retro" beam pattern indicates how one BRT-3 target will interact with multiple parallel retroreflective sensors that are mounted on close centers. The beam pattern also predicts whether a 3-inch reflector will be detected if it is traveling past the sensor parallel to the sensor face, or vice versa.

Most important, a retroreflective beam pattern is an accurate depiction of the size of the active beam area at distances of a few feet or more from the sensor. It is always good practice, if possible, to capture the entire emitted beam with retroreflective target area. The beam pattern indicates how much reflector area is needed at any distance where the beam size is greater than 3 inches wide.

Proximity Mode Beam Patterns

The beam pattern for any proximity mode photoelectric sensor represents the boundary within which the edge of a light-colored diffuse surface will be detected as it moves past the sensor. Beam patterns for diffuse, convergent, divergent, and fixed-field mode sensors are developed using a Kodak 90% reflectance white test card, which is about 10% more reflective than most white copy paper. The beam pattern will be smaller for materials that are less reflective, and may be larger for surfaces of greater reflectivity.

The test card used to plot the pattern measures 8 by 10 inches. Objects that are substantially smaller may decrease the size of the beam pattern at long ranges. Also, the angle of incidence of the beam to a *shiny* surface has a pronounced effect on the size and the shape of a diffuse mode beam pattern.



The horizontal scale is the distance from the sensor to the reflective surface. The vertical scale is the width of the active beam measured on either side of the optical axis (Figure A.48). The beam pattern for any diffuse, convergent, divergent, fixed-field, or adjustable-field sensor is equivalent to the sensor's effective beam.

The beam pattern (more commonly called the **response pattern**) for an ultrasonic proximity sensor is drawn for a square, solid, flat surface (Figure A.49). The size of the target is specified for each type of sensor. The size of an ultrasonic proximity response pattern is affected by the size, shape, texture, and density of the material being sensed.

Excess Gain

Excess gain is a measurement that may be used to predict the reliability of any sensing system. As its name suggests, excess gain is a measurement of the sensing energy falling on the receiver element of a sensing system over and above the minimum amount required to just operate the sensor's amplifier.

Once a signal is established between the emitter and the receiver of any sensor or sensing system, there may be attenuation (reduction) of that signal resulting from dirt, dust, smoke, moisture, or other contaminants in the sensing environment. The excess gain of a sensing system may be seen as the extra sensing energy that is available to overcome this attenuation.

Excess gain is usually clearly specified for photoelectric sensors. In equation form:

$$\text{Excess Gain (E.G.)} = \frac{\text{Light energy falling on receiver element}}{\text{Sensor's amplifier threshold}}$$

The **threshold** is the level of sensing energy required by the sensor's amplifier to cause its output to change state (i.e., to switch "on" or "off"). In a modulated photoelectric system, excess gain is measured as a voltage (typically at millivolt levels), usually at the first stage of receiver amplification. This measured voltage is compared to the amplifier's threshold voltage level to determine the excess gain. There is an excess gain of one (usually expressed as "1x" or "one times") when the measured voltage is at the amplifier threshold level.

If 50% of the original light energy becomes attenuated, then a minimum of 2x ("two times") excess gain is required to overcome the light loss. Similarly, if 80% of a sensor's light is lost to attenuation (i.e. only 20% left), then an available excess gain of at least 5x is required.

If the general conditions in the sensing area are known, the excess gain levels listed in Table A-1 may be used as guidelines for assuring that the sensor's light energy will not be entirely lost to attenuation.

Table A-1 lists an excess gain of 1.5x (i.e. 50% more energy than the minimum for operation) for a perfectly clean environment. This amount includes a safety factor for subtle sensing variables such as gradual sensor misalignment and small changes in the sensing environment. At excess gains above 50x, sensors will begin to **burn through** (i.e. "see" through) paper and other materials with similar optical density.

Figure A.48. Typical beam pattern for diffuse proximity mode sensors.

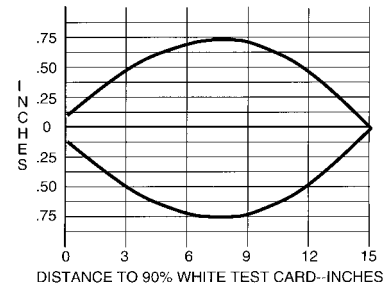
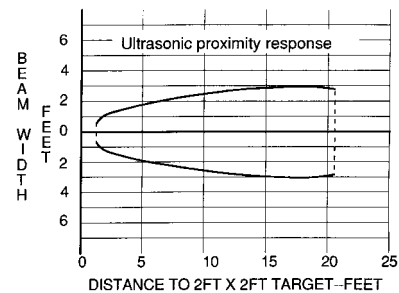


Figure A.49. Typical ultrasonic proximity mode response pattern.

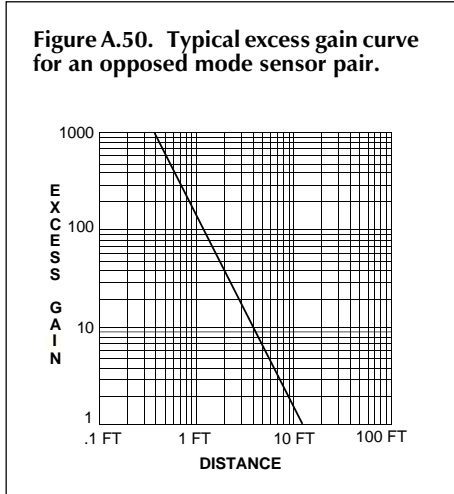


**TABLE A-1
Guidelines for Excess Gain Values**

Minimum Excess Gain Required	Operating Environment
1.5x	Clean air: no dirt buildup on lenses or reflectors.
5x	Slightly dirty: slight buildup of dust, dirt, oil, moisture, etc. on lenses or reflectors. Lenses are cleaned on a regular schedule.
10x	Moderately dirty: obvious contamination of lenses or reflectors (but not obscured). Lenses cleaned occasionally or when necessary.
50x	Very dirty: heavy contamination of lenses. Heavy fog, mist, dust, smoke, or oil film. Minimal cleaning of lenses.

The excess gain that is available from any sensor or sensing system may be plotted as a function of distance (Figure A.46). **Excess gain curves** are plotted for conditions of perfectly clean air and maximum receiver gain, and are an important part of every photoelectric sensor specification. The excess gain curve for any Banner sensor represents the lowest *guaranteed* excess gain available from that model. Most sensors are factory calibrated to the excess gain curve. Sensors that have a gain adjustment (also called a "sensitivity control") can usually be field-adjusted to exceed the excess gain specifications; however, this is never guaranteed.

The excess gain curve in Figure A.50 suggests that operation of this opposed sensor pair is possible in a perfectly clean environment (excess gain $\geq 1.5x$) at distances up to 10 feet apart, and in a moderately dirty area (excess gain $\geq 10x$) up to 4 feet apart. At distances inside 1 foot, these sensors will operate in nearly any environment.



