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## **Abstract**

This paper addresses the basic principles, performance measures and applications associated with laser scanner technologies. The objective of this report is to communicate and disseminate pertinent information related to state-of-the-art laser measurement systems that are currently available through commercial and research means. This paper should serve two-fold: (1) as a basic tutorial to laser scanning technology and (2) as a guide to current manufacturers and researchers of this technology.

## **Disciplines**

Other Computer Sciences

## **Comments**

University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-99-16.

# LASER SCANNER TECHNOLOGY

## Technical Report MS-CIS-99-16

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June 28, 1999

### Abstract

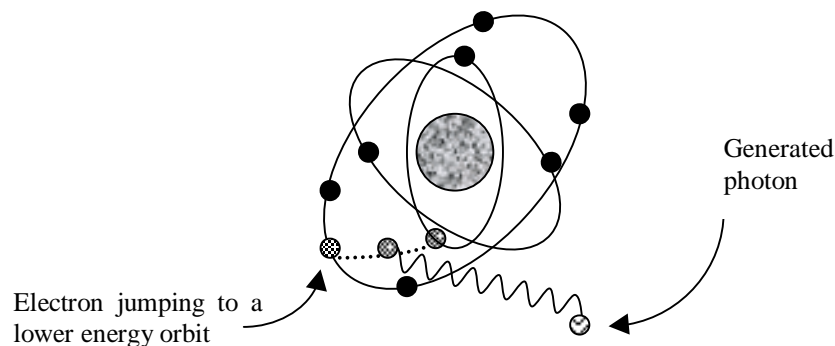
*This paper addresses the basic principles, performance measures and applications associated with laser scanner technologies. The objective of this report is to communicate and disseminate pertinent information related to state-of-the-art laser measurement systems that are currently available through commercial and research means. This paper should serve two-fold: (1) as a basic tutorial to laser scanning technology and (2) as a guide to current manufacturers and researchers of this technology.*

## 1. Optics

### 1.1. Light

#### 1.1.1 Generation of light

An atom is composed of a nucleus, which contains protons, and electrons that are orbiting that nucleus (think of a microscopic solar system). The orbiting electrons can occupy only certain orbits. When energy is added to an atom, electrons jump to a new orbit farther away from the nucleus. The number and choice of electrons that jump, and the size of the jump (how many orbits and which ones) depends on the amount of energy applied to the atom. Conversely, when electrons jump to orbits closer to the nucleus they release energy. One of the most convenient ways to release energy is as a quantum of electromagnetic energy, a *photon*. The energy carried by that photon equals the transition energy. Photons of different wavelengths carry a different amount of energy. (The shorter the wavelength, the higher the amount of energy a photon carries.) Thus, the wavelength(s) of light emitted by an atom depends on the amount of energy associated with each possible electron jump.



**Fig. 1.** Schematic representation of an atom releasing energy in the form of a photon

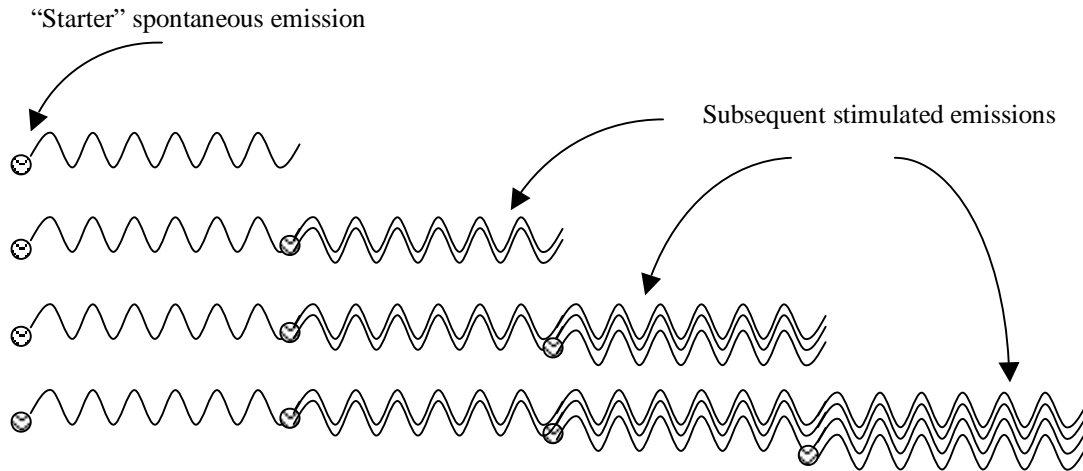
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\* This paper was submitted to Lt. Col. John Blitch as part of the Tactical Mobile Robotics initiative through a MURI grant (ARO #DAAH04-96-0007) funded by the Defense Advanced Research Project Agency (DARPA).

The control of photon emission is critical for lasers. There are two types of emissions: *spontaneous* and *stimulated*. Spontaneous emission occurs all by itself and is the source of virtually all light we see in nature: the sun, the stars, the television monitor, the incandescent as well as the fluorescent bulbs. In spontaneous emission, if the electrons of an atom are in an energy level above the lowest possible one, they can drop to a lower energy level, releasing energy (often in the form of light), without outside intervention. Atoms by default prefer to be in the lowest possible energy state, also known as the ground state.

### 1.1.2 Stimulated emission

In stimulated emission, we start with atoms whose electrons are in a higher energy state. These excited atoms are triggered to release their energy in the form of light. One way of doing that is by shining light on the excited atom. Think of the light that is falling on the atoms as a collection of photons. At least one of these photons carries the same amount of energy, as the one that will be released by an excited atom when it goes to the lower energy state. When that photon hits an excited atom, it will stimulate it to release energy in the form of light. The provoked emission of light has the same wavelength and is precisely in phase with the photon that generated it. In other words, the photon that hits the atom causes the generation of a second identical photon. The new photon will then hit another excited atom causing the release of another photon, which will in turn stimulate a new emission. Thus, the “starter” photon triggers a cascade of stimulated emissions (see Fig. 2). This cascading effect is called **Light Amplification by the Stimulated Emission of Radiation (LASER)**.

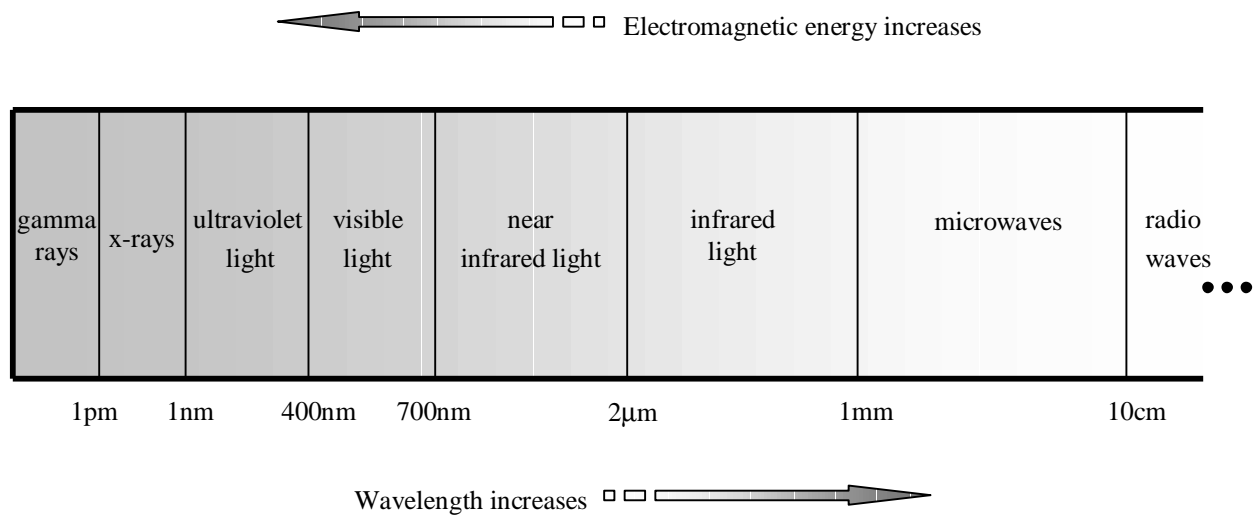


**Fig. 2.** Cascading stimulated emission

As mentioned before, only a portion of the photons that comprise the “starter” light have the proper amount of energy to start the cascading effect. The remaining photons are absorbed and/or converted to other forms of energy, typically heat. The proportion of the photons that have the proper characteristics to trigger stimulated emission is directly related to the efficiency of lasers (for more details see section 4.3.6).

