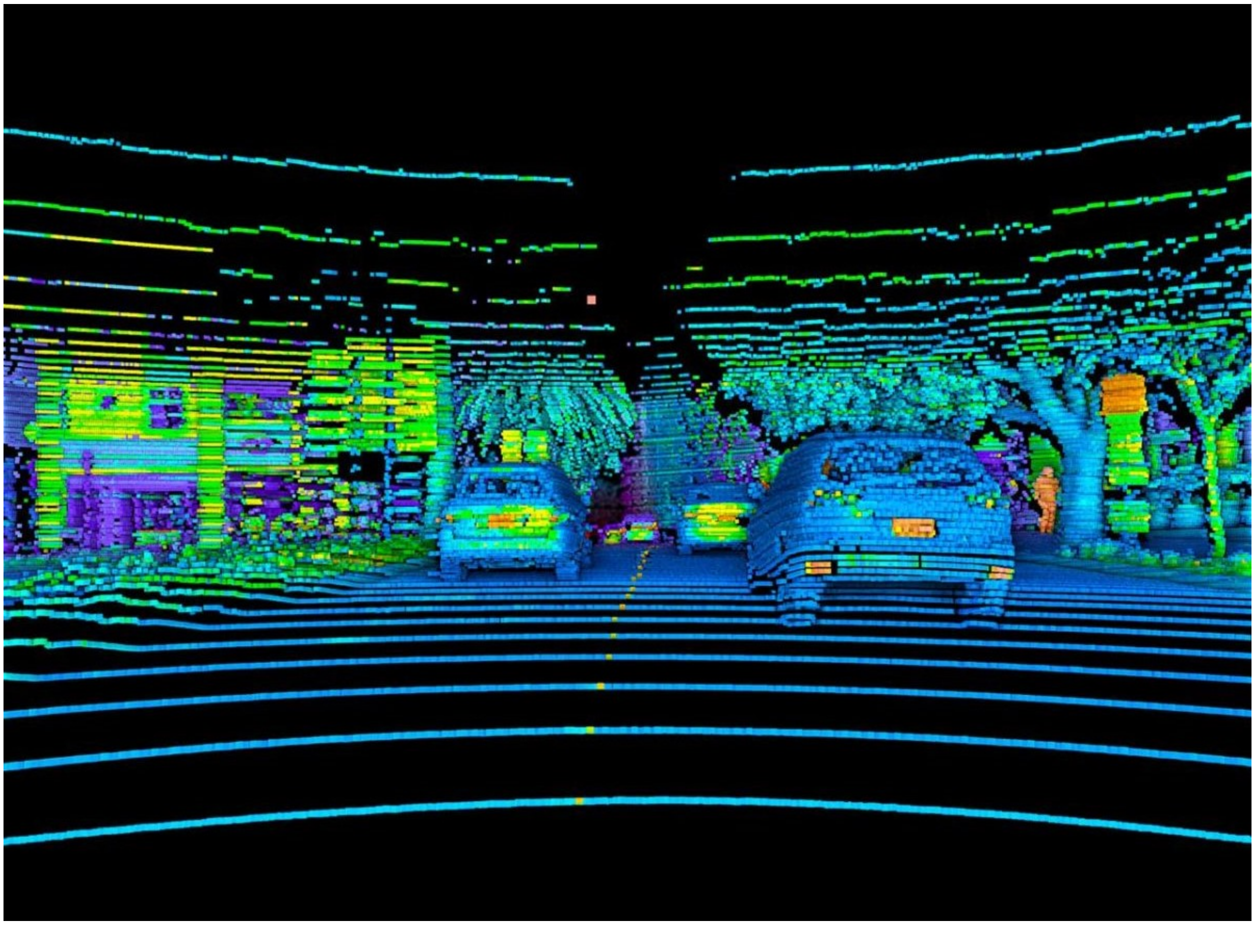
Fundamentals of Lidar Technologies



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Introduction

Light Detection and Ranging (Lidar) is a technology that uses laser beams reflected from objects to determine the distance between the laser source and the object. Lidar is analogous to the well-known Radar, but instead of microwaves it uses lightwaves to determine the object's characteristics. As the wavelength of light is smaller than the wavelength of the microwaves used by Radar, Lidar is capable of much higher resolution, which enables the creation of images that can be analyzed by computers.

Lidar has been around for more than 50 years, being first used by the military in rangefinders and weapons guidance systems. In recent years, the interest in Lidar has increased substantially, due to its envisioned wide scale application in autonomous vehicles and industrial robotics. Lidar has many areas of application including aerospace, agriculture, archaeology, construction, smart cities, security, wind farms, medical and pharmaceutics, and many more. As the cost of Lidar continues to decrease, it is expected that Lidar will be integrated into a wide range of machines, such as putting Lidar in intersections to monitor traffic, security systems to protect property, and many other applications.

Lidar has several advantages over other sensors such as Radar and cameras. It has higher spatial and angular resolution than Radar, is capable of 3D object detection at long sensing distance, performs well in harsh environmental and light conditions, and can be used in day time as well as during the night. More than 100 companies around the world are developing Lidar systems today, about half of these in North America.

Learning Outcomes

After studying this module, you will be able to:

- Describe the principle of operation of Lidar
- Identify the basic components of a Lidar
- Classify different types of Lidar
- Describe performance characteristics of different types of Lidar
- Describe various applications of Lidar

Pre-requisites: algebra, geometry, introductory light and lasers course

1. History of Lidar

Lidar started to be developed in the 1960's, soon after the invention of the laser. The first Lidar applications developed in the US were for military uses. They included laser rangefinders, altimeters, and designators. Laser rangefinders operate on the time-of-flight (TOF) principle, which is used by most Lidars. In laser rangefinders a laser beam and a single detector are used to find the distance to a target based on the time it takes for the light beam to reflect off the target and return to the detector. By knowing the time and the speed of light we can calculate the distance to the target, or the range. Due to the short wavelength of light, the range can be obtained with high resolution even for very large distances.

Different lasers have been used historically as light sources in Lidar. The ruby laser was used in the visible region ($\lambda = 694$ nm), Nd:YAG for the near infrared region ($\lambda = 1064$ nm), and CO_2 laser for the far infrared region ($\lambda = 10.6$ μm). A high power laser is needed when measuring very large distances, to compensate for the loss of power in the beam by the time it returns to the detector. In 1969, NASA Goddard Space Flight Center in Maryland was able to measure the distance to the Moon with a high accuracy around 3 cm, using a 60 J/pulse ruby laser. This took place in conjunction with the Apollo 11 mission to the Moon the same year, where astronauts placed a retroreflector on the surface of the Moon that reflected the ruby laser beam back to Earth. The Apollo 15 mission in 1971 once again used a Lidar, this time to map the surface of the Moon.

A Lidar altimeter uses the same principle as a rangefinder, but it includes multiple light beams and multiple detectors. The instrument can measure a surface's slope and roughness as well as its reflectivity. Starting in the 1970's, Nd:YAG became the preferred laser used in rangefinders and designators.

The next Lidar devices, developed in the 1970's, belong to the class of coherent Lidar. These Lidar devices are able to measure both the amplitude and phase of the light by mixing the received light signal with light from an optical local oscillator, in a scheme called heterodyne detection. This capability allows for imaging applications, and they are also capable of measuring a target's velocity in addition to the target's distance.

Coherent Lidar was developed for airborne applications, including ground imaging, obstacle avoidance, terrain following, and wind sensing. The first 3D image obtained with a Lidar dates from 1983 and was obtained using a CO_2 laser. Wind sensing has an important application in air travel, where it can detect turbulence ahead of an airplane and wind hazards around airports. Raytheon developed a CO_2 based Lidar for wind sensing and tested it for the first time in 1970. In later wind sensing Lidars the CO_2 laser was replaced by solid state lasers, such as Nd:YAG and more recently fiber lasers. Systems such as these can be used from ground, air or space.

The 1980's and 1990's saw the maturing of Lidar technology with the emergence of new applications. Lidars were launched into space and used in space shuttle damage detection sensors, guidance systems for landing and docking, and even mapping of a comet's surface. In parallel to the military applications, environmental applications of Lidar were developed. These applications focus on learning more about the composition of the atmosphere and of the oceans.

In the early 2000's a new application of Lidar emerged, to help a self-driving car navigate a course by creating a map of the car surroundings. The Grand DARPA Challenge, a prize competition for American autonomous vehicles, started in 2004 with a 120-mile course through the Mojave Desert. The Grand Challenge took place for a second time in 2005, and then again in 2007 as the DARPA Urban Challenge. The sensor invented by David Hall for the 2005 Grand Challenge race became the foundation for the modern Lidar used today to create accurate 3D maps of the environment. By 2007, a majority of the competing vehicles used 3D Lidar sensors to map their surroundings.

The use of Lidars in self-driving cars is likely to be the first widespread commercial application of Lidar. This is enabled by Lidar devices becoming smaller, lighter and cheaper. At the same time, Lidar is finding more applications in medicine. One example is in optical low-coherence tomography used for eye investigation and 3D reconstruction. Other fields of application rely on Lidar capabilities to penetrate dense media such as vegetation and handle diverse kinds of weather. New applications are expected to emerge as this versatile technology continues to mature.

Self-Test

1. What does Lidar stand for?
    a. Light Index Developed Against Radiation
    b. Light Detection And Ranging
    c. Light Is Determined And Ready
    d. Laser Is Detrimental And Required
2. Lidar has better resolution that Radar due to:
    a. Higher cost
    b. Use by the military
    c. Lower wavelength of lightwaves compared to microwaves
    d. Higher power

3. The first applications of Lidar did not include:
    a. Rangefinders
    b. Altimeters
    c. Imaging
    d. Designators
4. In early Lidar one of the first laser sources used was a:
    a. Ruby laser
    b. Diode laser
    c. Fiber laser
    d. Excimer laser
5. A widespread commercial application of Lidar is expected to be:
    a. Measuring the distance to the Moon
    b. Wind sensing
    c. Measuring the composition of the atmosphere
    d. Self-driving cars

2. Lidar Principle of Operation

Lidar is an *active optical sensor* that has its own light source, usually a laser to take advantage of features such as coherence and small beam divergence. By contrast *passive optical sensors* such as cameras rely on solar radiation as the source of light rather than their own light source. In Lidar the laser light is directed towards the target, and a photodetector is used to detect the light reflected by the target.

Most Lidars operate based on the time-of-flight (TOF) principle. By measuring the time it takes for the emitted light to travel to the target and be reflected back to the detector, the device determines the distance to the target. The TOF principle is illustrated in the figure below.