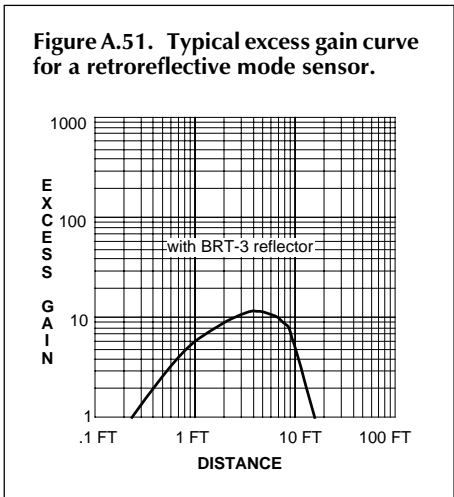
Excess Gain - Opposed Mode Sensing

The relationship between excess gain and sensing distance is different for each photoelectric sensing mode. For example, the excess gain of an opposed mode sensor pair is directly related to sensing distance by the inverse square law. If the sensing distance is doubled, the excess gain is reduced by a factor of $(1/2)^2 = \text{one-fourth}$. Similarly, if the sensing distance is tripled, the excess gain is reduced by a factor of $(1/3)^2 = \text{one-ninth}$, and so on. As a result, the excess gain curve for opposed mode sensors is always a straight line when plotted on a log-log scale.

Since the light from the emitter goes directly to the receiver, opposed mode sensing makes the most efficient use of sensing energy. Therefore, the excess gain that is available from opposed mode sensors is much greater than from any other photoelectric sensing mode.

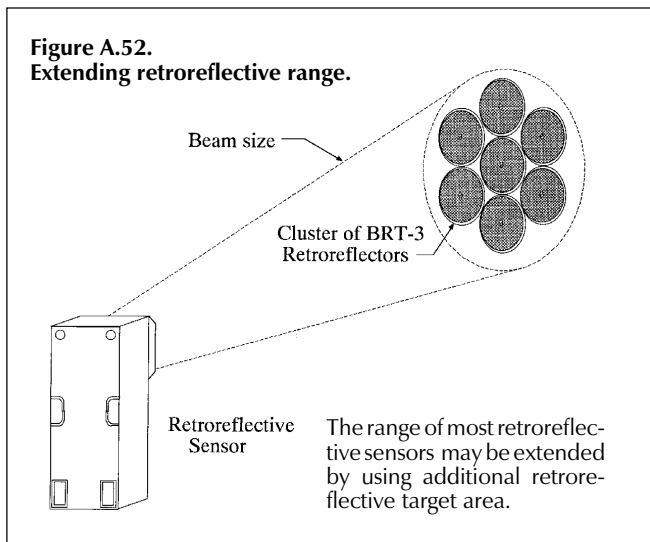
Excess Gain - Retroreflective Mode Sensing

The shape of excess gain curves for the other sensing modes are not as predictable. Retroreflective excess gain curves are plotted using a model BRT-3 three-inch diameter retroreflector, except where noted. The shape of retroreflective excess gain curves is affected by the size of the retroreflective target. Several BRT-3 targets, used together in a cluster, will usually result in longer sensing range and a higher maximum excess gain (Figure A.52). A smaller corner-cube reflector, like the one-inch diameter model BRT-1, yields a smaller curve.



The type of retroreflective target material used also affects excess gain. The Banner product catalog lists a "Reflectivity Factor" for each type of retro material. This factor compares each retroreflective material to the reflectivity of target model BRT-3. Any point on an excess gain curve may be multiplied by this factor to approximate the excess gain for an equivalent amount of reflective area of the retro target material in question.

Most retroreflective sensors are designed for long-range performance, and use separate lenses for the emitter and the receiver. A good retroreflector has the property of returning most of the incoming light directly back to the sensor. At close ranges, the retroreflector sends most of the incoming light directly back into the *emitter* lens (see Figure A.53). As a result, many two-lens retroreflective sensors suffer a **blind spot** at close-in ranges, which is evident on excess gain curves and may be seen in Figure A.51.



Special single-lens retroreflective sensors are available for close-in sensing of retro material. This design typically uses a beam splitter device located directly behind the lens. Model SM502A is a good example of a single-lens retro design. It can even sense retro material that is actually in contact with the lens itself.

Figure A.53 illustrates an important consideration to make, especially when using retroreflective sensors in dirty locations. The light energy must pass through two surfaces (lens surfaces) on each end of the sensing path, so it is necessary to account for double attenuation on both ends. This is equivalent to saying that the actual excess gain drops off twice as fast in a retroreflective system as in an opposed system, in any sensing environment.

Excess Gain - Proximity Mode Sensing

Generally speaking, photoelectric proximity modes are inefficient sensing modes. The receiver must "look" for a relatively small amount of light that is bounced back directly from the surface of an object. As a result, the excess gain available from a proximity mode sensor is usually lower than that of the other photoelectric sensing modes.

The curves for diffuse, convergent, divergent, and fixed-field sensors are plotted using a Kodak 90% reflectance white test card as the reference material. The excess gain of diffuse sensors is dramatically influenced by the reflectivity of the surface to be sensed. Any material surface may be ranked for its reflectivity as compared to the Kodak 90% reflectance white reference card (Table A-2).

In Table A-2, the numbers in the "Excess Gain Required" column indicate the *minimum* excess gain that is required to sense the material. For example, if the material to be sensed is opaque black plastic (excess gain required = 6.4), then the diffuse sensor with the excess gain curve of Figure A.54 will "see" the material from 0 (zero) to 10 inches. This assumes perfect sensing conditions.

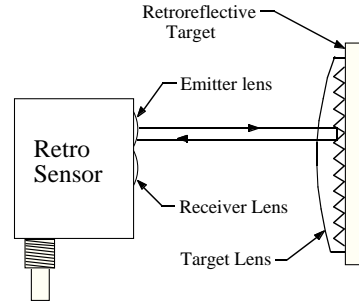
To get the actual required excess gain for diffuse sensing of any material, multiply the material's **reflectivity factor** by the excess gain level that is required for the sensing conditions (from Table A-1). For example, to sense black opaque plastic in a slightly dirty environment, the minimum required excess gain is:

$$\text{Excess gain required} = 6.4 \text{ (reflectivity factor)} \times 5 \text{ (minimum E.G. required)} = 32.$$

Under these conditions, the diffuse sensor of Figure A.54 will reliably sense the black plastic from 1/2 to 4 inches, even after there is a slight build-up of dirt on the lens.

The excess gain of diffuse mode sensors is also affected by the size and the profile of the object to be detected. The excess gain curves assume a white test card that fills the entire area of the diffuse sensor's effective beam. If the object to be detected only fills a portion of the

Figure A.53. Retroreflective "blind spot". Most retroreflective sensors with separate emitter and receiver lenses have a "blind spot" at very close range.



**TABLE A-2
Relative Reflectivity Chart**

Material	Reflectivity (%)	Excess Gain Required
Kodak white test card	90%	1
White paper	80%	1.1
Newspaper (with print)	55%	1.6
Tissue paper: 2 ply	47%	1.9
1 ply	35%	2.6
Masking tape	75%	1.2
Kraft paper, cardboard	70%	1.3
Dimension lumber		
(pine, dry, clean)	75%	1.2
Rough wood pallet (clean)	20%	4.5
Beer foam	70%	1.3
Clear plastic bottle*	40%	2.3
Translucent brown		
plastic bottle*	60%	1.5
Opaque white plastic*	87%	1.0
Opaque black plastic		
(nylon)*	14%	6.4
Black neoprene	4%	22.5
Black foam carpet backing	2%	45
Black rubber tire wall	1.5%	60
Natural aluminum,		
unfinished*	140%	0.6
Natural aluminum,		
straightlined*	105%	0.9
Black anodized aluminum,		
unfinished*	115%	0.8
Black anodized aluminum,		
straightlined*	50%	1.8
Stainless steel, microfinish*	400%	0.2
Stainless steel, brushed*	120%	0.8

*For materials with shiny or glossy surfaces, the reflectivity figure represents the maximum light return, with the sensor beam exactly perpendicular to the material surface.

sensor's effective beam, there will be proportionately less light energy returned to the receiver.