### 1.1.3 Light and electromagnetic waves

Before we proceed further into more details about the behavior of light and lasers, it is important to clarify that, no matter what range of wavelengths we are operating in, we are always talking about electromagnetic waves. Electromagnetic (EM) waves are grouped in different categories according to their wavelength (see figure 3).



**Fig. 3.** The electromagnetic spectrum

Table 1 shows in more detail the various types of electromagnetic radiation. Although the nature of radiation is the same over the whole spectrum, EM waves in one category behave somewhat different from EM waves in other categories. The range of wavelengths that compose the near infrared spectrum (IR) is not clearly defined. Some researchers refer to the range of EM waves between 30mm to 10cm as far IR.

**Table 1.** Types of Electromagnetic Waves

Electromagnetic Waves	Range of Wavelengths	
Gamma rays	< 1pm	or $10^{-12}$ m
X-rays	1pm to 1nm	or $10^{-12}$ m to $10^{-9}$ m
Ultraviolet light	1nm to 400nm	or $10^{-9}$ m to $400 \times 10^{-9}$ m
Visible Light	400nm to 700nm	or $400 \times 10^{-9}$ m to $700 \times 10^{-9}$ m
Near Infrared light	700nm to 2μm	or $700 \times 10^{-9}$ m to $2 \times 10^{-6}$ m
Infrared light	2μm to 1mm	or $2 \times 10^{-6}$ m to $10^{-3}$ m
Microwave	1mm to 10cm	or $10^{-3}$ m to $10^{-1}$ m
Weather Radar	around 10cm	
FM Radio	2.8m to 3.4m	
Short Wave	10m to 100m	
AM Radio	200m to 500m	

## 1.2. Light Propagation

The application of lasers is closely tied with the behavior of light as it travels through various materials. When light is transmitted through gases, liquids, or solids, a combination of the following propagation phenomena takes place:

- **Refraction:** Part of the light falling on a surface propagates through the material. The beam of light changes directions (i.e. bends) at the point of entrance to the new medium (example: light travelling through water). This phenomenon is called refraction. The observed deflections are typically a function of wavelength.
- **Reflectance:** Part of the light falling on a surface is reflected back, away from the surface.
- **Absorption:** Part of the light falling on a surface is absorbed as it propagates through the material. The electromagnetic energy of the beam is converted into other forms, usually into heat.
- **Scattering:** When light falls on particles of random distribution, like smoke or fog particles, it gets diffused in many directions.
- **Polarization:** When light falls on a surface, the plane of oscillation of the light beam may change.

The aforementioned phenomena may alter the intensity, wavelength, direction of propagation, and plane of oscillation of a light beam. Different materials exhibit different combinations of propagation effects. GRASP has a specialized photometry laboratory where researchers study the behavior of light in different materials.

The two phenomena that are of higher interest to us are refraction and reflectance. Refraction is directly related with the speed of light as it travels through various materials. Light travels faster through vacuum (roughly 186,000 miles/sec, or 300,000 kilometers/sec). When light travels through any material, for example air, it slows down to approximately 185,950 miles/sec, or 299,920 km/sec in one atmospheric pressure. An important measure is the *index of refraction*,  $n$ :

$$n = \text{speed of light in vacuum} / \text{speed of light in material}$$

The index of refraction is always larger than 1.0. The wavelength of light,  $\lambda$ , the frequency of the light wave,  $\nu$ , and the velocity by which it travels,  $c$ , are related:

$$\lambda = c / \nu$$

When the light travels through different media, its frequency,  $\nu$ , remains the same. Since the velocity,  $c$ , changes, the wavelength,  $\lambda$ , changes too:

$$\lambda_{\text{material}} = \lambda_{\text{vacuum}} / n_{\text{material}}$$

As a ray of light passes from one transparent medium (for instance, air) to another (for instance, water) it “bends”. The angle of “bending”, called angle of refraction, is directly related to the index of refraction of the two materials. If and when the light passes back out to the first material, the reverse refraction takes place. Depending on the homogeneity of the material and its geometry, the 2nd refraction may not necessarily cancel the first one (for example, prism effect).

Reflectance also alters the direction in which light travels. When light falls on a surface, part of it will be redirected away from the surface. There are two types of reflectance, depending on how the light gets redirected: specular and diffuse. Specular, or mirror-like, reflectance is the type of light that we get reflected from a surface like glass, or polished metals, surfaces that are smooth on the scale of the wavelength of the light. Such smooth surfaces (specular surfaces) reflect the light back in a single direction (just like a mirror does). The direction of the reflected beam depends on the shape of the surface and the direction of the light that fell on the surface. Diffuse reflectance on the other hand is produced by matte surfaces, like a piece of paper, that are rough on the scale of the wavelength of light. The light that is falling on a diffuse surface is scattered in all possible directions. Most surfaces exhibit a combination of diffuse and specular reflectance. All surfaces reflect a portion of the light that is falling on them, unless they are covered by special anti-reflection coatings.

## 2. Lasers

### 2.1. Building a Laser

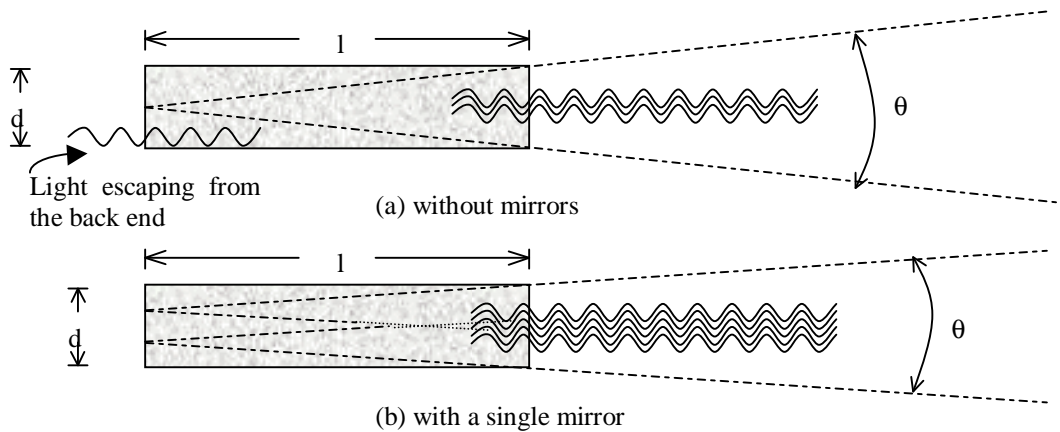
#### 2.1.1 *Population Inversion*

The bottleneck of stimulated emission is that it requires that the majority of the atoms should be in a high-energy state. Unfortunately, this is not the default energy state under thermodynamic equilibrium. Thus, a prerequisite for the generation of Light Amplification by the Stimulated Emission of Radiation (LASER) is that the distribution of atoms be altered so that there are more excited atoms, ready to emit energy, than low-energy atoms, ready to absorb it. The process of altering the energy distribution of atoms so that most of them will be in a high energy state is called population inversion. Lasers did not become a reality, until methods to achieve population inversion became feasible in the 1950s.