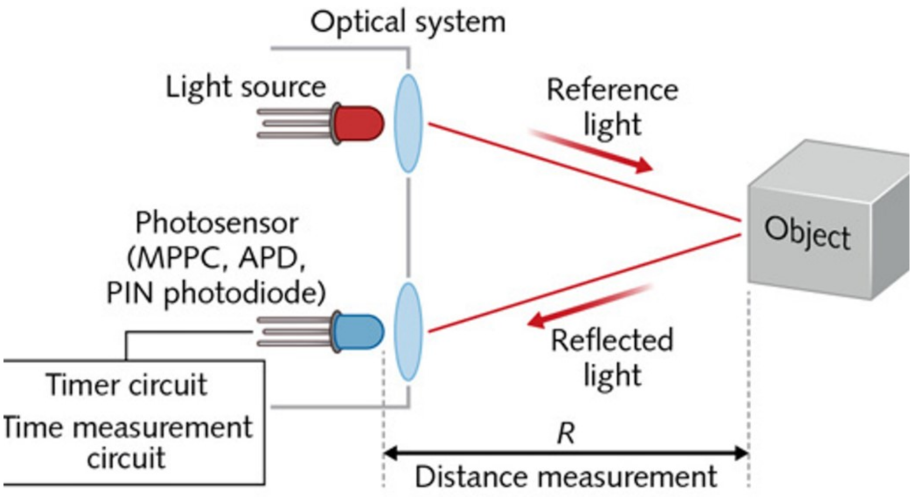


Fig. 1. Time-of-flight principle illustration. From Ref. [7].

Using the known value of the speed of light it is easy to relate the round trip travel time to the distance to the target, also called range, as shown in the equation below:

$$R = \frac{ct}{2} \qquad (1)$$

where R is the range in meters, $c = 3 \times 10^8$ m/s is the speed of light in vacuum or air, and t in seconds is the measured time interval between light being emitted from the light source and the reflected light being detected by the photodetector.

The distances measured by Lidar can range from around 1m to hundreds of meters. For automotive applications a desired typical range is 150 m to 200 m. If we assume a 150 m distance to the target, the round trip time t is given by:

$t = 2R/c = 2*150\ \text{m}/(3 \times 10^8\ \text{m/s}) = 1 \times 10^{-6}\ \text{s} = 1\ \mu\text{s}$ (2)

With such a short round trip time it is possible to make a very large number of distance measurements very quickly. For example in 1 second we can make $1/(1 \times 10^{-6}) = 1{,}000{,}000$ different distance measurements, provided we change the direction of the laser beam to scan over the target object during this time. This way a 3D map of points can be created in a very short time. This collection of points forms what is called the *3D point cloud image*. The point cloud provides spatial location and depth information to identify, classify and track moving objects in real-time.

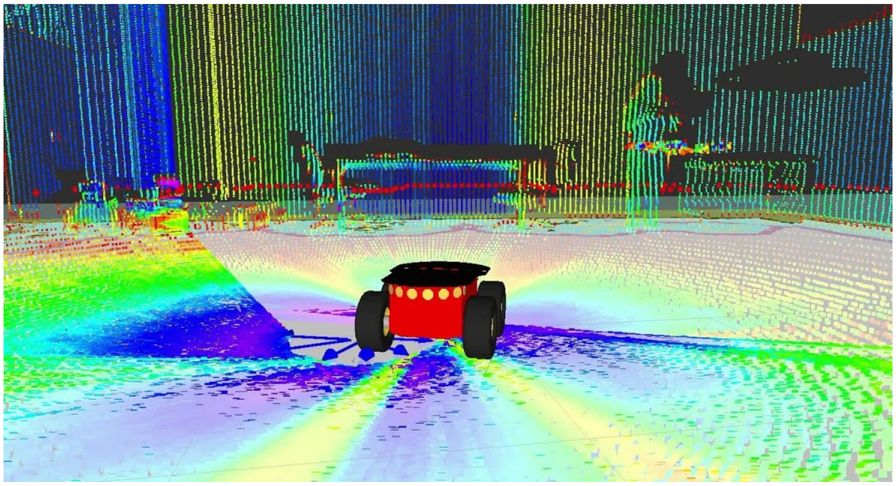


Fig. 2. Lidar generated 3D point cloud image.

To achieve the spatial 3D scanning a beam steering system needs to be added to the laser, photodetector and electronics, as shown in the figure below.

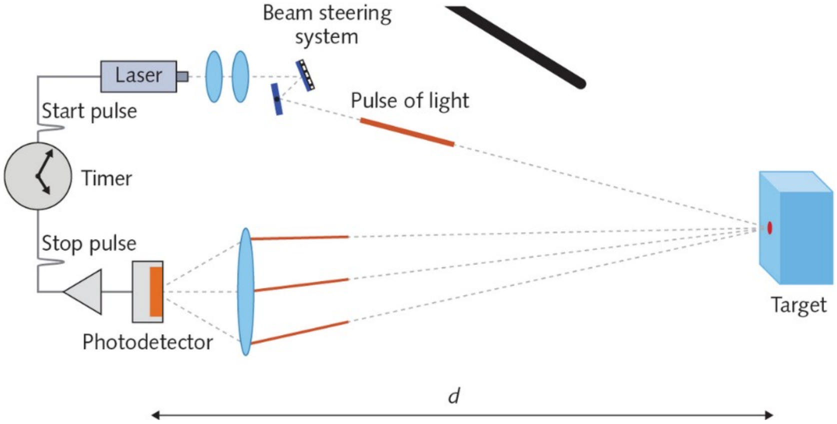


Fig. 3. Lidar components. From Ref. [8].

In addition to the range, R, another important quantity is the range resolution, ΔR, which describes the uncertainty in the distance measurement. The range resolution directly impacts the accuracy of the 3D map created by Lidar. Using equation (1) again, the range resolution ΔR is given by:

$\Delta R = \frac{c\Delta t}{2}$ (3)

where Δt is the uncertainty in the measured round trip travel time t. If we desire a resolution on the order of centimeters, for example 10 cm, Δt has to be less than 6.7×10^{-10} s = 0.67 ns. The reader can use equation (3) to verify the above Δt when ΔR = 10 cm.

Uncertainties in the time needed for the photodetector and the electronic circuits to process the received signal impact Δt. High bandwidth photodetectors and low jitter electronic circuits are needed to ensure good range resolution.

Another contributing factor to the range resolution is the pulse duration of the light emitted by the laser. The pulse duration is equivalent to a spatial spread of the light, which needs to be smaller than the desired range resolution. Using equation (3) again with ΔR = 10 cm, we see that the pulse duration needs to be less than 0.67 ns. Very short pulses of light, picosecond (10^{-12} s) to nanosecond (10^{-9} s) in duration, must be used in applications requiring range resolution on the order of cm.

In addition to equation (1) another fundamental equation for Lidar is the equation for the *received power*,

$$P_r = \frac{\rho P_t D_r^2 \eta_{atm} \eta_{sys}}{4R^2} \cos(\Theta_i) \qquad (4)$$

where P_r is the power received by the photodetector, P_t is the laser transmitted power, R is the range, ρ is the target reflectivity, D_r^2 is the photodetector receiving area, η_{atm} is the atmospheric attenuation, η_{sys} is the optical system efficiency, and Θ_i is the angle of incidence of the light on the target.

The received power is an important quantity in Lidar design. Only a small amount of power returns to the photodetector from a faraway or non-reflective target, so the design needs to ensure that the photodetector is capable of detecting P_r.

Looking at equation (4) with the goal of maximizing P_r, we can derive several important features of Lidar. P_r is proportional to the transmitted power P_t, so P_r can be increased by increasing P_t. However in specific applications such as autonomous vehicles for example, the power emitted by the laser must be kept in the safe range for the human eye. This depends on the wavelength of the laser but in general it means P_t can only be on the order of watts (W). In other applications such as airborne Lidar, much higher laser powers can be used.

Another feature is that P_r decreases with the square of the range, R^2. The figure below illustrates the rapid decrease in P_r when the distance to the target reaches ~50 m. For the long ranges desired in applications such as autonomous vehicles, 150 - 200 m, ways to increase P_r need to be considered.

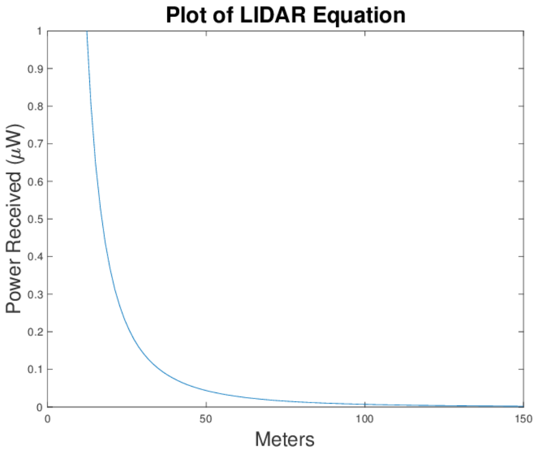


Fig. 4. Received power vs distance to target, showing the rapid decrease in P_r at longer target distances.

Another factor that has to be taken into account in Lidar design is the target reflectivity. As equation (4) shows, P_r is proportional to ρ, so that lower reflectivity of the target results in lower received power. The target reflectivity can vary widely as shown in the table below. Lidar used in autonomous vehicles must work accurately not only for highly reflective car license plates and road signs, but also with pavement, car tires, bare trees and other targets that have much lower reflectivity. The specifications of Lidar typically include values for the maximum range at a reflectivity of 10% to account for targets with low reflectivity.

Table 1. Reflectivity of different materials showing a wide range of values from <5% to almost 100%.

White paper	Up to 100%
Snow	80-90%
Beer foam	88%
Deciduous trees	~ 60%
Coniferous trees	~ 30%
Dry sand	57%
Wet sand	41%
Asphalt with pebbles	17%
Black neoprene	5%
Clear water	< 5%

Equation (4) also shows that atmospheric conditions play a role in the number of photons received by the photodetector. The effect of the atmosphere is captured in the term η_{atm}. Scattering and absorption of the laser beam in air decrease the transmission efficiency and result in lower η_{atm} and P_r. These effects are more pronounced in bad weather, such as rain, fog and snow. In these conditions Lidar performance worsens, by contrast with Radar which is less affected.