Like the diffuse mode, the excess gain of divergent mode sensors is affected by the reflectivity and size of the object to be sensed. However, the effect of these variables is less noticeable in divergent sensing, simply because divergent mode sensors lose their sensing ability within such a short range.

Since most of the energy of a convergent beam sensor is concentrated at its focus, the maximum available excess gain is much higher than for any of the other proximity modes. This relatively high excess gain allows the detection of materials of very low reflectivity, where diffuse, divergent, adjustable-field, and fixed-field mode sensors would fail. The effect of an object's relative reflectivity is most noticeable in the size of the resultant depth of field. Also, because the effective beam of a convergent beam sensor is so small, even objects with narrow profiles can return a relatively high percentage of the incident light.

Excess Gain and Sensor Alignment

The most common mistake made when installing infrared (invisible light) LED sensors is failing to center the light beam on its receiver or target. An installer often will simply adjust a sensor's position until the alignment indicator LED lights or until the output load switches. It is likely that this sensor has been only marginally aligned, with very little excess gain available to overcome dirt build-up and other sensing variables. Most photoelectric sensor lenses have accurately-placed optical axes. However, it is seldom absolutely safe to assume that perfect mechanical sensor alignment is exactly equivalent to the best optical alignment.

Excess gain measurement is the easiest and best way to assure optimal sensor alignment and to monitor sensor performance. Banner offers two excess gain measurement schemes. The OMNI-BEAM sensor family features the **D.A.T.A.**™ light system. The **D.A.T.A.** system (Figure A.55) displays relative received signal strength on a built-in ten element LED array. As more light is received, more LEDs in the array are lighted. Table A-3 shows the direct relationship between the number of lighted LEDs and the excess gain.

Other self-contained sensor models in the MULTI-BEAM, MAXI-BEAM, VALU-BEAM, Q45, and MINI-BEAM families, plus component systems using modulated amplifiers in the MAXI-AMP or MICRO-AMP families, offer the **AID**™ (Alignment Indicating Device) feature. The **AID** feature allows measurement and monitoring of relative excess gain. Many Banner sensor lines include a marginal excess gain indicator and alarm system.

When alignment is first established, the alignment indicator on the sensor (or amplifier module) will come "on" at full brightness. After one or two seconds, the **AID** circuitry will superimpose a pulse rate, oscillating between full and half brightness. The pulse (or flash) rate in beats-per-second is directly proportional to the excess gain of the sensing system. Alignment simply involves adjusting the sensor's position to yield maximum flash rate.

It is difficult to judge relative pulse rates beyond about ten beats per second. The **D.A.T.A.** light system lights all ten LEDs at an excess gain of about 4x (Table A-3). In many sensing situations, the available excess gain can or must be much higher. In such situations, which include most opposed and retroreflective sensing applications, more accurate alignment can be accomplished using one of two simple methods.

Figure A.54. Typical excess gain curve for a diffuse proximity mode sensor.

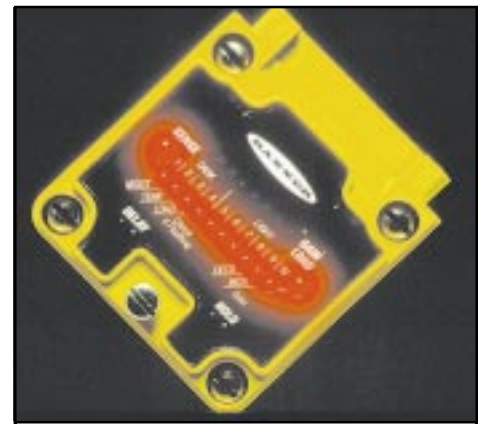
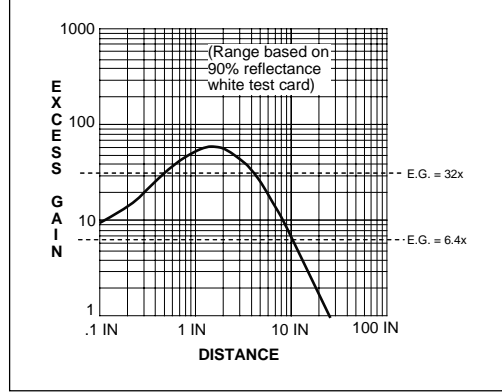


Figure A.55. The D.A.T.A. system array of OMNI-BEAM sensors.

TABLE A-3. Relationship between Excess Gain and D.A.T.A. System Lights

D.A.T.A. light LED number	Excess Gain
#1	0.25x excess gain
#2	0.35x
#3	0.5x
#4	0.7x
#5	1.0x
#6	1.3x
#7	1.7x
#8	2.2x
#9	2.9x
#10	3.7x (or more)

If the sensor has a sensitivity (gain) control, the receiver gain can be temporarily adjusted downward so that fine increments of alignment again register an easily discernible difference on the **AID** or **D.A.T.A.** signal strength display.

If the sensor has no sensitivity control, the signal strength may be temporarily attenuated by masking the lens(es). This may be done by affixing layers of paper tape to the lens(es). A piece of thin paper held or taped over the lens(es) will serve the same purpose. If total coverage of the lens yields too much attenuation, then the lens may be masked so that only a portion of the lens center is exposed. In retroreflective sensing, the retro target may be masked so that only a small amount of the center area is exposed. Lens masking may be used in conjunction with temporary sensitivity reduction for accurate alignment in situations like short-range opposed sensing where excess gain is very high.

Signal strength indicators also serve the important function of system monitoring. A slow pulse rate of the **AID** indicator or a short string of LEDs on the **D.A.T.A.** display is a visual indication of marginal signal strength. (Additionally, the **D.A.T.A.** display flashes a warning LED and energizes an alarm output signal whenever excess gain approaches 1x.)

The concept of excess gain is not intended to be an exact science, but rather is a guideline for the sensor selection process. Knowing values from an excess gain curve can be valuable information for predicting the success of a particular sensor in a given sensing environment. *In most sensing situations, high excess gain relates directly to sensing reliability.*

Contrast

All photoelectric sensing applications involve differentiating between two received light levels (Figure A.56). **Contrast** is the ratio of the amount of light falling on the receiver in the “light” state as compared to the “dark” state. Contrast is also referred to as the “light-to-dark ratio”, as represented by the following equation:

$$\text{Contrast} = \frac{\text{Light level at the receiver in the light condition}}{\text{Light level at the receiver in the dark condition}}$$

It is always important to choose the sensor or lensing option that will optimize contrast in any photoelectric sensing situation. Many situations, like a cardboard box breaking a retroreflective beam, are applications with infinitely high contrast ratios. In this type of high-contrast application, sensor selection simply involves verifying that there will be enough available excess gain for reliable operation in the sensing environment.

Many of today’s industrial photoelectric sensing applications are not so straightforward. Most problems with contrast in opposed and retroreflective applications occur when:

- 1) the beam must be blocked by a material that is not opaque, or
- 2) less than 100% of the effective beam is blocked.