The first step is to produce a population inversion by selectively exciting atoms to particular energy levels. The most common laser excitation techniques are light and electrons. In the very first laser, Theodore Maiman used flashlamp pulses to excite the atoms of a red ruby. The resulting laser beam was a pulsed beam of 694nm. Such primitive excitation techniques require an intense burst of energy. Modern lasers use much more complicated excitation methods. Often population inversion creates sublevels of high and low energy levels resulting in lasers that can emit in multiple wavelengths simultaneously (multiline lasers). The medium that is being excited (and frees the photons that collectively form the laser beam) can be a combination of two or more materials, like helium and neon. Through population inversion the laser medium gets excited and is capable of producing stimulated light when it is hit by a photon.

#### 2.1.2 *Light Amplification*

Once the population of a laser material has been inverted, a “starter” photon will trigger a cascade of stimulated emissions. The magnitude of the cascading effect increases sharply with the distance the light travels through the laser material. Thus, in order to build brighter lasers, light is emitted along an elongated rod of laser material. The intensity of the beam can be further increased, by placing mirrors at opposite ends of the laser rod. This forces the stimulated light to travel back and forth between the ends of the rod, increasing the distance the light travels before it exits the laser medium. Figure 4 (adapted from Hecht’s [5] book) shows a schematic representation of a laser’s basic principle of operation.



**Fig. 4.** Stimulated emission in a laser rod

The oscillation of light back and forth in the laser cavity causes the formation of a narrow laser beam. The radius of the beam depends on the length the light has to travel within the laser medium. For example, the light emitted from a laser with no mirrors is concentrated in an angle  $\theta$ , defined by:

$$\theta = \sin^{-1} ((d \times n) / (2 \times l))$$

where  $d$  = rod diameter,  $l$  = rod (cavity) length,  $n$  = index of refraction of the laser material. If a single mirror is used, the diameter of the beam becomes:

$$\theta = \sin^{-1} ((d \times n) / (4 \times l))$$

The goal of these examples is to show the direct effect that mirrors have on the beam diameter. The relationship between the shape of the beam and the number of mirrors, their shape and their position is quite complex. We have glossed over many design details.

The optics used in the laser cavity are related to the wavelength of the laser beam. In general, the mirror(s) used in the back end of the rod reflect all incident light, while the mirror(s) in the front reflect only part of the light and transmit the rest. Both mirrors are usually curved to better focus the beams towards each other.

### 2.1.3 Beam characteristics

The distribution of light intensity is not uniform along the cross-section of a laser beam. Typically, the beam is brighter in the middle with the intensity dropping off gradually at the sides. Another characteristic of the beam is its divergence, i.e. the fact that it spreads out as it moves away from the laser cavity. The angle of divergence,  $\phi$ , depends on the wavelength of the laser,  $\lambda$ , the beam diameter at its source,  $D$ , and the intensity distribution of the beam:

$$\phi = \sin^{-1} (K \times \lambda / D)$$

where  $K$  is a constant near 1.0 that depends on the distribution of light intensity in a cross-section of the laser beam.



### 2.1.4 Wavelength

There are several factors that determine the wavelength a laser emits. Foremost, the emitted wavelength depends on the laser material and its quantum properties. The procedure used in achieving population inversion directly affects the wavelength of the stimulated emission. Finally, the optics of the laser cavity can alter the emitted wavelength by selectively oscillating either just a subset of the stimulated emission wavelengths, or by selecting the emitted wavelength through the inclusion of a prism (or diffraction grating) in the laser cavity.

## 2.2. Laser Types

Depending on the material used as the laser medium, lasers can be grouped in three major categories: gas lasers, solid-state lasers, and semiconductor lasers. Gas lasers form a very big group, partly because it is very easy to test a gas for laser capabilities. They are typically excited via an electric discharge. They range from weak lasers emitting just 0.001 Watts of light, to very powerful ones emitting thousands of Watts. Some emit continuously, while others emit pulses of light. Most gas lasers contain a mixture of gases. Some of the most common gas mixtures can be found in Table 2. An important variant of the gas lasers is far-infrared lasers (emitting between 30mm and 1000mm) that are powered by a shorter-wavelength infrared gas laser beam.

**Table 2.** Gas Lasers

<b>Laser Medium: Gas</b>	<b>Main Wavelength</b>	<b>Other Wavelengths</b>
Nitrogen	337nm	
Helium-Cadmium (He-Cd) – a metal vapor	441.6nm	325nm (UV)
Argon ion – a rare-gas ion	488-514.5nm	351.1nm (UV)
Copper vapor – a metal vapor	511nm	578nm
Gold vapor – a metal vapor	628nm	
Helium-Neon (He-Ne)	632.8nm	543nm
Krypton ion – a rare-gas ion	647.1nm	350.7nm (UV)
Hydrogen fluoride (HF) – a chemical laser	2600-3000nm (IR)	
Deuterium fluoride (DF) – a chemical laser	3600-4000nm (IR)	
Carbon monoxide (CO)	5000-7000nm (IR)	
Carbon dioxide (CO <sub>2</sub> )	9000-11000nm (IR)	

In a solid-state laser (not to be confused with semiconductors) the atoms that emit light are dispersed in a crystal or glassy material that contains many other elements. The solid-state lasers are different from semiconductor lasers, although both are crystalline materials. Solid-state lasers unlike semiconductors are electrically nonconductive. In solid state lasers, the light-emitting material (i.e. chromium, neodymium, cobalt, etc.) is just a dopant added to a compound that acts as a crystalline agent. Typically only 1% of the total laser material is light emitting. Solid state lasers are usually shaped in small diameter rods, about the shape of a short pencil. This shape is ideal for generating a bright laser beam while at the same time dissipating the heat produced from the laser process as efficiently as practically possible. Because solid state lasers are electrically nonconductive, they must be excited optically by light from an external light source, like a flashlight for example. The variety of solid-state lasers is not as big as in gas lasers. Solid state lasers can operate in either pulsed or continuous mode. The most common solid-state lasers can be found in Table 3.

**Table 3. Solid-state Lasers**

<b>Laser Medium: Solid-state</b>	<b>Main Wavelength</b>	<b>Other Wavelengths</b>
Ruby	694.3nm	
Alexandrite – a vibronic solid-state laser	700-830nm (IR)	325nm (UV)
Neodymium-YAG (Nd-YAG) (YAG = Yttrium Aluminum Garnet)	1064nm (IR)	266nm (UV), 355nm (UV) and 532nm
Neodymium-glass (Nd-glass)	1080nm (IR)	1054nm and 1062nm (IR)
Erbium	1540nm (IR)	850nm (IR), 1230nm (IR), 1730nm (IR), 2900nm (IR)

Semiconductor lasers (also known as diode or injection lasers) emit light when current flows through a junction between two semiconductor materials. This family of lasers is the target of most current research in the development of new lasers. Many of the diode lasers, as can be seen in Table 4, operate in the infrared range. It was not until 1988 that the first visible diode lasers became commercially available. The preferred mode of operation is pulsed, because of heat dissipation concerns.