In discussing features of equation (4) we focused on the requirement for P_r to be greater than the minimum power required by the photodetector. Another significant parameter is the Signal-to-Noise Ratio, or SNR, which reflects the ability of the photodetector to distinguish between the return light signal and the undesired light background. Ideally, the detected power should come only from the laser beam reflected from the target. Detected ambient light from sunlight, incoming headlights, or other sources, constitutes noise for the detector and should be reduced as much as possible. Narrow band filters that only allow a narrow wavelength range around the wavelength of the laser beam to pass are used for this purpose, but they cannot reduce the received ambient light to zero. Antireflection coatings are also used on all external windows of the Lidar to eliminate unwanted reflections which can also contribute to the noise.

Self-Test

6. In Lidar, the time-of-flight (TOF) principle is used to determine:
    a. The speed of light in vacuum
    b. The distance to the target
    c. The wavelength of the laser
    d. The power of the laser
7. The range resolution refers to:
    a. The uncertainty in the measured value of the range
    b. The round trip time to the target and back
    c. The power received by the photodetector
    d. The power to decide what the range is
8. For range resolution on the order of cm, the laser pulse duration must be:
    a. Higher than 1ms
    b. Around 1s

    c. Less than 1µs
    d. Less than 1ps
9. To increase the power received by the photodetector we can:
    a. Increase the power emitted by the laser
    b. Increase the photodetector receiving area
    c. Increase the optical system efficiency
    d. All of the above
10. Which of the following is not considered noise:
    a. Ambient sunlight
    b. Light beam reflected by the target object
    c. Headlights from other cars
    d. Reflections from objects different than the target

3. Lidar Components

A Lidar system typically includes the following components:

- one or more laser light sources acting as transmitters of light signals
- one or more photodetectors acting as receivers of reflected light signals
- a beam steering system, in scanning type Lidar
- electronics for synchronization and data processing
- Global Positioning System (GPS) and Inertial Measurement Unit (IMU) devices to determine the absolute position and orientation of the Lidar

Some Lidars have one laser and one photodetector, while others use multiple laser sources paired with arrays of photodetectors that receive the reflected light for each laser source. Laser sources and photodetectors used in Lidar are discussed below. The beam steering system is discussed in section 4, covering Lidar types. The other components are outside the scope of the module.

3.1 The Laser Light Source

The performance of the Lidar light source plays an important role in the overall performance of the system. Lasers are distinguished from other light sources by several important characteristics. Light emitted by a laser is *monochromatic*, *coherent* and *directional*. Being monochromatic means that the laser wavelength occupies a narrow band in the spectrum, centered on a specific value. Each laser has its own wavelength depending on the type of laser. Lasers used in Lidar can have wavelengths ranging from the ultraviolet (100 - 400 nm), visible (400 - 750 nm), and near infrared (NIR) (750 nm - 1 µm) regions of the spectrum to the short-wave infrared (SWIR) (1 - 2.5 µm) and even long-wave infrared (LWIR) (8 - 12 µm) regions. Typically, Lidar laser wavelength is between 355 nm and 1550 nm.

The wavelength chosen depends on the application and associated eye safety requirements. Different wavelengths create different hazards to the human eye. Visible and near infrared light with wavelength in the range 400 - 1400 nm can damage the retina and result in blind spots. Infrared light in the range 750 - 1400 nm is especially dangerous, as the eye does not perceive it and is thus not able to use the blinking reflex to protect itself. On the other hand, UV light with wavelength < 400nm is absorbed by the lens or cornea and can produce injuries at relatively low powers. Above 1400 nm, the laser light is less dangerous as it is absorbed by the eye before reaching the retina.

Using the 1550 nm wavelength common to telecommunication applications has the advantage of providing better eye safety than the 905 nm wavelength many Lidar devices rely on. The power of the laser can be increased 40 to 50 times by going from 905 nm to 1550 nm while remaining compliant with eye safety requirements. Increased laser power allows for longer maximum range for the Lidar. In addition, the 1550 nm wavelength has the advantage of low absorption of the light by the atmosphere, resulting in more light being returned to the photodetector.

Atmospheric Lidar, which is used to map the 3D distribution of aerosols and molecules to characterize everything from pollution to clouds, wind, and even volcanic emissions, uses the 355 nm UV wavelength. As high backscattering coefficients from the atmospheric particulate are desired in this application, eye safety is ensured.

For the application of bathymetry, which is the high-resolution mapping of the sea bottom and coastal areas, the laser used is a high power, frequency-doubled laser at the 532 nm green wavelength. This wavelength represents the best compromise between high transmission in pure water and limited backscattering from submarine particulates.

In airborne topographic mapping, a wavelength around 1 μm is typically used, in which case the beam is expanded large enough to be considered eye-safe. For automobile applications, any visible laser would be a significant distraction to nearby traffic. As a result, infrared wavelengths are usually chosen since they are not visible to the human eye.

The *directionality* of the laser light means that the laser has small beam divergence, which allows it to travel long distances without spreading out appreciably. This is illustrated in the figure below, where Lidar is seen to have better lateral resolution than Radar, allowing it to better identify a target.

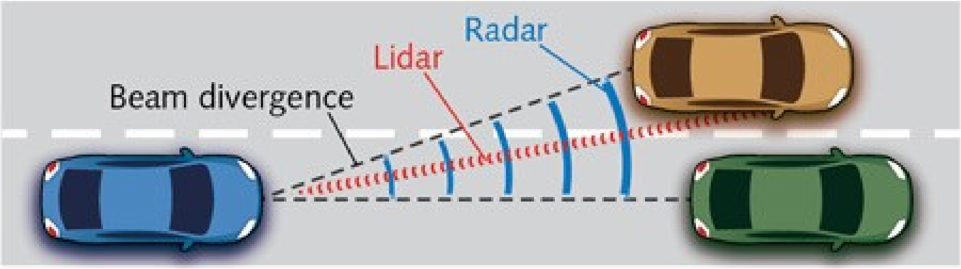


Fig. 5. Lateral resolution of Lidar vs Radar. From Ref. [7].

For pulsed laser light, important characteristics are the pulse duration and the repetition rate. As discussed in section 2.1, the short duration of the laser pulses allows for high longitudinal or range resolution, while a high repetition rate for the pulses allows for faster scanning and high data throughput.

In addition to wavelength, transmitted power, pulse duration and repetition rate, other important parameters for the laser are its size and weight, cost, power consumption, need for cooling, sensitivity to shock and vibrations, and ability to work in harsh environments.

Historically a variety of laser types have been used in Lidar. These included the ruby laser and the CO_2 laser, which are not used anymore. Currently the laser source in Lidar is either a laser diode or a diode-pumped solid state laser (DPSSL). In the latter category, we can have a bulk solid state laser or a fiber laser. Laser diodes are inexpensive and efficient, but tend to have limited power, broad laser linewidth and broad beam. DPSSL have narrow linewidth, small beam divergence, and can reach high power. If the power is not high enough, as is the case with fiber lasers, they can operate with high duty cycle.

3.1.1 Laser Diodes

Laser diodes are one of the most common laser sources used in Lidar. Laser diodes are based on semiconductor materials as the active medium and use electrical power as an energy source. They have very good power efficiency, are small in size, cost effective, and reliable. Laser diodes play an important role in high speed telecommunications and datacom equipment. They are also widely used in consumer products, such as mobile devices and gaming systems. Laser diodes used in Lidar emit light at the near-infrared (NIR) wavelengths of 850 nm, 905 nm and 940 nm. These wavelengths are well matched to the wavelength range of Silicon (Si) photodetectors, which efficiently detect light up to 1 µm wavelength. Si detectors are less expensive than the InGaAs (Indium Gallium Arsenide) photodiodes used with the 1550 nm wavelength. This makes the combination laser diode - Si photodetector very cost effective. Drawbacks of laser diodes are the limited pulse repetition rate, lower peak power, and overheating effects.

Laser diodes fall under two types: edge emitting lasers (EEL), which emit light from the edge of the substrate, parallel to the mounting surface, and vertical cavity surface emitting lasers or VCSEL, which emit light perpendicular to the mounting surface. While the laser beam emitted by EEL has an elliptical shape resulting in higher beam divergence in one direction, the shape of the beam emitted by VCSEL is circular. The figure below shows the beam shape for VCSEL, EEL and also Light Emitting Diode (LED), which is not a laser. We can see that the beam emitted from the latter spreads rapidly in both directions. For EEL, lenses are used to shape and collimate the laser beam.

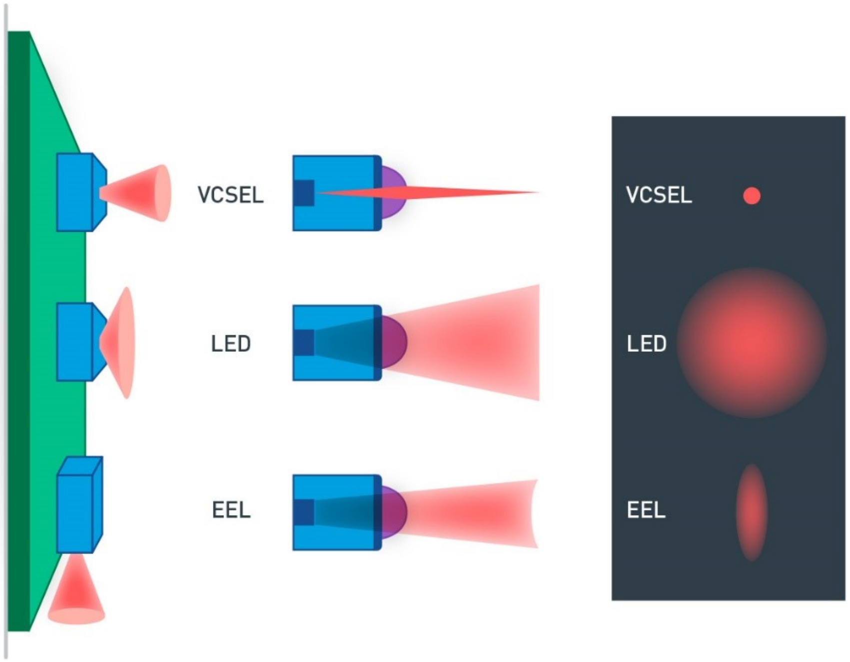
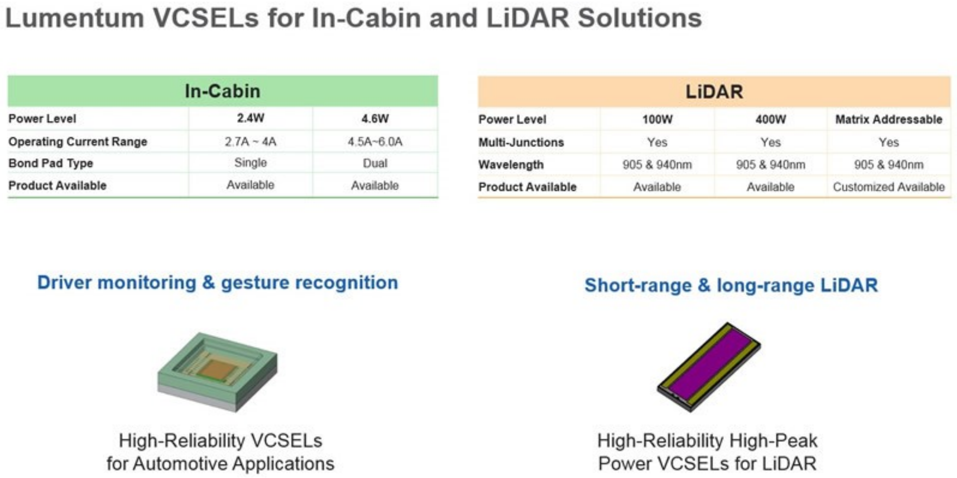


Fig. 6. VCSEL, EEL laser diodes and LED beam shape and divergence. From Ref. [1].