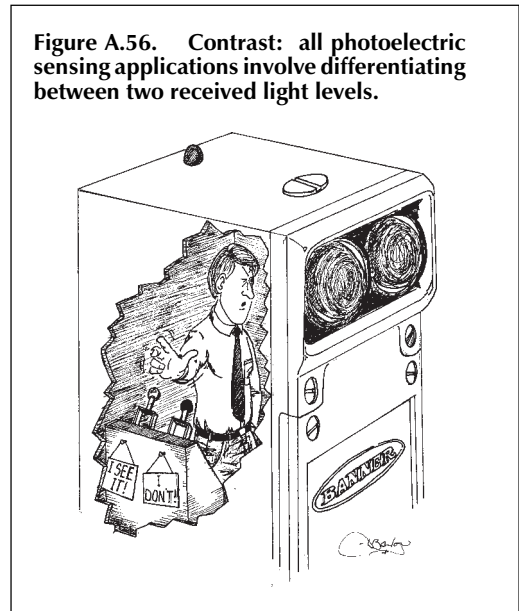
When proximity mode sensors are used, most low contrast problems occur where there is a close-in background object directly in the scanning path. This problem is compounded when the background object’s reflectivity is greater than the reflectivity of the object to be detected. Fixed-field, adjustable-field, or ultrasonic proximity mode sensors can often deal successfully with this problem.

As a general rule, a contrast of 3 is the minimum for any sensing situation. This is usually just enough to overcome the effect of subtle variables that cause light level changes, such as small amounts of dirt build-up on the lenses or inconsistencies in the product being sensed. Table A-4 gives suggested guidelines for contrast values.

TABLE A-4. Contrast Values and Corresponding Guidelines

Contrast	Recommendation
1.2 or less	Unreliable: evaluate alternative sensing schemes.
1.2 to 2	Poor contrast: consider sensors with ac-coupled amplification.
2 to 3	Low contrast: sensing environment must remain clean and all other sensing variables must remain stable.
3 to 10	Good contrast: minor sensing system variables will not affect sensing reliability.
10 or greater	Excellent contrast: sensing should remain reliable as long as the sensing system has enough excess gain for operation.

Figure A.56. Contrast: all photoelectric sensing applications involve differentiating between two received light levels.



Close Differential Sensing

Some applications offer a contrast of less than 3, regardless of the sensing method used. These low contrast situations fall into the category of **close differential sensing** applications. Most color registration mark applications qualify as close differential sensing. Another common close differential sensing situation involves breaking a relatively large effective beam with a small part, as in ejected small part detection or thread break detection.

Color Registration Mark Sensing

Color registration mark applications require the sensor to differentiate between two colors which may sometimes be very similar in hue and reflectivity. The most modern sensors deal with this challenge in two ways: with programmed sensor setup technology and by offering a choice of light source LED colors to optimize sensing contrasts. One or both of these technologies are offered in the Banner D11, D12, MINI-BEAM, and R55 product lines.

Programmed ("TEACH" mode) setup is a step-by-step sequence in which two sensing reference points ("light" and "dark") are established. Some sensors use a simple push button programming procedure. The sensor circuitry then automatically sets its sensitivity (and expands its low-end sensitivity range, if necessary) to an optimal level. LED color can be important: a red LED will not see red marks on white, but will see blue and green. A green LED sees red and blue, but not green. A blue LED sees green and red, but not blue. With proper choice of light source color, even very "light" colors ("pastels") on white, and other very small color differences, can be detected.

AC-coupled Sensing

In applications where very small and variable signal changes will be encountered, as in ejected part detection or thread break detection, the use of an **ac-coupled sensor** should be considered. Most sensing systems use dc-coupled amplifiers. A dc-coupled amplifier is one that amplifies all received signal levels. AC-coupled amplifiers may sometimes be used more reliably in close differential sensing, since they amplify *only ac (changing) signals*, while completely ignoring dc (steady) signals. This means that very small changes in received light level can be highly amplified. AC-coupled sensors incorporate *pulse stretcher* circuitry in order to produce a uniform, useable sensor output from light signal changes of varying magnitudes and durations. The AC-coupled sensor of Figure A.58 uses rectangular fiber optics to produce a flattened, rectangular light beams. Objects passing through the beam can be detected, even when they present very different orientations and light signal changes within the sensing beam.

Model SM53R, a modulated receiver, has a specially-conditioned analog output that is compatible with ac-coupled amplifiers. Models SM53E and SM53R form an opposed mode pair that may be fitted with lenses, apertures, or fiberoptic adaptors for a variety of close-differential sensing applications such as yarn break, wire break, and web flaw detection. The power of this modulated LED opposed sensor pair, plus the sensitivity of an ac-coupled amplifier, offers a solution to many otherwise impossible sensing applications. The OMNI-BEAM and D12 modulated self-contained sensor families also include ac-coupled sensor models.

As useful as they are, ac-coupled amplifiers should be avoided whenever the contrast is high enough for a dc-coupled device. Because they are so sensitive to very small signal changes, ac-coupled amplifiers may unwantedly respond to conditions like electrical "noise" or sensor vibration. Also, ac-coupled amplifiers require a sensing event to occur at a minimum rate of change. As a general guideline, a target must move into the sensing beam at a minimum speed of one inch per second.

In the contrast range of 2 to 3, consider a dc-coupled device as a first choice. However, in order for a dc-coupled sensor to be reliable in this low contrast range, sensing variables like dirt build-up on lenses, reflectivity or translucency of the part being sensed, and the mechanics of the sensing system must remain constant. If it is known that these variables might gradually change over time, ac-coupled amplification should be considered.



Figure A.57. MINI-BEAM TEACH-mode color-mark sensors

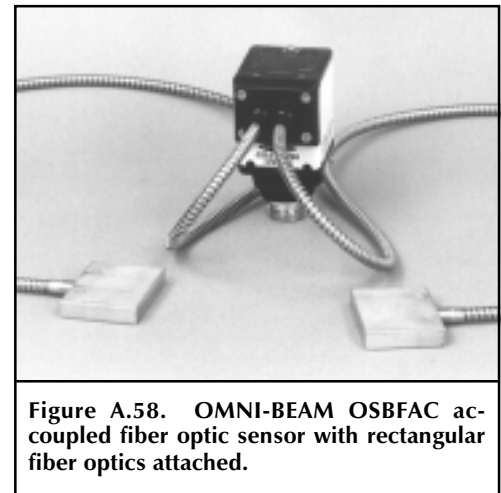


Figure A.58. OMNI-BEAM OSBFAC ac-coupled fiber optic sensor with rectangular fiber optics attached.

Measuring Contrast

Contrast may be calculated if excess gain values are known for both the light and the dark conditions:

$$\text{Contrast} = \frac{\text{Excess gain (light condition)}}{\text{Excess gain (dark condition)}}$$

OMNI-BEAM D.A.T.A. and Banner A.I.D. Systems

The **D.A.T.A.** light system of the OMNI-BEAM provides an easy way to determine sensing contrast. Both the light and the dark sensing condition (e.g. “part present” and “part absent”) are presented to the OMNI-BEAM, and the signal level for each condition is read from the **D.A.T.A.** display. The ratio of the two numbers (from Table A-3) that correspond to the highest **D.A.T.A.** light numbers registered for the light and the dark conditions determines the sensing contrast.