**Table 4. Semiconductor Lasers**

<b>Laser Medium: Semiconductor</b>	<b>Main Wavelength</b>	<b>Other Wavelengths</b>
GaN/SiC	423nm	405–425nm
GaInPAs/GaAs	670-680nm	
GaAlAs/GaAs	720-900nm (IR)	
GaAs/GaAs (pure)	904nm (IR)	
InGaAsP/InP	1000-1700nm (IR)	
PbSnSe – a lead salt diode laser	8000-30000nm (IR)	

There are some additional types of lasers, which are worth mentioning that do not fit in any of the aforementioned categories. The need for tunable wavelength lasers has motivated the creation of dye lasers. They use organic dyes dissolved in liquid solvents as their laser material. Another family of tunable lasers is free-electron lasers. The principle of operation is having a beam of “free” electrons, which are unattached to any atom, pass through a special magnetic field. The movement of the electrons causes the release of light. Finally, there is ongoing work in developing lasers in even shorter wavelengths (x-rays, gamma rays, and nuclear-pumped lasers). In such shorter wavelengths, the physics of electromagnetic rays change and the techniques used to stimulate emission of radiation are very different.

Another important laser classification method is with respect to safety. The highly concentrated beam of light can cause permanent eye damage. All lasers are classified as belonging to one of six possible categories, depending on how hazardous they are (see table 5). The health risk associated with a laser is directly related to the energy output of the laser, which in turn depends on the wavelength, the average output power in Watts, the total energy per pulse, the pulse duration and the pulse frequency.

**Table 5. Laser Classes**

<b>Class</b>	<b>Description</b>
Class I	Not hazardous for continuous viewing, or access to radiation is prohibited.
Class II	Visible light lasers that can cause damage if viewed directly for extended periods of time.
Class IIa	Visible light lasers not intended for viewing. Eye damage can be caused if viewed directly for more than 1000secs (16.67 min).
Class IIIa	Not hazardous if viewed momentarily. Damaging if viewed through collecting lenses.
Class IIIb	Hazardous to eyes and skin if viewed directly.
Class IV	Hazardous to eyes if viewed in any way. Fire hazard. Could cause skin burn.

### 2.3. Laser Light Detection

Many applications of lasers involve the detection and measurement of the light produced by a laser. Special instruments, called for historical reasons *photodiode receivers*, are used in the detection of light. These instruments are made out of special materials (typically semiconductors), which have the ability to convert to electricity the light that is falling on them. The amount of electricity that is generated is directly proportional to the amount of light that is hitting the photosensitive material. Video cameras are an example of such receivers. Different photodetectors are sensitive to different ranges of wavelengths, depending on the material out of which they are made (see Table 6).

**Table 6. Laser Detectors**

<b>Detector Medium</b>	<b>Wavelengths</b>
Silicon	400-1000nm (visible light)
Germanium	600-1800nm (visible and infrared light)
Indium arsenide	1500-3000nm (infrared light)
Lead selenide	1500-6000nm (infrared light)

## 3. Applications

### 3.1. General Applications

Laser technology today is applied in many diverse areas ranging from items we use on a daily basis, to medical and military applications. Lasers have become part of our life. Compact disk (CD) players use lasers, instead of a needle, to “read” the music (or data) stored in a CD. Photocopiers and laser printers use lasers to transfer information to a photoconductive material, which prints the document. Bar code scanners use lasers to illuminate the bar code and read the special stripes. The holograms seen on some credit cards or bank notes are produced using lasers. Telecommunications data is transferred through fiber optic cables in the form of pulses of laser beams.

The speed, precision and resolution of lasers have made them particularly attractive to the medical community. Corrective eye surgery is achieved by quickly and precisely burning the tissue of the lens of the eye, correcting

deformities that cause myopia, astigmatism etc. Lasers can also stop bleeding by penetrating deep in the tissue and coagulating the area. Other types of lasers are used for precise and “clean” incisions. Dermatologists use lasers to remove (potentially) harmful skin blemishes. Lasers are also used for non-invasive diagnosis of tumors. Recently (May 1997) the Federal Drug Administration approved the use of lasers as a replacement to the dental drill.

Similar applications of lasers can be found in the industrial sector, where lasers are employed in cutting, welding, hardening, melting and evaporating. Of particular interest to us (we will explore this topic later in the paper) is the use of lasers in obtaining accurate distance measurements. The collection of such measurements provides information about the three-dimensional shape of an object, which can be used to form high-resolution accurate 3-D models of the objects.

The controlled wavelength and high resolution of lasers make them particularly suitable for spectroscopy, i.e. the analysis of materials through the study of reflectance and absorption of light. (An interesting use of laser spectroscopy is in the field of forensic science for the identification of trace residuals). Other applications of lasers are in interferometric measurements, in optical gyroscopes, in photolithography, in Fourier optics, in laser light shows etc.

### **3.2. Military Applications**

A big percentage of the aforementioned applications were technologies that were initially developed for military purposes. Nowadays, the military is seeking to use off-the shelf laser equipment. To this end, the Ballistic Missile Defense Organization is cooperating with CoreTek in Boston, Massachusetts. CoreTek is selling tunable lasers, called VCSEL (Vertical Cavity Surface-Emitting Laser). The current VCSELs have a "tune range" of 30nm centered on 850nm and 980nm (both near IR). In the next 5-6 months the new VCSEL lasers will be out. They will have a "tune range" of 50nm centered on 1550nm (near IR). The next goal for CoreTek, according to Parviz Tayebati, CoreTek's president, is to expand the "tune range" to 120nm [7]. The tunability feature of these lasers makes them particularly attractive for high-speed local area communications.

The military is also interested in the capabilities of lasers to destroy short and medium-range tactical missiles in the air, before they hit the ground. Lasers are the defense weapons of preference because of their fast re-targeting and the speed by which they can impact projectiles traveling at Mach velocities. The US Navy initiated the work in that area. As a result, in 1989, a Vandal missile, simulating the flight of a cruise missile, was shot down by Miracl. Miracl, which stands for **mid-infra-red advanced chemical laser**, was developed by TRW Inc., of Redondo Beach, California. Currently, the US Navy is funding the development of a high-energy free-electron laser developed at the Thomas Jefferson National Accelerator Facility, a US Department of Energy laboratory in Newport News, Virginia. The latest achievement of research supported by the Office of Naval Research was the creation of a 500W laser emitting at mid IR, 4.9 $\mu$ m, or 4900nm. Lt. Douglas Small, a researcher at the Naval Surface Warfare Center in Dahlgren, Virginia, is actively involved in the development of this free-electron laser.

The US Army Space Command is also interested in using lasers as tactical missiles. They assumed stewardship of the Miracl equipment in 1990. Currently, the US Army and Laser Command is working with researchers in the Lawrence Livermore National Laboratory in Livermore, California. Their goal is the development of a solid-state laser that could be used as a missile. According to George Albrecht [7], a physicist at the laser division of the lab, they are concentrating their efforts in building a near IR, 1.05 $\mu$ m or 1050nm, laser. Since 1996, there is ongoing effort to take the lasers airborne. Boeing in Seattle is working on fitting a laser into a 747-400. Lockheed Martin Missiles and Space in Sunnyvale, California is providing the target acquisition and beam and jitter control for the system. TRW is working on the laser itself, which is again a chemical laser that is emitting in the near IR, at 1.3 $\mu$ m, or 1300nm.