The power from a single laser diode is in the range of mW to a few W. The power output can be increased by combining multiple emitters in a 1D or 2D configuration, forming laser diode bars and arrays. Powers up to 1kW have been reached with High Power Diode Laser Arrays (HPDLA).

VCSEL offer several advantages over EEL. They are less expensive and have lower complexity than EEL. They offer a wider selection of wavelengths, have a narrower spectrum and are more stable with respect to temperature. The laser light emitted by VCSEL has a spectral width of 1-2 nm. Due to the low thermal wavelength shift of only 0.065nm/K, the spectrum of the light emitted by VCSEL remains narrow over a range of temperatures, which allows for a simple filter in front of the photodetector to achieve efficient background suppression. This in turn enables VCSEL to work well even with smaller transmitted power.

A single VCSEL emitter emits about 10mW of power. While this power is too small for many applications, the power output can be increased by using a VCSEL array. There are also applications where a lower power is not an issue, such as applications that require a short range. VCSEL is very well suited for these applications, including driver gesture recognition and driver monitoring, which enhance the autonomous driving capability of a vehicle. The figure below shows VCSEL fabricated by Lumentum for short range applications on the left, and long range applications on the right.



Lumentum VCSELs for In-Cabin and LiDAR Solutions

In-Cabin		
Power Level	2.4W	4.6W
Operating Current Range	2.7A ~ 4A	4.5A~6.0A
Bond Pad Type	Single	Dual
Product Available	Available	Available

LiDAR			
Power Level	100W	400W	Matrix Addressable
Multi-Junctions	Yes	Yes	Yes
Wavelength	905 & 940nm	905 & 940nm	905 & 940nm
Product Available	Available	Available	Customized Available

Fig. 7. VCSEL laser diodes for short range and long range applications. Courtesy of Lumentum.

VCSEL are very fast, allowing for on-off switching times on the order of picoseconds (10^{-12} s). The operating wavelength range for VCSEL is 650 - 1300 nm.

In addition to being used directly as the laser light source, laser diodes are used to optically pump the other types of laser used in Lidar: fiber lasers and DPSSL. The laser diodes are operated in pulsed mode with pulse durations between 0.1 - 1 ms and duty cycles between 1% and 10%. This avoids the overheating issues that can be present with laser diodes with high output powers.

3.1.2 Fiber Lasers

Fiber lasers use optical fibers doped with certain materials as the active medium responsible for emitting the laser light. Optical fibers consist of a narrow circular core surrounded by a cladding, where the index of refraction of the core is higher than that of the cladding. Light traveling inside the core in a direction almost parallel to the axis of the fiber will be subject to the phenomenon of Total Internal Reflection (TIR). In TIR light is entirely reflected back into the core every time it hits the interface between core and cladding, remaining “trapped” in the core and traveling for long distances with very little loss of power.

Optical fibers are used extensively in communication systems to transmit signals over long distances. For communication applications optical fibers made of glass, or amorphous silicon dioxide (SiO_2), contain additional elements such as Germanium (Ge) and others in the core to raise its index of refraction above the index of the cladding. To create a fiber laser, the fiber core is doped with a rare earth element, such as ytterbium (Yb), erbium (Er), thulium (Tm), neodymium (Nd), holmium (Ho), and praseodymium (Pr). Rare earth elements have efficient light emitting properties at desired wavelengths. Yb emits wavelengths between 1030 and 1100 nm, while Er emits wavelengths around 1550 nm. The latter wavelength is preferred for Lidar operation due to its eye safety characteristics.

A laser also requires an energy source acting as a pump. Fiber lasers use laser diodes for this purpose, as illustrated in the figure below, where multiple laser diodes are used to increase the power output of the laser. The active medium emitting the light is in the fiber coil, and pump light is coupled to the fiber coil by the multimode coupler.

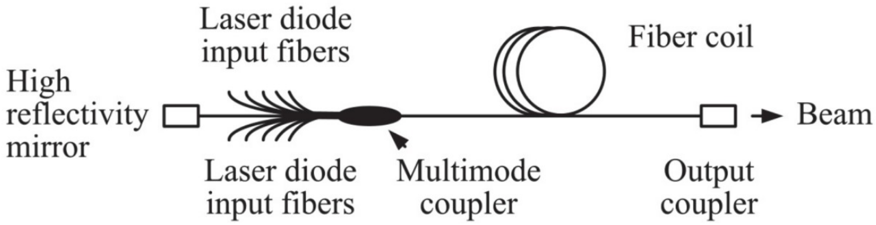


Fig. 8. Fiber laser schematic.

Fiber lasers can emit CW or pulsed light. A direct method of obtaining a pulsed output is to turn the pump power from the laser diodes on and off. This approach can provide laser pulse durations around 10 ms with repetition rates up to 50 KHz. Other methods used for pulsed output include Q-Switching and mode locking. Q-Switching is a technique used to reduce the pulse duration and increase the peak power of the pulses. It involves inserting a switchable device in the laser cavity that initially has high loss and prevents the laser from operating. Then the loss of the device is quickly switched off, and the laser can emit a short, high-power pulse. Peak powers on the order of MW (megawatts) and pulse durations of tens and hundreds of nanoseconds (ns) can be obtained with this method. Mode locking can provide even shorter pulse durations, down to the order of femtoseconds (fs), or 10^{-15} s. A laser produces mode locked pulses when there is a fixed phase relationship between the modes in the resonant cavity. Interference between these modes produces a train of pulses of very short duration.

Fiber lasers are very efficient, and do not require large amounts of power to operate. They don’t require maintenance, are reliable and have a very long life. Due to their long and thin geometry, the laser beam is of high quality. Light from a fiber laser can be easily coupled to an optical fiber for routing to multiple sensor locations. A typical 1550 nm Lidar fiber laser has pulse repetition rates of 5 to 250 kHz at power levels from 10 to 15 kW and 200 to 300 W, respectively. Fiber lasers operating in CW mode are used in coherent Lidar, which will be described in a later section.

Disadvantages of using fiber lasers vs laser diodes in Lidar are higher cost and complexity and lower level of technology readiness.

3.2 The Photodetector

A photodetector is a device that converts the light incident on it into electrical current. Photodetectors used in Lidar are semiconductor based PIN photodiodes, Avalanche Photodiodes (APD), Single-Photon Avalanche Diodes (SPAD), and Silicon Photomultipliers (SiPM). The Lidar device can contain a single PD used as a single pixel, a line of PDs, or a 2D array or matrix of PDs.

A photodiode is essentially a p-n junction working under a reverse bias condition, with the p-side of the junction connected to the negative terminal of the battery and the n-side to the positive terminal. While p-n junction photodiodes have modest performance, numerous improvements in the structure of photodiodes have been made over the years resulting in excellent characteristics. The PIN photodiode includes a wide intrinsic (undoped) area between the p- and n- layers of the junction, which improves the efficiency and speed of the PD. The Avalanche Photodiode (APD) generates multiple charge carriers for each absorbed photon, which is expressed by the gain factor, M. This makes the APD capable to detect very low levels of light. The Single-Photon Avalanche Diode (SPAD) takes this even further, having the ability to detect a single photon incident on it, as well as the time of arrival of the photon with high temporal resolution of the order of ps. SiPM are arrays of SPADs built on a common substrate, resulting in an efficient, compact size receiver. Of note, SiPM require a reset time between consecutive signal measurements resulting in a “dead time” of 400 ns to 1 μs.

Linear-mode avalanche photodiodes (LMAPDs) have a linear relationship between the number of received photons and the number of generated electrons, while Geiger-mode APDs always generate a maximum number of electrons when one or more photons are received.

Materials used in the construction of the photodetectors used in Lidar include silicon (Si), indium gallium arsenide (InGaAs), mercury cadmium telluride (HgCdTe), and others. Si based PDs work well for wavelengths below 1 µm. For the eye safe 1550 nm wavelength, InGaAs PDs are used most of the time. HgCdTe PDs are efficient for a wide range of wavelengths from UV to Middle Wavelength Infrared (MWIR) but need cooling and have higher cost.

Photodetectors used in Lidar devices need to satisfy several stringent requirements. They must have:
- high sensitivity to detect low-intensity light signals as the amount of power that returns to the photodetector can be very small,
- high dynamic range to detect the low level of power returning from distant low reflectivity targets as well as high level of power from nearby high reflectivity targets,
- low noise and high signal-to-noise ratio to detect very weak signals mixed with background noise,
- high efficiency in converting photons to electrons,
- high speed of response or large bandwidth, to be able to handle the very short pulses and high repetition rates of the light emitted by the laser.

There are several sources of noise associated with photodetectors, each having a different impact and mitigation strategy. Noise sources associated with the photodetector itself are dark current, thermal noise and shot noise. Dark current is the electrical current generated by a photodetector in the absence of any light incident on it. Fluctuations in this current result in noise. Thermal noise is electronic noise generated by the thermal agitation of charge carriers (usually the electrons) inside an electrical conductor. Shot noise is related to the quantization effect, or the discrete distribution of the light energy among photons.

Background noise on the other hand is related to light incident on the photodetector coming from a source other than the desired signal. One example relevant to Lidar is solar radiation. The peak radiance from the sun takes place around the 500 nm wavelength. The radiance goes down significantly at 1550 nm, which is another advantage of using this wavelength with Lidar. Most background noise from solar radiation and other sources can be eliminated by placing a narrow band filter in front of the detector, which allows only a small portion of the spectrum to pass through. Current technology is capable of producing filters with a 1 nm bandwidth for collimated light at normal incidence, which broadens to 9 - 10 nm when the angle of incidence of the light on the filter is increased.