For example, if **D.A.T.A.** system LEDs #1 through #8 come “on” in the light condition and LEDs #1 and #2 come “on” on the dark condition, the contrast (referring to Table A-3) is calculated as follows:

$$\text{Contrast} = \frac{2.2x}{0.35x} = 6$$

The sensor’s position and/or the sensor’s gain control may require adjustment in order for the **D.A.T.A.** display to register a difference between the light and the dark conditions. If the gain is too high, the display may show all LEDs lighted for both conditions. If the gain is too low, the display may show fewer than five LEDs lighted for both conditions. The best adjustment places the #5 LED midway between the light and the dark levels.

The most reliable sensor adjustment will cause all ten **D.A.T.A.** LEDs to come “on” for the light condition, and will cause *no* LEDs to come “on” in the dark condition. In this condition (such as an application in which an opaque box breaks the beam of an opposed mode emitter and receiver):

(from table A-3) Contrast is greater than $\frac{3.7x}{0.25x} = 15$

OMNI-BEAM sensor heads and CM Series MAXI-AMP amplifier modules are programmable for **hysteresis**. Switching hysteresis is an electronic design parameter that requires the signal level (i.e. the amount of received light) at the operate (turn-on) point of an amplifier to be different from the signal level at the release point. This differential prevents the output of a sensor from “buzzing” or “chattering” when the received signal is at or near the amplifier threshold.

Most sensing is done using the NORMAL hysteresis setting. The LOW hysteresis setting allows the sensing system to be used without an ac-coupled amplifier for some poor contrast (1.2 to 2) sensing applications. The OMNI-BEAM’s **D.A.T.A.** display should be programmed for FINE scale factor whenever the LOW hysteresis setting is used. This scale factor expands the display to indicate smaller differences in excess gain (Table A-5) and can, therefore, be used to register smaller contrast ratios. All sensing conditions must remain perfectly stable for such small contrasts to be reliably sensed.

The **D.A.T.A.** system of the OMNI-BEAM includes an alarm that warns of low contrast. In the low hysteresis mode, the alarm output energizes whenever sensing contrast drops below 1.2, and alerts the operator to readjust the sensing parameters. Also, an alarm output will energize if the sensing gain drifts downward (e.g. as dirt builds up on the lenses), or if the gain drifts upward (e.g. as the object changes in reflectivity or translucency). Flashing LEDs on the **D.A.T.A.** array tell the operator whether gain is too high or too low, or if the contrast is too low.

TABLE A-5. The relationship between Scale Factor and D.A.T.A. System Lights

D.A.T.A. light LED number	STANDARD scale factor	FINE scale factor
#1	0.25x E.G.	0.5x E.G.
#2	0.35x	0.7x
#3	0.5x	0.8x
#4	0.7x	0.9x
#5	1.0x	1.0x
#6	1.3x	1.1x
#7	1.7x	1.2x
#8	2.2x	1.3x
#9	2.9x	1.7x
#10	3.7x (or more)	2.2x (or more)

NOTE: The scale factor is selected by programming switch #4 inside the sensor head. "OFF" = STANDARD; "ON" = FINE. Use the FINE scale only for setup and monitoring of close-differential sensing applications where LOW hysteresis is required.

When using a sensor or sensing system with the **AID** feature, contrast cannot be measured exactly, but it can be estimated. First, present the light condition and align the sensor for the fastest pulse rate of the alignment indicator. If the maximum attainable pulse rate is less than about 10 per second, estimate the maximum rate and fix the sensor in that position. If the pulse rate is greater than about 10 per second, adjust the gain control downward (counterclockwise adjustment) until the pulse rate is roughly 10 per second.

Next, present the dark condition and estimate the number of pulses per second. If the alignment indicator turns “off”, then assume a pulse rate of one per second (usually, this assumption is conservative). The ratio of the estimated pulse rates for the light and dark conditions is a rough approximation of the sensing contrast. This procedure cannot produce an accurate *measurement* of contrast; however, it will identify a low contrast situation.



Figure A.59.
D12 Plastic Fiber Optic TEACHable Sensor.

TEACH Mode Sensors

Some sensors are designed with "TEACH" mode programming capability. Special sensor circuitry, combined with a step-by-step application setup process, enables a user to program the "light" and "dark" sensing conditions into the sensor via a push button. The sensor then automatically optimizes its sensitivity range accordingly. On some sensors, a multiple-element LED bargraph signal strength indicator identifies the optimum contrast conditions during setup (Figure A.59).

Sensors without Signal Strength Indicators

When using sensors or component amplifiers not having a signal strength indication system, a simple procedure using the sensitivity control and alignment indicator (or output indicator) can be used to determine whether the contrast ratio is more than or less than 3. First, turn the sensitivity to minimum (fully counterclockwise) and program the output, where applicable, for “light operate”. Next, present the light condition to the sensor and increase the sensitivity until the alignment indicator (or output indicator) just turns “on” (this is the threshold, where the excess gain is 1x). Then, present the dark condition and further increase the sensitivity until the indicator, again, just turns “on”. See Figure A.60.

The difference between these two set points (thresholds) should represent at least one-third of the full range of the sensitivity adjustment control. (Note that most

multi-turn potentiometers have 15 turns from minimum to maximum gain.) Thirty percent of the full sensitivity adjustment relates to a contrast of about 3. The ideal operating sensitivity setting is midway between these two thresholds. If the indicator LED does not come “on” in the dark condition when the gain is adjusted to maximum, the operating sensitivity setting should be left at or near the fully clockwise position in order to take advantage of the full amount of available excess gain.

If the two thresholds occur within the bottom 20 percent of the sensitivity adjustment, there is *too much excess gain* for the dark condition. There may actually be a contrast of 3 or more, but it becomes impossible to find a stable setting near the bottom end of a sensitivity range. A common example is a paper web detection application. Although opposed sensors usually offer the best sensing contrast, they may offer so much excess gain (10,000x, or more!) that they “see” right through the paper. In cases like this, it may be necessary to mechanically attenuate the light energy by intentional misalignment of the sensors or by adding apertures in front of the sensor lenses. *It is always best to attenuate the light energy so that the operating sensitivity setting ends up near the midpoint of the gain adjustment range.*

Sensors without Sensitivity Controls

Sensors *without* sensitivity controls, such as ECONO-BEAM, THIN-PAK, and Q14 Series sensors, are popular for OEM use (Figure 61). These sensors should be used only in applications that offer contrast values of 10 or higher, and when it is known that the sensors offer enough excess gain to easily survive the operating conditions.

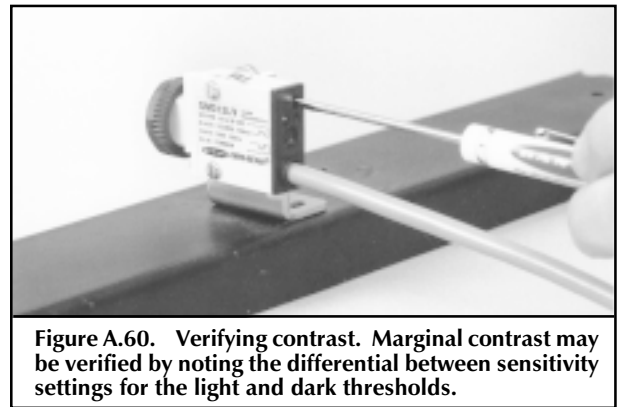


Figure A.60. Verifying contrast. Marginal contrast may be verified by noting the differential between sensitivity settings for the light and dark thresholds.



Figure A.61. Sensors without sensitivity controls should be used only in high-contrast applications.