## 4. Laser Measurement Systems

### 4.1. Principle of operation

There are many different ways to use lasers for measuring the distance of an object point to a laser. All of them take advantage of three basic attributes of laser light: unobscured light travels in straight lines; the velocity of light when travelling in space is known; the light produced by a laser is typically only a single wavelength light and is thus easy to detect. There are two traditional approaches in measuring distance with lasers (range-finding): time-of-flight and triangulation.

#### 4.1.1 Time of Flight

The principle behind all time-of-flight (TOF) implementations is to measure the amount of time,  $t$ , a light pulse takes to travel to the object and return. Since the speed of light,  $c$ , is known, it is possible to determine the distance traveled. The object's distance,  $d$ , from the laser would then be equal to approximately one half of the distance the laser pulse traveled:

$$d = c \times t / 2$$

In time-of-flight measuring systems, a scanner typically emits pulses of laser electromagnetic radiation (ER). The emitted radiation is focused to a narrow collimated beam and pointed towards a target object. That object reflects a portion of the pulsed laser ER back to a photosensitive sensor (i.e. a photodiode receiver) that is mounted on the scanner. An internal clock measures the time that elapsed between the transmission and reception of the pulse. A built-in microprocessor performs the aforementioned time-of-flight measurement(s) and reports the distance of the target object relative to the laser scanner. Figure 5 illustrates how a time of flight laser scanner works in block diagram form. For all practical purposes, the angle  $\theta$  in figure 5 is very small and has thus no effect on the accuracy of the TOF distance measurement. The high velocity of light allows TOF scanner to take hundreds, or thousands of measurements per second (rates of 50,000 samples/sec are not unusual). Often, multiple pulses are used and used in a least squares fitting to improve reliability. A variation of TOF is the phase shift method for determining distance measurements. Distance is computed by comparing the phase shift between emitted wavelength and the received light.

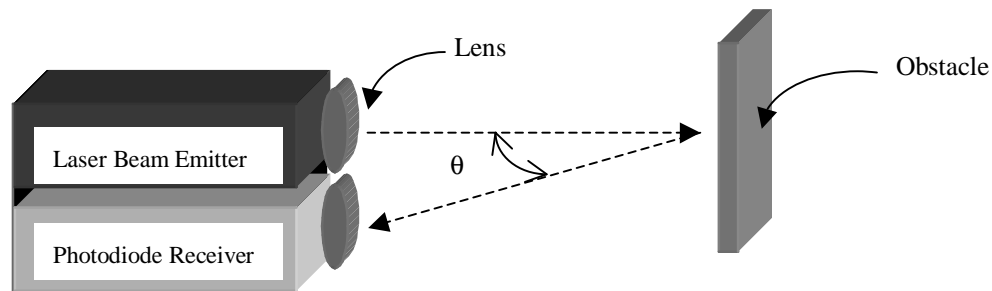


Fig. 5. Time of flight illustration

### 4.1.2 *Triangulation*

The idea behind triangulation is to have two laser beams instead of one. The two beams can be produced by either two separate lasers, or by splitting the beam of a single laser. The two beams intersect at the target object. The position of the two laser sources is known. By measuring the angle formed by the intersection of the two beams, one can compute the distance to the target object. This principle is used with LEDs in autofocusing 35mm cameras. A very common variation of triangulation-based range-finders involves the replacement of one of the laser beams with a video camera.

## 4.2. **Sensor setup and configuration**

### 4.2.1 *2D measurements*

The setups described in the previous section provide distance measurements for a single point. By aiming the scanner setup to a new point on the target object, a second distance measurement to another point of the target can be computed. One can repeat this process multiple times, by pointing the laser scanner at different directions. When all these directions lie on a plane, the collected data provides the two-dimensional profile of the shape of the target object at that plane. The process of altering the position of the laser emitter-receiver setup is done automatically either by mounting the setup on a rotating platform, or, more compactly, through the use of a rotating mirror that can re-aim the emitter-receiver. Such devices are usually called line scanners, since they scan a line, instead of measuring the distance to a single point.

### 4.2.2 *3D measurements*

A natural extension to the 2D scanners is the collection of multiple parallel line scans. After “sweeping” the laser along a plane, we can proceed collecting more data, by “sweeping” the laser scanner along a parallel plane, resulting in the measurement of a second two-dimensional profile. We can proceed in this manner, “sweeping” several planes, one after the other. The stack of two-dimensional profiles generates a 3D model of the target object. Again, this process can be automated through the use of either a rotation stage, or a rotating mirror.

There are commercially available systems (i.e. SICK LMS, Acuity AR4000, and RIEGL LMS-Z210) which include the software that controls the “sweeping” motion, the data capture and analysis, as well as the distance measurement representation. Most of the laser scanners in the market use semiconductor lasers.

## 4.3. **Overview of performance criteria**

### 4.3.1 *Wavelength*

Each type of laser emits a characteristic wavelength or range of wavelengths, depending on the laser material, its optical system and the employed excitation method. Some lasers emit light at different wavelengths under different conditions. For example, helium-neon (He-Ne) lasers typically produce light at 632.8nm. However, under different optics, the same gas mixture emits at 534nm and under yet another set of optics, it can emit in infrared. Other lasers emit in two or more wavelengths simultaneously (multiline lasers).

### 4.3.2 *Output power*

The output power,  $P$ , refers to the strength of the laser beam. It is the amount of light energy produced by the laser per unit of time:

$$P = dE / dt$$

where  $dE / dt$  is the derivative of output energy with respect to time.

As in light bulbs, the output power,  $P$ , is measured in Watts and it varies from mW to kW. It depends on the type of material that emits the light and the emitted wavelength (the shorter the wavelength, the higher the energy carried by the beam).

#### 4.3.3 Duration of emission

Lasers can emit either a steady beam of light, or pulses of light. The duration (or length) of a pulse can range from milliseconds ( $10^{-3}$ sec) to femtoseconds ( $10^{-15}$ sec). The pulses can be repeated once a minute, or even millions of times per second. There are important fundamental relationships among length, energy, repetition rate, and power. For example, the energy per pulse,  $E_p$ , is the integral of the output power over the time duration of the pulse.

$$E_p = \int_{t_1}^{t_2} P(t) dt$$

The pulse energy,  $E_p$ , is measured in Joules. It can be approximated by:

$$\text{Pulse Energy} = \text{Peak Power} \times \text{Pulse Length}$$

The average power in a pulsed laser beam differs from the peak power since it is a measure of the average energy flow per second:

$$\text{Average Power} = (\text{Number of Pulses in time } \Delta t \times \text{Pulse Energy}) / \Delta t$$

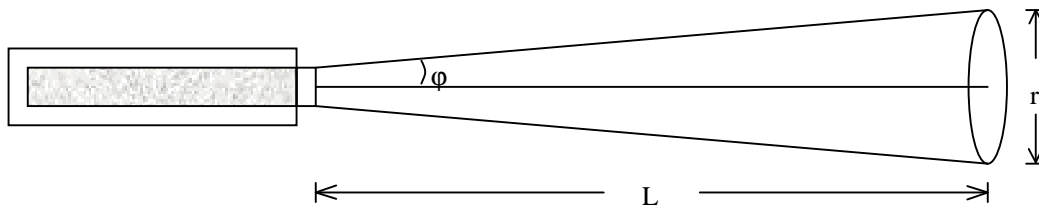
where  $\Delta t$  is the period of time over which we are measuring the average power.