When used in Lidar applications, each type of PD described above has several advantages as well as disadvantages. Advantages of PIN PDs include fast response time, low price, scalability into array form, and technology readiness. However, their reduced sensitivity is a drawback which prevents them from being used in long range Lidar.

Avalanche Photodiodes can be used for long range sensors, and can be scaled into arrays or matrices. They work well in near infrared (NIR) and short wave infrared (SWIR) range, and they benefit from a mature technology. On the minus side, their response time is high and they are expensive.

SPAD and SiPM have great sensitivity, detector gain, and response time. They can be built in arrays and work well in near infrared (NIR) and short wave infrared (SWIR) range. Their disadvantages are cost and lack of maturity of the technology.

Self-Test

11. A Lidar system does not include:
    a. Light source, most often a laser
    b. Microwave antenna
    c. Photodetector

    d. Electronics for synchronization and data processing

12. The best wavelength for eye safety in Lidar is:
    a. 355 nm
    b. 850 nm
    c. 905 nm
    d. 1550 nm
13. A laser type often used in Lidar today is:
    a. Ruby laser
    b. Nd:YAG laser
    c. Laser diode
    d. Excimer laser
14. Compared to EEL, VCSEL have advantages such as:
    a. Narrower spectrum
    b. Wider selection of wavelengths
    c. More stable with temperature variations
    d. All of the above
15. What is the spectral width of the light emitted by VCSEL?
    a. 1- 2 cm
    b. 1-2 mm
    c. 1-2 μm
    d. 1-2 nm
16. A high dynamic range of the photodetector refers to the ability of the photodetector to:
    a. Detect very low power lightwaves
    b. Detect both low power and high power lightwaves
    c. Detect lightwaves very fast
    d. Distinguish between noise and signal lightwaves
17. SPAD stands for:
    a. Similar Power Avalanche Diode
    b. Single-Photon Avalanche Diode
    c. Single-Photon Analog Digital
    d. Structural Photon After Detection

4. Lidar Types and Characteristics

One of the criteria for classifying Lidar devices refers to the method used to cover the area of interest in order to detect an object or map an area. From this perspective, Lidar devices can be of *scanning* or *flash* type. In scanning Lidar, a beam steering system is used to scan the laser beam over the target with the receiver detecting the reflected signal from each point on the target area sequentially. In flash Lidar, the entire target area is illuminated simultaneously much like with a camera, and the reflected signals are detected by an array of photodetectors.

The figure below illustrates the principle of operation of the two types of Lidar. In flash Lidar, shown on the left, the laser beam needs to be enlarged so that is covers the entire target area at its location. This Lidar does not use a beam steering system or scanner.

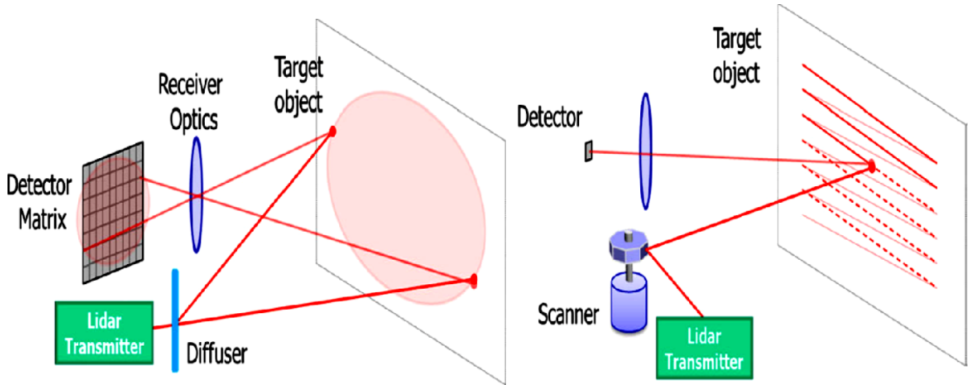


Fig. 9. Flash vs scanning Lidar principle of operation. From Ref. [16].

Scanning Lidar using a two axes scan is shown in the figure on the right. Scanning takes place horizontally and vertically, in which case a single detector is sufficient to capture the reflected signal. Another option, encountered in many automotive Lidars, is to use a 1D detector array that covers the full required elevation. In this case scanning is done only in azimuthal direction (horizontally), which reduces the scanning time.

Flash Lidar uses a large array of detectors, for example a 128 x 128 pixel array, to capture the image. In this case the reflected light is distributed onto the array of detectors with each detector receiving a small amount of power. This requires a light source capable of high peak-illumination power and/or very sensitive detectors compared to a single-pixel detector or an array with a limited number of detectors.

When considering eye safety with the two Lidar types, a scanning laser hits the eye only for a brief time period. By contrast, the laser in a flash Lidar illuminates the eye for a much longer time period. Because a scanning Lidar does not illuminate the eye for as high a percentage of time, the emitting laser can be more powerful without exceeding the eye safety threshold.

Another way to classify Lidar devices is based on the detection method, where we can have *direct detection* vs *coherent detection*. In direct detection, the detector measures the intensity of the reflected signal but not its phase, as the detector is not capable of responding to the very high frequency of the light. The intensity information together with the time of flight information are used to create the 3D point cloud image discussed in Section 2. The Lidar types presented in sections 4.1 and 4.2 below are usually direct detection Lidar devices.

Coherent detection can measure both intensity and phase. In coherent Lidar, the reflected light interferes with laser light from a Local Oscillator (LO) that is a sample of the outgoing laser signal. By measuring the frequency of the beat signal between the two interfering optical signals, the distance to the target can be determined. When the target is moving, there will be two beat frequencies, allowing for the determination of target velocity and direction of travel, in addition to the distance to the target. Frequency Modulated Continuous Wave (FMCW) Lidar, which is based on the coherent detection principle, is described in section 4.3.

4.1 Scanning Lidar

4.1.1 Mechanically Scanned Lidar

This Lidar uses a mechanical beam steering system to scan the beam across the target area. The sensor Field of View (FOV) resulting from the scan can be described by an azimuthal angle and an elevation angle. A complete rotation in horizontal plane results in a 360° azimuthal angle, which is useful for autonomous vehicles that need complete information about the surrounding environment. If the horizontal

FOV is smaller than 360°, multiple Lidars can be placed around the vehicle to fully cover the surroundings. In vertical direction a typical scan angle is around 30°. The rotational frequency in the horizontal plane is generally between 5 Hz and 30 Hz.

Mechanically scanned Lidar is the most popular Lidar for automotive applications at this time, benefitting from a mature technology pioneered by David Hall for the 2005 Grand Challenge. He went on to found Velodyne, a company that produces many of the Lidars seen on the roof of vehicles with various levels of autonomy. The Velodyne family of products includes rotating Lidars with 32 or 64 lasers stacked in a vertical column to allow for the collection of a large number of data points per second. The figure below shows several Lidar devices commercially available from Velodyne.

Fig. 10. Velodyne family of commercial Lidar products.

Mechanically scanned Lidars have a large object detection range, 360° FOV, and a high Signal to Noise Ratio (SNR). Scanning Lidar is very effective for scenes that are relatively static over time, but not as effective with rapidly changing scenes. That is because scanning involves a significant time overhead. Some other drawbacks include their large size, robustness, need for regular maintenance, and cost. Even though the cost has come down significantly in recent years, it is still higher than the other types of Lidar described below.

4.1.2 Solid State Lidar

In solid state Lidar the mechanical steering mechanism is replaced with one based on solid state components. This greatly reduces the size, weight and cost of the device, and makes it much faster. It can also improve its robustness. On the other hand, these Lidars have smaller FOV, so more than one device is needed to cover the entire surroundings of a vehicle for autonomous applications. For example, three such devices each with a 120° FOV are needed to replace a 360° FOV Lidar.

In MEMS or MOEMS Lidar, beam steering is performed by small mirrors that change the direction of the light. The mirrors have sizes on the order of a few millimeters (mm), and can be tilted by applying a voltage in order to change the direction of the laser beam. MEMS stands for Microelectromechanical Systems and MOEMS for Microoptoelectromechanical Systems. MEMS and MOEMS are based on semiconductor materials and are built using the fabrication technology for integrated circuits.

Various configurations for 2D mirror scanning are possible. One approach is to tilt the mirror in one direction only, while the other direction is covered by some other method. In the figure below, a MEMS mirror scans the horizontal direction, while the vertical direction is taken care of by using a one dimensional array (line) of lasers. The reflected light signals are captured with a 2D photodetector array. The configuration requires very good alignment between the lasers and the mirror plate in order to ensure good angular resolution of the device.

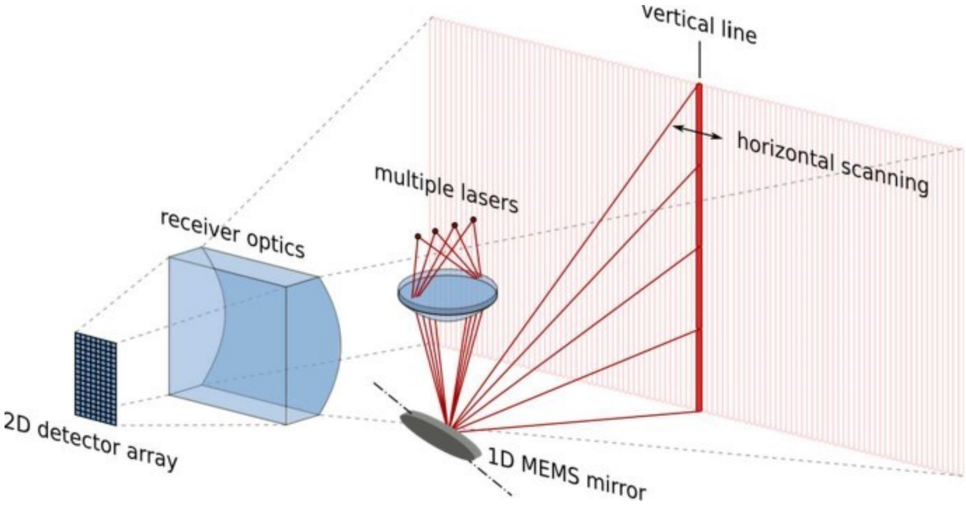


Fig. 11. Solid state scanning Lidar using a MEMS mirror scanning horizontally. From Ref. [15].