Contrast should always be considered when choosing a sensor, and should always be maximized by alignment and gain adjustment during sensor installation. *Optimizing the difference in the amount of received light between the light and dark conditions of any photoelectric sensing application will always increase the reliability of the sensing system.*

Sensor Outputs

The output of a self-contained sensor or of the remote amplifier of a component sensing system is either digital or analog. A **digital output** (Figure A.62) is more commonly called a *switched* output. A switched output has only two states: "on" and "off". "On" and "off" commonly refer to the status of the **load** that the sensor output is controlling. The load might be an indicator light, an audible alarm, a clutch or brake mechanism, a solenoid valve or actuator, or a switching relay. The load might also be the input circuit to a timer, counter, programmable logic controller, or computer.

In photoelectrics, the sensing event (input) and the switched output state are characterized together by one of two sensing terms. **Light operate** describes a sensing system that will energize its output when the receiver "sees" more than a set amount of light. **Dark operate** means that the sensor's output will energize when its receiver is sufficiently dark.

In an opposed mode sensing system (Figure A.63), "dark operate" means that the output energizes its load when an object is present (breaking the beam). The light condition occurs when the object is absent.

In a retroreflective sensing system (Figure A.64), the conditions are the same. The dark condition occurs when the object is present, and the receiver sees light when the object is absent.

These conditions are reversed in all proximity sensing modes (Figure A.65). The light condition occurs when the object is present, "making" (establishing) the beam. When the object is absent, no light is returned to the receiver.

An **analog output** (Figure A.66) is one that varies over a range of voltage (or current) and is proportional to some sensing parameter. The output of an analog photoelectric sensor is proportional to the strength of the received light signal (e.g. OMNI-BEAM analog sensors).

The output of an analog ultrasonic proximity sensor is proportional to the distance between the sensor and the

object that is returning the sound echo (e.g. ULTRA-BEAM 923 Series and some Q45U Series sensors). The output is proportional to the time required for the echo to return to the sensor.

Figure A.62. Digital sensor output.

A "digital" sensor supplies an output that exists in only one of two states: "ON" or "OFF".

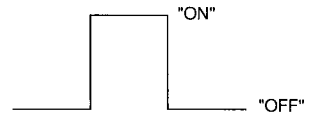


Figure A.63. LIGHT operate vs. DARK operate for an opposed mode system.

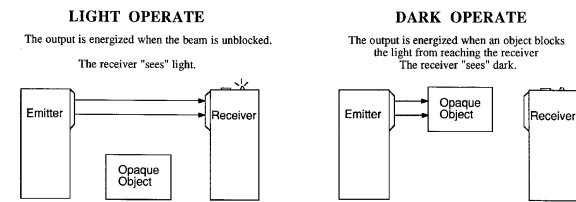


Figure A.64. LIGHT operate vs. DARK operate for a retroreflective mode sensor.

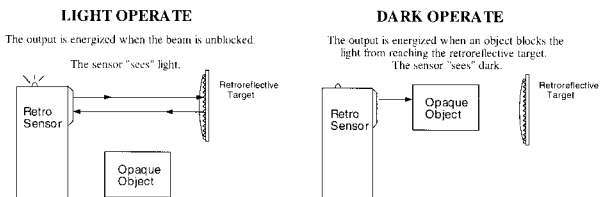


Figure A.65. LIGHT operate vs. DARK Operate for a proximity mode sensor (diffuse, divergent, convergent, and background suppression modes).

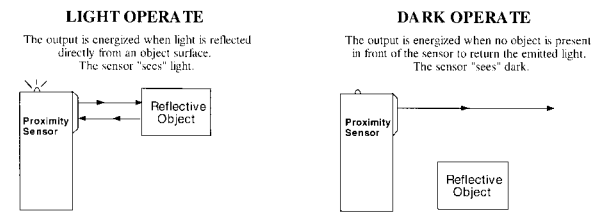
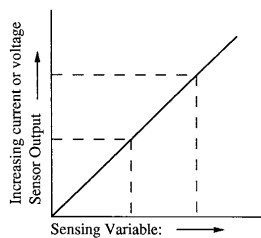


Figure A.66. Analog sensor output: output varies over a range of voltage or current and is proportional to a sensing parameter.



Photoelectric: Increase (or decrease) in received light level
-or-
Ultrasonic: Movement of object toward (or away from) sensor

Sensors with analog outputs are useful in many process control applications where it is necessary to monitor an object's position or size or translucency, and to provide a continuously variable control signal for another analog device, like a motor speed control.

Response Time

Every sensor is specified for its response time. The **response time** of a sensor or sensing system is the maximum amount of time required to respond to a change in the input signal (e.g. a sensing event). It is the time between the leading edge (or trailing edge) of a sensing event and the change in the sensor's output. With a switched output, the response time is the time required for the output to switch from "off" to "on" or from "on" to "off". These two times are not always equal. With an analog output, the response time is the maximum time required for the output to swing from minimum to maximum or from maximum to minimum. Again, these two times are not necessarily equal.

The response time of a sensor is not *always* an important specification. For example, sensors that are used to detect boxes passing on a conveyor do not require fast response. In fact, time delays are sometimes added to extend sensing response to avoid nuisance trips or to add simple timing logic for flow control applications.

Response time does become important when detecting high-speed events, and becomes quite critical when detecting small objects moving at high speed. Narrow gaps between objects or short times between sensing events must also be considered when verifying that a sensor's response is fast enough for the application.

Required Sensor Response Time

The required sensor response time may be calculated for a particular sensing application when the size, speed, and spacing of the objects to be detected are known:

$$\text{Required Sensor Response Time} = \frac{\text{Apparent width of object as it passes the sensor}}{\text{Speed (velocity) of the object as it passes the sensor}}$$

As an example, consider an application in which seed packets on a conveyor are counted by a convergent beam sensor (Figure A.67). The following information is known:

- 1) The seed packets are processed at a rate of 600 per minute.
- 2) The packets are 3 inches wide.
- 3) The packets are equally spaced with about a one inch separation between adjacent packets.

To compute the required sensor response time, the processing rate is first converted to packet speed:

$$600 \text{ packets/minute} = 10 \text{ packets/second}$$

$$\text{Each packet accounts for } 3 \text{ inch (packet width)} + 1 \text{ inch (space)} = 4 \text{ inches of linear travel.}$$

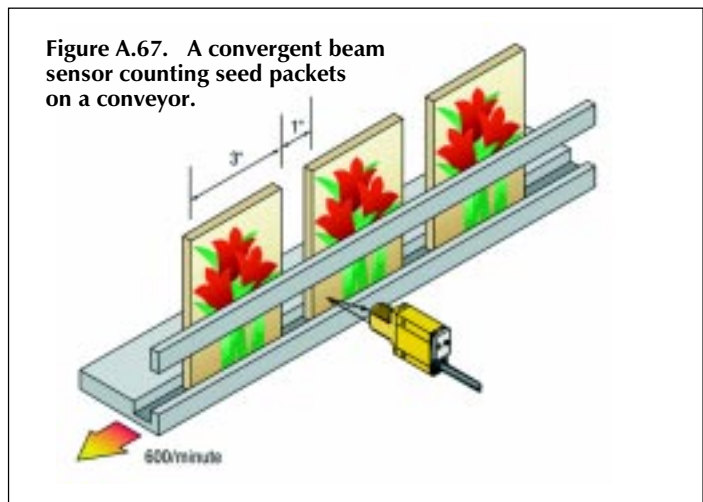
$$\text{Speed of the packets} = 4 \text{ inches/packet} \times 10 \text{ packets/second} = 40 \text{ inches/second.}$$