#### 4.3.4 Beam divergence and size

Beam characteristics, such as size, light distribution and divergence, depend on the design of the laser cavity and the output optics. Beam size refers to the diameter of the beam at the point of exit from the laser cavity (see fig. 4). Beam divergence, is a measure of how rapidly the beam is spreading as we move away from the laser (see fig. 6). Divergence is typically measured in milliradians. Beam divergence allows one to calculate the radius of a laser spot:

$$r = L \times \sin(\phi)$$

where  $r$  is the radius of the laser spot,  $L$  is the distance from the laser to the spot and  $\phi$  is the beam divergence.

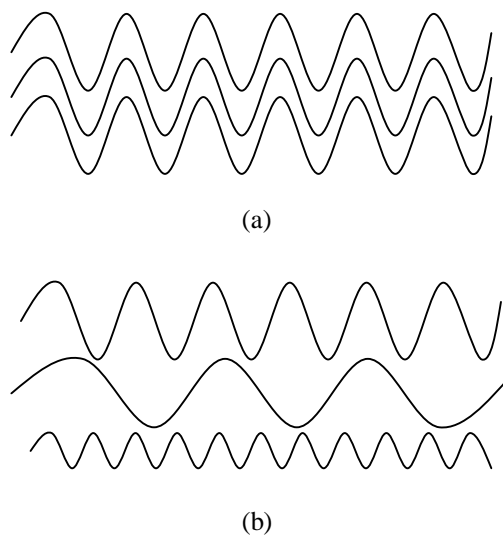


**Fig. 6.** Laser beam divergence

Unlike gas (i.e. He-Ne) and solid state (i.e. Ruby) lasers, which produce an approximately circular beam, semiconductor lasers produce, by construction, an oblong beam. In diode lasers the small size of the laser cavity together with the unusual shape of the emitting area, produce a non-circular beam. The two dimensions, which define the elliptical shape, do not necessarily diverge equally. More complex optics can be added to alter and reduce beam divergence. For example, if a laser is shot through the small end of a telescope, it will have a converging beam over a set distance.

#### 4.3.5 Coherence

Light waves are said to be coherent if they are in phase with one another, i.e. the peaks and valleys are all lined up. Laser light is coherent as opposed to light from the sun, or incandescent or fluorescent light. Monochromatic light need not be coherent, but light that is not monochromatic can not stay coherent over long distances.



**Fig. 7.** (a) Coherent versus (b) Non-coherent light

#### 4.3.6 Efficiency and power requirements

Lasers convert input energy, usually electricity, to light energy. Typically, only 20% of the input energy is converted to light. Some lasers are quite inefficient converting only 0.01% or even 0.001% of the input energy to light. Usually, the remaining energy is dissipated as heat.

## 5. Available Systems

### 5.1. Commercial

Commercially available laser scanner systems are rather limited. Laser scanners are sometimes called laser RADAR (**R**adio **D**etection and **R**anging) systems, since they provide similar information to RADAR but via laser means. Another commonly used term is LIDAR, which stands for **L**ight **D**etection and **R**anging. Table 7 summarizes selected laser scanner manufacturers by product, applications and some general specifications.



**Table 7. Laser Scanner Systems**

<b>Vendor</b>	<b>Product</b>	<b>Application(s)</b>	<b>Specifications</b>
Acuity Research www.acuityresearch.com	AccuRange Line Scanner and AccuRange 4000 Distance Measurement Sensor	Scans and collects distance data over a full circle. High-speed interface available.	<ul style="list-style-type: none"> <li>• 780nm (near IR) laser</li> <li>• 0.25mm resolution</li> <li>• 0 to 165m range</li> <li>• <math>\pm 2.5</math>mm accuracy</li> <li>• Class I laser</li> <li>• Highest resolution</li> </ul>
RIEGL Laser Measurement Systems www.riegl.co.at	LMS-Z210	Scene acquisition for virtual reality modeling applications, 3D imaging of buildings, topographic mapping, and dimensional measurements.	<ul style="list-style-type: none"> <li>• 900nm (near IR) laser</li> <li>• 25.4mm resolution</li> <li>• 0.5 to 300m range</li> <li>• <math>\pm 25.4</math>mm accuracy</li> <li>• Class I laser</li> <li>• Last Pulse feature (see section 6.2.2)</li> </ul>
RMD Radiation Monitoring Devices www.rmdic.com	Laser RADAR (in research stage)	3D imaging of surroundings, measurement of objects.	<ul style="list-style-type: none"> <li>• 900nm (near IR) laser</li> <li>• N/A resolution</li> <li>• 0 to 410m range</li> <li>• N/A accuracy</li> <li>• Class I laser</li> <li>• One line at a time</li> </ul>
SICK Optic-Electronic www.sickoptic.com	Laser Measurement System (LMS) Scanner	For measurement of objects and position determination, monitoring areas and vehicle guidance and collision control.	<ul style="list-style-type: none"> <li>• Near IR laser</li> <li>• 10mm resolution</li> <li>• 0 to 30m range</li> <li>• <math>\pm 15</math>mm accuracy</li> <li>• Class I laser</li> <li>• Used in Antarctic exploration</li> </ul>

Systems that provide a single distance measurement (i.e. range-finders) are much more common. These systems do not scan an environment. They are designed to measure distance when aimed at a particular object. All the vendors presented in Table 7 carry laser range-finders as well, since range-finders are just “stripped-down” versions of laser scanners. Table 8 shows some additional commercial companies that market laser distance meters.

**Table 8.** Laser Range-finders

<b>Vendor</b>	<b>Product</b>	<b>Application(s)</b>	<b>Specifications</b>
Gateway Information Systems Inc. <a href="http://www.inetex.com/gateway">www.inetex.com/gateway</a>	Impulse	GIS/GPS mapping, timber cruising, utility/asset mapping, mine face profiling, space planning, landscape design, traffic engineering, construction site measurements.	<ul style="list-style-type: none"> <li>• Up to 500m range</li> <li>• <math>\pm 40</math>mm accuracy</li> <li>• Class I laser</li> <li>• Handheld</li> </ul>
Laser Measurement Inc. <a href="http://www.lasertech.com">www.lasertech.com</a>	SharpShot 2000	Surveying, general measurement, forestry, utility/asset mapping, mining, speed enforcement, GIS/GPS mapping	<ul style="list-style-type: none"> <li>• 900nm (near IR) laser</li> <li>• Class I laser</li> <li>• Handheld</li> </ul>
Swarovski Optik K.G. <a href="http://www.tyrol.at/optik/birding/sona_brf.htm">www.tyrol.at/optik/birding/sona_brf.htm</a>	RF-1 Laser Range Finder	Birding	<ul style="list-style-type: none"> <li>• Up to 1000m range</li> <li>• <math>\pm 1</math>m accuracy</li> <li>• Class I laser</li> <li>• Handheld</li> </ul>

## 5.2. Research

As it can be seen from Table 8, laser range-finders are very widely applicable, ranging from Global Positioning Systems (GPS) to pass-times like birding. Laser scanners on the other hand are quite sophisticated systems that are mainly used as an aid to autonomous navigation systems. Table 9 lists some researchers that are using laser RADAR in their robotics research.