Another approach is to rotate the mirror using a small motor, as shown in the figure below. By contrast with mechanically scanned Lidar where the entire set of lasers and receivers are rotated to cover the target area, here only the small mirror is rotated, resulting in the small size and weight advantages discussed above. The mirror scans in vertical direction while scanning in the horizontal direction is done by the small rotor.

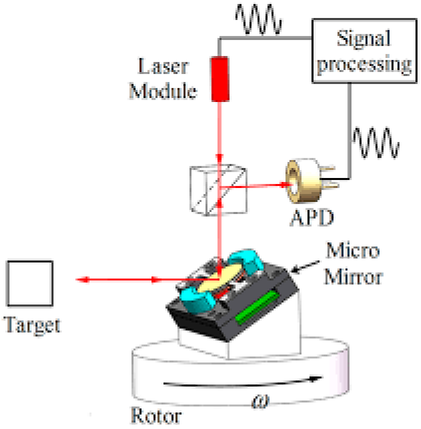
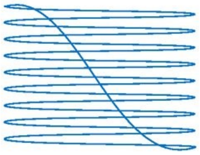
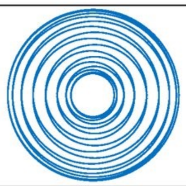
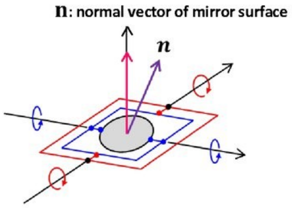
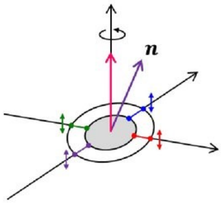


Fig. 12. Solid state scanning Lidar using a MEMS mirror scanning vertically. The horizontal scanning is done using a small rotor. From Ref. [15].

Another configuration involves the mirror scanning in both directions. The table below shows how scanning is performed in two different Lidar devices, one with a smaller FOV, the other one a wide-view type. The mirror geometry is shown in the last row of the table, and the scanning pattern in the middle row.

Table 2. 2D scanning MEMS Lidar characteristics. From Ref. [12].

	Front-facing type	**Wide-View type**
Appearance of LiDAR unit		
Scan pattern		
Structure of MEMS scanner		

While Lidar based on MEMS mirror scanning is smaller, lighter and faster than the first-generation mechanically scanned Lidar, it still contains moving parts and is subject to sensitivity to vibrations and potential reliability issues. These issues will be eliminated in the next generation solid state Lidar based on Optical Phase Arrays (OPA), currently in development by several companies. An OPA is the optical analog of the phase array used in radar. In OPA based Lidar, the steering of the light beam takes place by adjusting the phase difference between the light transmitted by each element of the array. This produces an interference pattern that results in the beam pointing in the desired direction. The operating principle for one dimensional scanning using OPA is illustrated in the figure below, where TX is the transmitter, C is the controller, A is the array and Φ represents the phase.

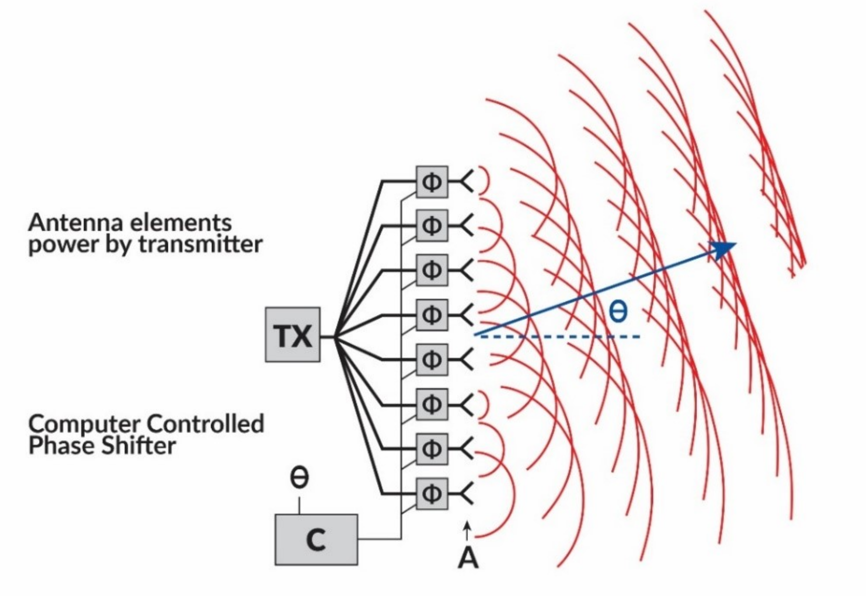


Fig. 13. Optical Phased Array beam steering principle. From Ref. [2].

OPAs are fabricated using the mature manufacturing processes for photonic and electronic integrated circuits. Material platforms for the OPA chip include silicon (Si) and silicon nitride (Si_3N_4). The phase modulation can be achieved through an electro-optic, thermo-optic, wavelength tuning, or hybrid mechanism. OPA are expected to be mass produced and thus low cost, further driving down the Lidar cost. At this time OPA based Lidar has lower performance in range and FOV than other types of Lidar, making it suitable for industrial applications, but not for autonomous vehicles. However, its performance is expected to improve, which coupled with the high reliability, small size, and low cost makes this Lidar the "holy grail" of Lidar technologies. The figure below shows the current and expected performance of OPA Lidar.

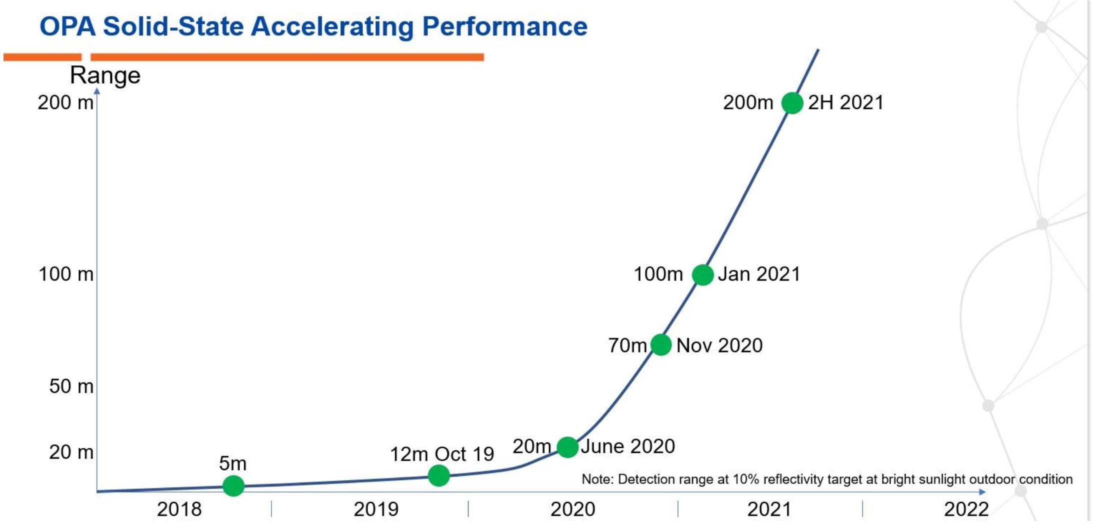


Fig. 14. Optical Phased Array roadmap. From Ref. [2].

Even though less popular, beam steering in two dimensions can also be achieved using Liquid Crystal (LC) technology.

4.2 Flash Lidar

Flash Lidar operates in a similar way to a standard digital camera using an optical flash, hence the name. A wide-angle emitting source is needed to ensure that the beam covers the entire target area. Wide-angle optics such as a fisheye lens are used for the reflected signal, which is captured simultaneously by a focal plane array of photodetectors. Flash Lidar is faster than mechanically scanned Lidar, due to its ability to capture the entire scene in one shot. Other advantages of flash Lidar include compact size, no moving parts, increased immunity to vibrations, and long lifetime.

On the downside, flash Lidar does not have a long range, unless a laser with very high peak power is used. By contrast with the scanning Lidar where the entire laser power is directed to a point on the target at one time, in the flash Lidar the laser power is spread across the entire target. When this is reflected back to the array of photodetectors, each photodetector receives only a small fraction of the total power.

Moreover the Lidar resolution depends on the size and density of the photodetectors in the array. A large number of pixels in the detector array requires high laser power. This can increase the cost of the Lidar. For example, the high resolution flash Lidar used by NASA for its space-station docking operations costs over one million dollars. It operates at 1550 nm wavelength and consumes up to 100 kW power. Such a high cost is prohibitive in automotive applications. Another disadvantage of flash Lidar is the susceptibility to noise signals coming from the environment, which can "blind" the photodetector array.

Sense Photonics is one of the companies producing flash Lidar. Their 3D flash Lidar uses a large VCSEL array with 15,000 VCSELs emitting at 940 nm as the light source. The array emits high power, short pulses of light, and the return signal is captured by a Single-Photon Avalanche Diode (SPAD) detector array with 140,000 pixels fabricated using CMOS technology. The Lidar has a range of 200m at 10% reflectivity, under full sunlight conditions, and capturing tens of millions of points per second. The figures below show the laser and photodetectors array, and the packaged Lidar device.

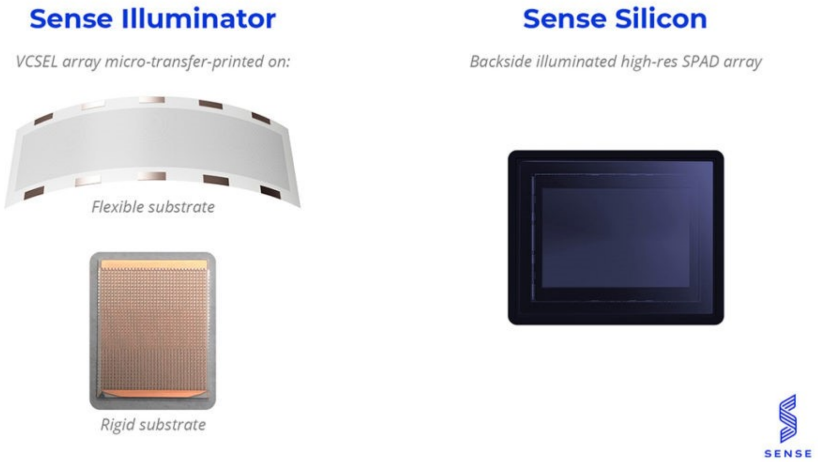


Fig. 15. VCSEL array and SPAD array for 3D flash Lidar. Courtesy of Sense Photonics.

Fig. 16. Global shutter flash Lidar. Courtesy of Sense Photonics.