The time during which a packet is "seen" by the convergent beam sensor is:

$$\text{Time of light condition} = \frac{\text{Object width}}{\text{Object speed}} = \frac{3 \text{ inches}}{40 \text{ in./sec.}} = .075 \text{ seconds} = 75 \text{ milliseconds.}$$

(Time of packet passing the sensor)

In this application, the time between adjacent packets is actually much less than the time during which the sensor "sees" a packet. As a result, it is the dark or "off" time between packets that is the most important to consider when specifying a sensor:



$$\text{Time of dark condition} = \frac{\text{Width of space}}{\text{Object speed}} = \frac{1 \text{ inch}}{40 \text{ in./sec.}} = .025 \text{ seconds} = 25 \text{ milliseconds.}$$

(Time of space between packets)

A sensor with a specified response time of less than 25 milliseconds will work in this counting application. It is always wise to include a safety factor, and to choose a sensor with a response time faster than required.

Response Requirements for Rotating Objects

When sensing a rotating object, the calculation for the required sensor response time is the same. The only additional calculation is conversion of rotational speed to linear speed. For example, calculate the required sensor response time for sensing a retroreflective target on a rotating shaft, given the following information:

- 1) The target is a 1 inch by 1 inch square piece of retroreflective tape on a 3-1/4 inch diameter shaft.
- 2) Maximum shaft speed is 600 revolutions per minute = 10 revolutions per second.

To convert rotational speed to linear velocity:

$$\begin{aligned} \text{Circumference of the shaft} &= \pi \times \text{diameter} = \pi \times 3.25 \text{ inches} = 10 \text{ inches} \\ \text{Linear velocity on shaft circumference} &= 10 \text{ inches/revolution} \times 10 \text{ revolutions/second} = 100 \text{ inches/second.} \end{aligned}$$

The required sensor response time is:

$$\text{Time of light condition} = \frac{\text{Target length}}{\text{Linear speed}} = \frac{1 \text{ inch}}{100 \text{ in./sec.}} = 0.01 \text{ second} = 10 \text{ milliseconds.}$$

(Time sensor "sees" retro tape)

Ten milliseconds is the fastest response requirement in this application, since the untaped portion of the circumference is 9 times longer. A retroreflective sensor with a small effective beam and a response time faster than 10 milliseconds, like a MINI-BEAM model, will reliably sense the tape at the maximum shaft speed. To ease the response time requirement in applications like these that simply require one pulse per revolution (or per cycle), a target should cover 50% of the shaft circumference so that half of the revolution is light time and the other half is dark time.

Response Time Requirements for Small Objects

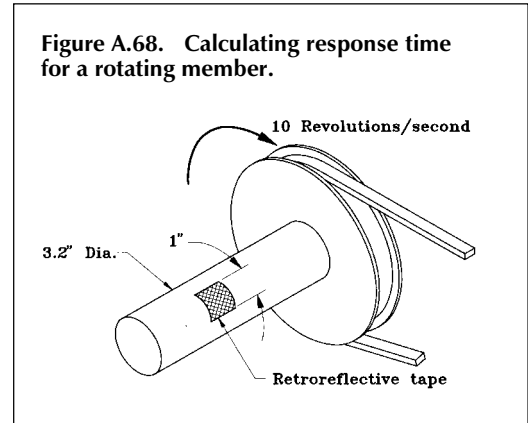
A safe assumption to make when calculating the response time requirement for an object with a small cross section is that the object must fill 100 percent of the sensor's effective beam to be detected. Whenever the size of a small object begins to approach the size of the effective beam, the apparent size of the object as "seen" by the sensor becomes less than the actual width of the object. A safe assumption in these situations is to reduce the apparent size of the object by an amount equal to the diameter of the effective beam at the sensing location. As a result, the required response time decreases:

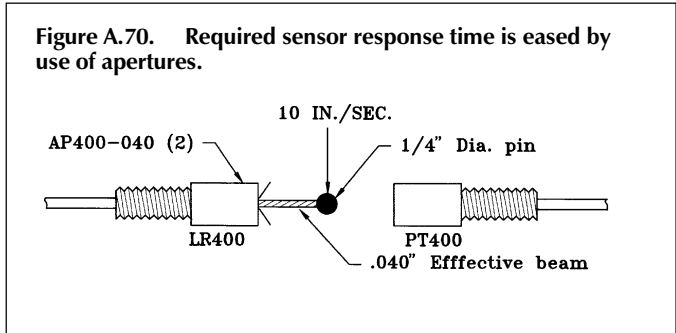
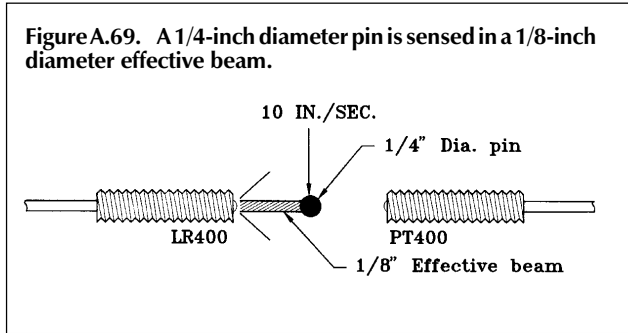
$$\text{Required response time} = \frac{\text{Width of object} - \text{Diameter of effective beam}}{\text{Speed of the object through the beam}}$$

To illustrate the effect of small objects on response time requirements, consider the following example of a small pin that breaks the beam of an opposed sensor pair (Figure A.69):

- 1) 1/4-inch diameter pins pass through the beam of an opposed LR400 emitter and PT400 receiver pair that has a 1/8-inch diameter effective beam.
- 2) The maximum speed of the pins is 10 inches per second.

Computing the required sensor response time:





$$\begin{aligned} \text{Time of dark condition} &= \frac{\text{Pin diameter} - \text{Effective beam diameter}}{\text{Speed of the pin through the beam}} = \frac{.25 \text{ inch} - .125 \text{ inch}}{10 \text{ inches/second}} \\ &= \frac{.12 \text{ inch}}{10 \text{ in./sec.}} = .012 \text{ seconds} = 12 \text{ milliseconds} \end{aligned}$$

The addition of apertures on the LR400 and the PT400 (Figure A.70) will ease the response time requirement because the pin will block the smaller effective beam for a longer time. If the standard AP400-040, .040 inch diameter apertures are used:

$$\text{Time of dark condition} = \frac{.25 \text{ inch} - .04 \text{ inch}}{10 \text{ inches/second}} = \frac{.21 \text{ inch}}{10 \text{ in./sec.}} = .021 \text{ seconds} = 21 \text{ milliseconds}$$

Due to resulting low excess gain, it is usually impractical to aperture an opposed beam to less than about .02 inch. Objects with cross sections smaller than about .03 inch are usually sensed most reliably using one of the proximity sensing modes. The wider the proximity beam, the longer a small part will be sensed. This eases the sensor response requirement. A divergent-beam sensor (e.g. model LP400WB) or a bifurcated fiberoptic sensor are preferred for sensing very small profiles.