**Table 9.** Researchers using Laser Scanners

<b>Institution/Organization</b>	<b>Contact</b>
NASA Jet Propulsion Laboratory Machine Vision and Tracking Sensors Group <a href="http://robotics.jpl.nasa.gov/groups/mvts/homepage.html">robotics.jpl.nasa.gov/groups/mvts/homepage.html</a>	Larry Matthies <a href="mailto:Larry.matthies@jpl.nasa.gov">Larry.matthies@jpl.nasa.gov</a>
Oak Ridge National Laboratory <a href="http://www.ornl.gov">www.ornl.gov</a>	Lynne Parker <a href="mailto:ParkerLE@Ornl.gov">ParkerLE@Ornl.gov</a>
SRI International <a href="http://www.sri.com">www.sri.com</a>	Kurt Konolige <a href="mailto:Konolige@ai.sri.com">Konolige@ai.sri.com</a>
Stanford University Autonomous Observers Stanford CS Robotics Lab <a href="http://underdog.stanford.edu">underdog.stanford.edu</a>	Jean-Claude Latombe <a href="mailto:Latombe@cs.stanford.edu">Latombe@cs.stanford.edu</a>
Yale University <a href="http://www.cs.yale.edu">www.cs.yale.edu</a>	Darius Burschka <a href="mailto:Burschka@cs.yale.edu">Burschka@cs.yale.edu</a>

Locating research on laser scanning systems has proved to be a difficult task. Most of the research that is currently being performed relates to the laser technologies themselves and their possible applications. Table 10 summarizes those institutions, which appear to be pursuing research related to laser scanner technologies.

**Table 10.** Laser Scanner Research

<b>Institution/Organization</b>	<b>Research Area</b>
AFIT C3EM Research Team <a href="http://www.afit.af.mil/Schools/EN/ENG/LABS/C3EMRT/c3emrt.htm">www.afit.af.mil/Schools/EN/ENG/LABS/C3EMRT/c3emrt.htm</a>	<ul style="list-style-type: none"> <li>• Command, Control, Communications, Electromagnetic, and their applications to solving problems on the modern battlefield</li> </ul>
Carnegie Mellon University's Robotics Institute, University of Pittsburgh, and NASA Ames Research Center <a href="http://www.ri.cmu.edu">www.ri.cmu.edu</a>	<ul style="list-style-type: none"> <li>• SICK Laser Scanners/Mobile Robots</li> </ul>
NASA Goddard Space Flight Center (GSFC), Laboratory for Terrestrial Physics (LTP), Laser Remote Sensing Branch (LRSB) <a href="http://denali.gsfc.nasa.gov/research/laser/rascal">denali.gsfc.nasa.gov/research/laser/rascal</a>	<ul style="list-style-type: none"> <li>• RASCAL – RASter Scanning Airborne Lidar</li> </ul>

Table 11 lists some major research organizations and their research areas. This table is by no means comprehensive, but it does show the diversity of research currently being pursued.

**Table 11.** Laser Research

<b>Institution/Organization</b>	<b>Research Area</b>
American Institute of Physics <a href="http://www.aip.org/physnews/graphics/html/lfission.htm">www.aip.org/physnews/graphics/html/lfission.htm</a>	<ul style="list-style-type: none"> <li>• Laser-Induced Fission</li> </ul>
Beckman Laser Institute & Medical Clinic <a href="http://www.bli.uci.edu/research/reseacrh.html">www.bli.uci.edu/research/reseacrh.html</a>	<ul style="list-style-type: none"> <li>• Mechanisms of Light Interaction with Biological Systems</li> <li>• Use of Light to Study Fundamental Problems in Cell Biology</li> </ul>
Center for Laser and Photonics Research <a href="http://www.okstate.edu/laser-center/clr_main.html">www.okstate.edu/laser-center/clr_main.html</a>	<ul style="list-style-type: none"> <li>• THz Optoelectronics and Ultrafast Laser Science</li> <li>• Preparation and Laser Processing of Optical Materials</li> <li>• Laser and Nonlinear Systems</li> <li>• Solid State Laser Materials for Remote Sensing Applications</li> <li>• Optical Device Modeling</li> </ul>
Coherent Technologies, Inc. And CLR Photonics, Inc. <a href="http://www.ctilidar.com">www.ctilidar.com</a>	<ul style="list-style-type: none"> <li>• Weather/Particle Detection</li> </ul>

Heriot-Watt University <a href="http://www.phy.hw.ac.uk/resrev/HighP.html">www.phy.hw.ac.uk/resrev/HighP.html</a>	<ul style="list-style-type: none"> <li>• High Power Pulsed IR/UV</li> </ul>
Kyushu University, Institute for Ionized Gas and Laser Research <a href="http://denrisv.ence.kyushu-u.ac.jp/www-ion">denrisv.ence.kyushu-u.ac.jp/www-ion</a>	<ul style="list-style-type: none"> <li>• Laser Aided Plasma Diagnostics (LAPD)</li> </ul>
Lawrence Livermore National Laboratory <a href="http://lasers.llnl.gov/lasers">lasers.llnl.gov/lasers</a>	<ul style="list-style-type: none"> <li>• Inertial Confinement Fusion (ICF)</li> <li>• Atomic Vapor Laser Isotope (AVLIS)</li> <li>• Strategic Materials Applications Program (SMAP)</li> <li>• Advanced Microtechnology</li> </ul>
Laser Research Center, Russian Academy of Sciences <a href="http://www.infoline.ru/g23/9749/nict1/activity_1.html">www.infoline.ru/g23/9749/nict1/activity_1.html</a>	<ul style="list-style-type: none"> <li>• Laser Materials Processing</li> <li>• Industrial Lasers</li> <li>• Laser Microtechnologies</li> <li>• Laser Biomedicine</li> </ul>
Lasers Research Group – University of Hull <a href="http://www.eng.hull.ac.uk/AP/lasers/lasers_homepage.html">www.eng.hull.ac.uk/AP/lasers/lasers_homepage.html</a>	<ul style="list-style-type: none"> <li>• Laser Ablation, Patterning and Annealing</li> <li>• Medical Applications of Lasers</li> <li>• Laser Ablation Deposition and Patterning of Films</li> <li>• Laser Generated Ultrasound and Non-Destructive Testing</li> </ul>
University of California, Irvine <a href="http://www.eng.uci.edu/ferro.htm">www.eng.uci.edu/ferro.htm</a>	<ul style="list-style-type: none"> <li>• Ferroelectric &amp; Laser Research</li> </ul>
University of Victoria <a href="http://www.me.uvic.ca/~cbr/fibrelaser.html">www.me.uvic.ca/~cbr/fibrelaser.html</a>	<ul style="list-style-type: none"> <li>• Fiber Lasers for Sensors and Telecommunications</li> </ul>
Xerox PARC <a href="http://www.xerox.com">www.xerox.com</a>	<ul style="list-style-type: none"> <li>• Blue lasers</li> </ul>