4.3 Coherent Frequency Modulated Continuous Wave (FMCW) Lidar

In coherent Lidar the laser emits a continuous wave (CW) signal, in contrast with time-of-flight Lidar where the laser emits short pulses of light. In the FMCW Lidar, a portion of the emitted light is retained in order to combine it with the reflected light from the target. Moreover the transmitted signal is frequency modulated, meaning its frequency changes periodically with time, following a specific pattern. By detecting the frequency difference between the transmitted and the received signals, the device can measure the distance to the target in the case of stationary targets. For moving targets there will be two frequency shifts, allowing for the measurement of both the range and the relative velocity of the target.

The principle of operation of FMCW Lidar is shown in the figure below. The top part of the figure illustrates the laser frequency modulation, while the bottom part shows a graph of the frequency of the transmitted and received signals vs time. The equations for the two frequency shifts, f_{B1} and f_{B2}, are used to determine the target range, R, and velocity, V_r.

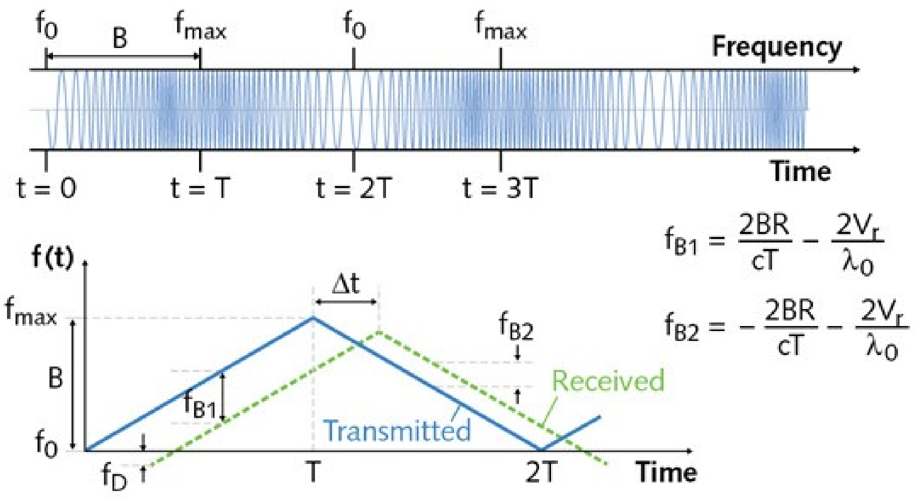


Fig. 17. Principle of operation of FMCW Lidar. From Ref. [7].

This measurement method is highly sensitive resulting in a long range, high resolution Lidar. The range resolution can be on the order of millimeters down to microns. The measurement is also immune to the effects of ambient light or the presence of other Lidars. However, the FMCW Lidar requires a precisely controlled tunable continuous wave laser source, which can modulate its frequency rapidly and with high repeatability. The laser light must have high coherence length so that the beam retains coherence all the way to the target and back to the detector. These stringent requirements for the laser source make the FMCW Lidar more expensive.

Most FMCW Lidars use the 1550 nm wavelength. An impressive range of 450 m and target velocities up to 150 m/s have been demonstrated by the FMCW Lidar developed by the company Blackmore (acquired by Aurora).

4.4 Lidar Performance

More than 100 companies around the world are developing Lidar systems today, about half of these in North America. Using Lidar in automotive applications is expected to result in the first widespread commercial use of Lidar, which has produced a veritable race between companies to bring to market high performing, low cost, reliable Lidar systems. The requirements for automotive applications include an eye-safe laser source operated in pulsed mode, powerful enough to detect a pedestrian wearing dark clothes at a distance of 100 m, with a range resolution on the order of cm, and operating over a wide temperature range from -40 to 85°C.

The cost of Lidar has decreased in recent years. While early Lidar systems had a cost of $75,000 or more, today's automotive Lidars cost between $4,000 and $8,000. This is still high for widespread adoption by the automotive industry, especially in the cases where more than one unit is needed per vehicle to cover the entire 360° FOV. Mass produced OPA Lidar is expected to have a cost of $100 to $200, but this type of Lidar is still under development. Most Lidar systems are still expected to cost more than $1,300 through 2025.

The performance of Lidar devices made by several companies covering the types of Lidar described above is presented below.

Velodyne Lidar (velodynelidar.com) was spun off from Velodyne Acoustics in 2016. However the company has a long experience with Lidar, starting with its founder's invention of the mechanically scanned Lidar in 2005. It offers a family of mechanically scanned Lidars and is also working on solid state Lidar. Their most popular product is the HDL-64E, which combines 64 lasers and detectors to scan 360°

in multiple horizontal planes and acquire up to 2.2 million points per second. The sensor can be used for obstacle detection and navigation of autonomous ground vehicles and marine vessels. While the cost of the mechanically scanned Lidar is on the order of thousands of $, the solid state Lidar the company is working on has a price point less than $500.

HDL-64E S3 specifications

Lidar type: mechanically scanned
Wavelength: 903 nm
Number of channels: 64
Horizontal FOV: 360°
Vertical FOV: 26.9°
Range: 120 m
Angular resolution (azimuth): 0.08° - 0.35°
Vertical resolution: ~0.4°
Rotation rate: 5 Hz - 20 Hz
Number of points per second: up to 2.2 million depending on rotation rate
Cost $: thousands

Luminar Technologies (luminartech.com) was started in 2012 by 17-year old Austin Russell. The company revealed its first product in 2017 and became publicly traded in 2020. Their Lidar uses a fiber laser emitting at 1550 nm wavelength, Indium Gallium Arsenide (InGaAs) photodetectors, and two axes scanning mirrors. Currently Luminar is commercially offering the Hydra product, and has previewed Iris, for which production will ramp up in 2022.

Hydra specifications

Lidar type: solid state with two axes scanning mirrors
Wavelength: 1550 nm
Horizontal FOV: 120°
Vertical FOV: 30°
Range: 500 m maximum range, 250 m at <10% reflectivity
Range resolution: 1 cm
Number of points in image: 200 points per square degree (°)
Cost $: expected to be less than $1,000

In addition to offering Hydra, the company is preparing to start high volume production of the Iris Lidar in 2022. Iris will create an image with > 300 points per square degree and is expected to have a lower cost due to high volume manufacturing.

Quanergy (quanergy.com) was formed in 2012 and produces 360° horizontal FOV mechanically scanned Lidars as part of their Series M products. However the company has been in the news in recent years due to their development of a true solid state Lidar based on Optical Phase Array implemented in CMOS silicon technology. These Lidars fall under the Series S products. At this time Quanergy produces the S3-2 OPA Lidar intended for robotics and industrial automation due to its shorter range of maximum 50 m. The company is working on increasing the sensor range to 200 m for use in autonomous vehicles. It is also targeting a much lower cost than other types of Lidars, with a price point around $500 for the long range sensor.

S3-2WMI-S00 specifications

Lidar type: solid state OPA
Wavelength: 905 nm
Horizontal FOV: 100°

Vertical FOV: 4°
Range: 50 m at 80% reflectivity, 20 m at 10% reflectivity
Range resolution: +/- 5 cm
Angular resolution: 0.1-0.5°

Continental (continental-automotive.com) is a large company with a broad portfolio of automotive related products. This includes different Lidar types, and in particular 3D flash Lidar sensors. The company offers the HFL 110 short range Lidar sensor for use in automotive, commercial vehicles, agriculture, construction, mining, UAV and other applications.

<u>HFL 110 specifications</u>

Lidar type: flash
Wavelength: 1064 nm
Horizontal FOV: 120°
Vertical FOV: 30°
Range: 50 m at 80% reflectivity, 22 m at 10% reflectivity
Resolution: 128 x 32 (4096) pixels
Capture rate: 25 frames per second
Cost: expected < $500 in high volume production

Blackmore Sensors and Analytics was one of the first companies developing a commercial FMCW Lidar. The company was acquired by Aurora (aurora.tech), a self-driving car start-up company, in 2019. FMCW Lidar directly measures both the distance to and the velocity of a target.

<u>Blackmore FMCW Lidar specs</u>

Lidar type: FMCW
Wavelength: 1550 nm
Horizontal FOV: 120°
Vertical FOV: 30°
Range: 450 m
Number of points per second: 2.4 million
Velocity: 150 m/s
Velocity resolution: 0.1 m/s
Cost: $20,000

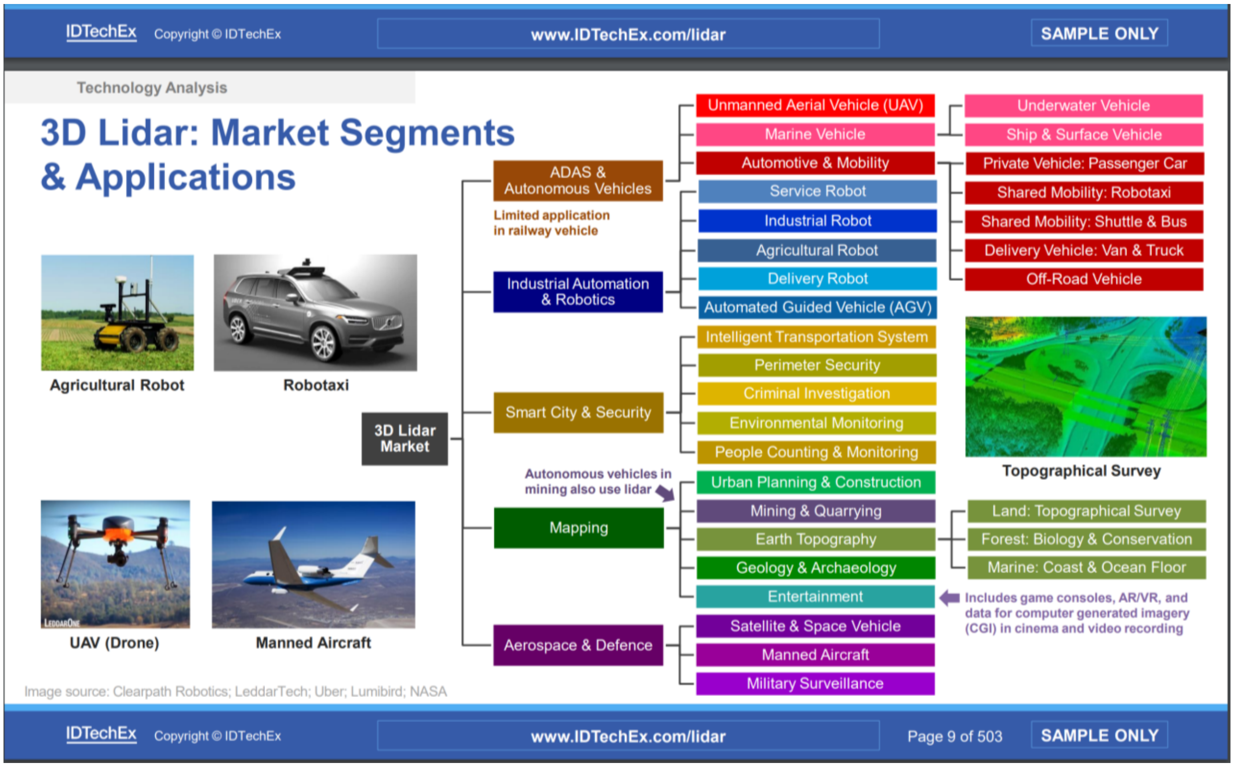
Self-Test

18. The following Lidar does not include a beam steering system:
    a. Mechanically scanned Lidar
    b. Optical Phase Array Lidar
    c. MEMS Lidar
    d. Flash Lidar
19. In flash Lidar:
    a. A single photodetector receives the light reflected from the target sequentially
    b. Two axes scanning is used to cover the entire target area
    c. An array of photodetectors captures the reflected light simultaneously
    d. The eye is exposed to the laser light for very short periods of time
20. In the OPA Lidar, beam steering takes place through:
    a. Rotating the laser(s) in horizontal plane
    b. Tilting the mirror to change the direction of the beam
    c. Interference between multiple beams with different phases