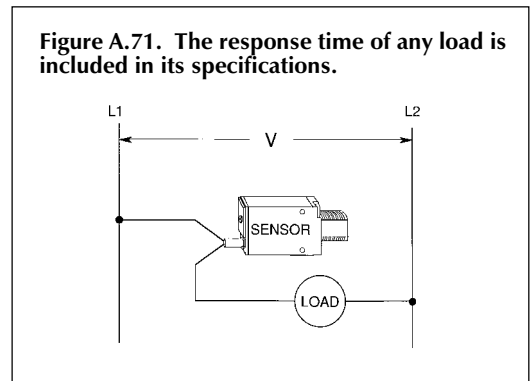
Another possible solution is to use a laser diode emitter paired with a photoelectric receiver. Banner M12 laser diode emitters produce a collimated, apertured laser beam only 2mm in diameter, with a divergence of less than 1 milliradian. Such systems can produce very high excess gain, and are useful for precision sensing in dirty atmospheres.

When sensing narrow gaps, opposed mode sensors should have a wide beam so that light is seen through the gap for a long time. Use of individual fiberoptics with a rectangular termination is one way to shape the effective beam and ease sensor response requirements. When sensing narrow gaps with a proximity sensor, the small effective beam of a convergent mode sensor is usually preferred.

Response Time of a Load

The **response time of a load** is the maximum time required to energize and/or de-energize a particular load, and is included in the load's specifications. In general, solid-state loads like counters and solid-state relays have faster response times than electro-mechanical devices like solenoids and contactors.

The response speed characteristics of any load to be controlled by a sensor's output should be checked to be sure that the duration of the output signal from the sensor and the time between adjacent outputs are both long enough to allow the load to react properly. In situations where the load is too slow to react, a delay timer may be required between the sensor output and the load to extend the duration of the sensor's output signal. An even better solution involves changing the sensing geometry, if possible, to equalize the durations of the light and the dark ("on" and "off") times.



Repeatability of Response

Sensor repeatability is a concern whenever a sensing event triggers a resultant action. This is especially important in cyclical operations that take place at high speed. Application examples include sensors used to trigger glue striping (on box flaps, envelopes, etc.), ink-jet printing (imprinting of product date codes, etc.), and label registration. In each of these examples, repeatability of sensor response is important to ensure consistent product appearance.

Repeatability of response is easily defined for most modulated photoelectric sensors. Today's digital modulation schemes count a defined number of received light pulses before responding to any light signal. This helps the sensor to discriminate between its emitter's light and all other interfering signals.

The number of modulated light pulses counted before the sensor's output is allowed to switch is typically three or four.

The "on" response time

for a modulated sensor is equal to the total amount of time taken for the sensor to count (i.e. demodulate) the required number of pulses. The sensor output changes state as soon as the sensor counts enough light pulses of the correct frequency. However, since the sensing event can occur at any time during a modulation cycle (period), the actual time between the sensing event and the sensor's output change can vary by up to one modulation cycle (see Figure A.72). This variation in sensing response is specified as the sensor's *repeatability*.

The sensor repeatability specification is multiplied by the velocity of the sensed object to define the mechanical repeatability (i.e. the amount of mechanical error) due to the sensor response. For example, while referring to Figure A.67, assume that the sensor shown is triggering an ink-jet printer to imprint a date code on the seed packets. The amount of variation in placement of the printing along the direction of travel is calculated as follows:

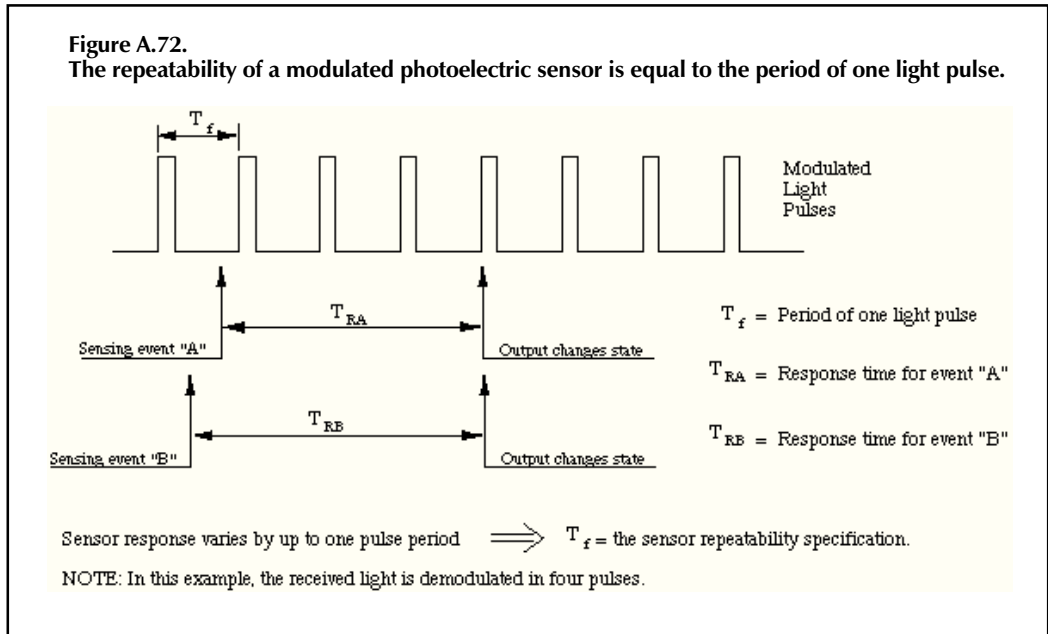
Velocity of seed packets = 40 inches/second

Sensor repeatability = 0.3 milliseconds = 0.0003 seconds (typical value)

Mechanical repeatability = 40 inches/second x 0.0003 seconds = 0.012 inch (due to sensor)

This amount of error in placement of the date code on each seed packet does not take the repeatability of the other control elements into account. Here, the control circuit for the ink-jet printer head and the control circuit for the printer mechanism itself each contribute to the total variation in the location of the imprint.

The sensor's repeatability specification is based on the transition from dark to light. Counting of modulated light pulses is not an issue to consider for each light-to-dark transition. Repeatability for dark-operated outputs is not specified; however, it is a much smaller amount of time than the repeatability specification given for dark-to-light (typically less than 10% of the specified "off" response time). The specified sensor repeatability time is a "worst case" value, which can be relied upon when evaluating applications that involve high speeds, where repeat accuracy is important.



NOTICE: Use of Photoelectric Sensors in Personnel Safety Applications

With the exception of Banner MINI-SCREEN, MICRO-SCREEN, MULTI-SCREEN, MACHINE-GUARD and PERIMETER-GUARD Systems, Banner sensors are NOT to be used for personnel safety applications! Only MINI-SCREEN, MICRO-SCREEN, MULTI-SCREEN, MACHINE-GUARD and PERIMETER-GUARD Systems have the built-in redundant self-checking circuitry necessary for personnel safety applications, so that, even in the unlikely event that a system component does fail, a failure to danger will not occur. Failures in sensors other than MINI-SCREEN, MICRO-SCREEN, MULTI-SCREEN, MACHINE-GUARD and PERIMETER-GUARD can result in *either* an energized or de-energized sensor output condition.

Only MINI-SCREEN, MICRO-SCREEN, MULTI-SCREEN, MACHINE-GUARD and PERIMETER-GUARD Systems meet OSHA and ANSI machine-safety standards for point-of-operation guarding devices. Other Banner sensors do not, and must not be used in personnel safety applications!

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