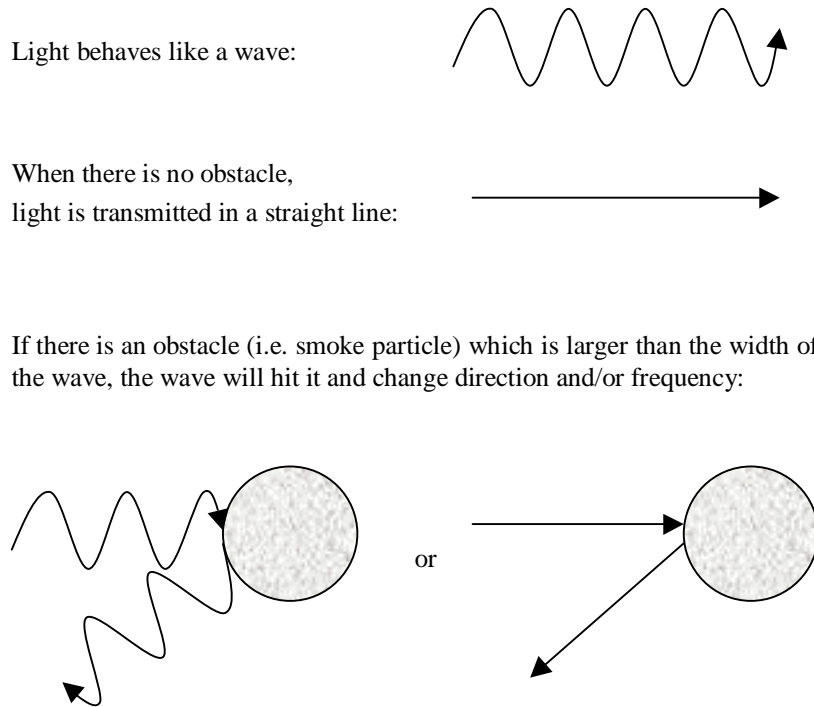
## 6. Atmospheric Obscurants

### 6.1. Obscurants

All laser measurements systems assume that part of the light that is emitted by the laser will be reflected back to the sensor. Different materials reflect different percentages of the light that is falling on them. The higher the percentage of light that a material reflects, the stronger the signal that is “bounced” back to the receiver of the laser scanning system. It is possible that the light that is reflected back is not strong enough to be detected. It is also possible that poor visibility conditions (smoke, fog) can cause the light to scatter or to cease travelling in straight paths. In these cases the basic assumptions/principles of the laser measurement systems are violated, and the distance computations become invalid.

Many commercial systems handle the “weak signal” problem by amplifying the light that falls on the receiver. The problem of atmospheric obscurants is more difficult to compensate for. Fine particles in the air, like those that compose smoke, snow, rain or fog, cause the narrow laser beam to scatter. As the photons that compose the laser beam hit a particle of smoke, they may get absorbed or refracted (i.e. the direction of the path, along which

the photon was travelling, got altered). It is almost impossible to precisely calculate (and thus correct) how smoke or fog will affect the laser beam. The type of the smoke (size of smoke particles, chemical composition, optical behavior of the particles) as well as the density and distribution of the obscurant directly affect how the laser beam will be altered.



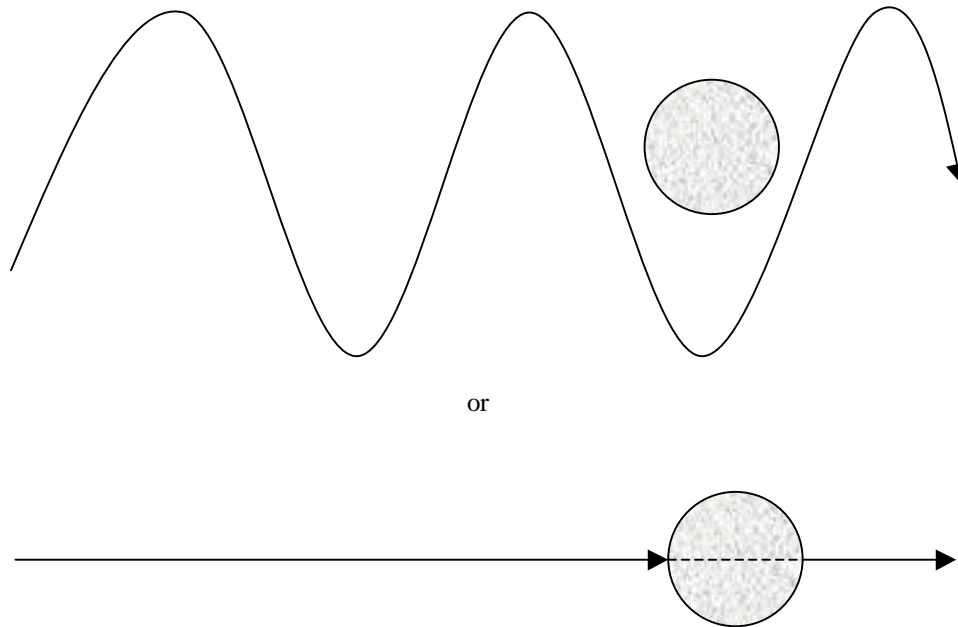
**Fig. 8.** Schematic representation of the smoke particle problem

## 6.2. Potential Approaches

### 6.2.1 Longer Wavelength

One possible solution to the atmospheric obscurants problem is to try to “bypass” the interfering particles. This can be achieved by using laser scanners that emit laser at longer wavelengths. Intuitively, once can imagine that at longer wavelengths (i.e. larger waves) the waves should be able to move around the particles (see figure 8). Autonomous vehicles used in mining operations already use this solution. These vehicles have to operate in all types of weather and in a very dusty environment. Their distance measurement system uses electromagnetic waves, which are 5 to 6 orders of magnitude longer than most lasers, i.e. they are in the mm (microwave) range [3]. Lasers can be made to emit in the millimeter range. The basic principles of lasers are valid through much of the electromagnetic spectrum. In fact, the first stimulated emission was in the microwave range of the electromagnetic spectrum.

At longer wavelengths, the light will “go through” the obstacle, as long as its wavelength is longer than the size of the obstacle:



**Fig. 9.** Schematic representation of the “bypassing” solution

The concept of using longer wavelengths to see through smoke is already being used by firefighters nationwide. They use infrared “night vision” goggles to navigate through rooms filled with smoke. The type of products they use can detect and display electromagnetic waves up to 0.14mm, or 14000nm (mid to far IR). For example, NightSight, a product of Raytheon in Lexington, Massachusetts, is advertised as being weather proof in detecting IR emissions.

### 6.2.2 Last Pulse Signal

Some commercially available laser measurement systems (i.e. RIEGL) have addressed the visibility problem by using the *last pulse* technique. The idea behind last pulse systems is that the distance meter provides the measurement from the very last target its beam hit. The assumption is that as the beam travels through smoke it will hit the smoke particles before reaching the desired target. The last strong signal that will bounce back will be the one coming from the true target and not the smoke particles. Initial testing by RIEGL of this technique with simulated snowfall was very promising. One concern of this practical solution is that the beam reflected from the target may be scattered on its way from the target to the receiver.

### 6.2.3 Donut Solution

Another possibility that has not been implemented yet is to use a powerful laser to burn through the obscurant. The laser beam used by the measuring system will be engulfed in a torus (i.e. donut) shaped beam that is capable of burning through the smoke. A high-energy laser beam that is hollow in the middle will be continuously emitted. Such a laser beam will create a tunnel of clean, unobscured path. The pulsed laser beam of a standard laser measurement system will then travel through that tunnel.

### 6.2.4 Coherent vs. non-coherent light

A more theoretical solution is to take advantage of the unique nature of laser light. As mentioned before, laser light is coherent. However, the repeated scattering caused by the beam bouncing around in the smoke will make the light non-coherent. A test for light-coherence will allow the measuring system to discriminate between a valid signal that has not been altered by smoke, and a signal that has undergone multiple scattering.

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