    d. Illuminating the entire scene at once
21. OPA Lidar is considered the ‘holy grail’ of Lidar due to:
    a. High reliability
    b. Low cost
    c. Small size
    d. All of the above
22. A disadvantage of FMCW Lidar is:
    a. Very long range capability
    b. Complex light source
    c. Insensitivity to ambient light
    d. Measuring target velocity together with range
23. This company’s Lidar can directly measure the velocity of a target with a resolution of 0.1 m/s:
    a. Quanergy
    b. Continental
    c. Velodyne
    d. Aurora

5. Lidar Applications

Since its initial development in the 1960’s, the number of applications of Lidar has continued to grow. A comprehensive summary of Lidar applications is presented in the figure below, reproduced here from the IDTechEx report on Lidar 2020-2030.



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Technology Analysis

3D Lidar: Market Segments & Applications

Agricultural Robot

Robotaxi

UAV (Drone)

Manned Aircraft

3D Lidar Market
- ADAS & Autonomous Vehicles
  - Unmanned Aerial Vehicle (UAV)
  - Marine Vehicle
    - Underwater Vehicle
    - Ship & Surface Vehicle
  - Automotive & Mobility
    - Private Vehicle: Passenger Car
    - Shared Mobility: Robotaxi
    - Shared Mobility: Shuttle & Bus
    - Delivery Vehicle: Van & Truck
    - Off-Road Vehicle
- Limited application in railway vehicle
- Industrial Automation & Robotics
  - Service Robot
  - Industrial Robot
  - Agricultural Robot
  - Delivery Robot
  - Automated Guided Vehicle (AGV)
- Smart City & Security
  - Intelligent Transportation System
  - Perimeter Security
  - Criminal Investigation
  - Environmental Monitoring
  - People Counting & Monitoring
- Mapping
  - Urban Planning & Construction
  - Mining & Quarrying
  - Earth Topography
    - Land: Topographical Survey
    - Forest: Biology & Conservation
    - Marine: Coast & Ocean Floor
  - Geology & Archaeology
  - Entertainment
- Aerospace & Defence
  - Satellite & Space Vehicle
  - Manned Aircraft
  - Military Surveillance

Autonomous vehicles in mining also use lidar

Topographical Survey

Includes game consoles, AR/VR, and data for computer generated imagery (CGI) in cinema and video recording

Image source: Clearpath Robotics; LeddarTech; Uber; Lumibird; NASA

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Fig. 18. Lidar market segments and applications. From Ref. [11].

The first market segment, Advanced Driver Assisted Systems (ADAS) and Autonomous Vehicles, includes a variety of driverless road vehicles, as well as unmanned aerial vehicles (UAV) such as the

UAVs used by Amazon to deliver purchases. Lidar is also used in marine vehicles, both underwater and surface types.

Industrial Automation and Robotics is a growing area, with Lidar being implemented in robots working on factory floors and also home environments. In these applications, the Lidar sensor provides reliable object detection, collision avoidance, and distance measurement for robots, automated guided vehicles (AGVs), and other industrial equipment in warehouses, factories, distribution centers, and ports. In spaces where humans and robots work together, Lidar helps to increase safety.

The Smart City and Security segment is very broad. Out of the many Lidar applications in this group, the figure below illustrates people counting and monitoring. Lidar devices can count and monitor the flow and behavior of people visiting public spaces like airports, shopping centers, museums, sport arenas, and others. In addition to counting the number of people entering and exiting these spaces Lidar can measure their actions, sizes, and movement. The devices can be continuously monitored thanks to an independent user interface with remote access.

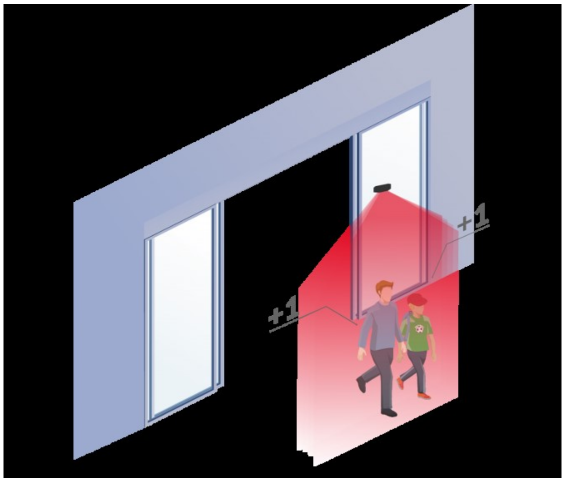

Fig. 19. Lidar application in people counting. Courtesy of BEA (us.beasensors.com).

The Mapping segment is also very large, with applications in a wide variety of environments. In urban planning and construction, Lidar can be used for designing and constructing new buildings and determining the location of specific items within the interior of a room for licensing regulations and to provide proof of compliance. Another interesting application is in forestry, where it can penetrate foliage to measure the vertical structure of forest canopies, map the ground beneath the forest, and estimate canopy bulk density, as shown in the figure below.

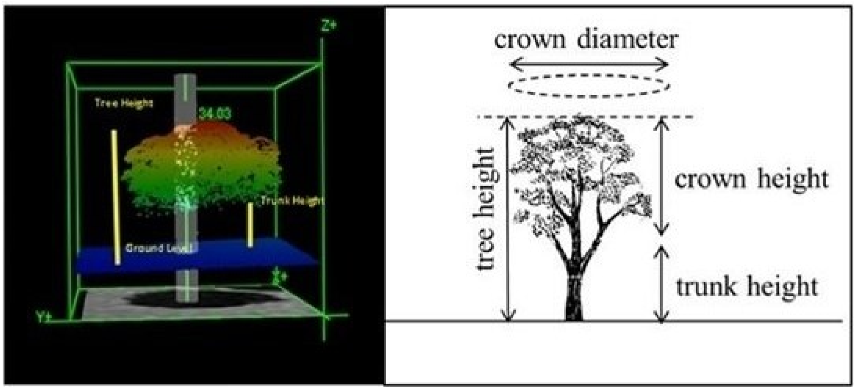

Fig. 20. Tree volume measurement using Lidar. From Ref. [14].

Lidar is able to map the ocean floor, producing detailed maps. One of these maps was created by the Wide Swath Subsea Lidar (WiSSL) at the Monterrey Bay Aquarium Research Institute. The figure below shows the capability of Lidar to create maps with much higher resolution vs other technologies such as sonar. The Lidar image shows very fine details that cannot be captured by the sonar.

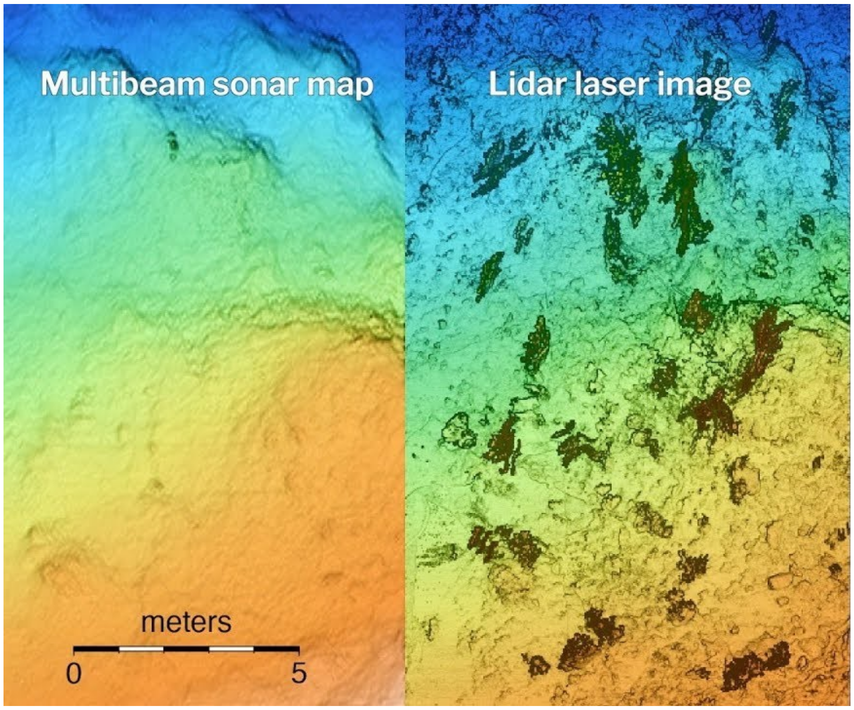

Fig. 21. Seafloor mapping with the Wide Swath Subsea Lidar (WiSSL) at Monterrey Bay Aquarium Research Institute. From Ref. [6].

Aerospace and Defense applications were some of the first Lidar applications, as discussed in the section on History of Lidar. These have continued to grow throughout the years. The military uses Lidar technology to accurately map out the terrain of the battlefield and know the exact position of the enemy and their capacity. 3D map data can be used for route planning to avoid being seen from a certain location. The technology can be used for precise object identification, to locate all enemy weaponry including tankers and help in neutralizing the threat on a much larger scale.

As the technology keeps evolving, new Lidar applications continue to emerge, limited only by people's imagination and inventiveness.

Self-Test

24. The Smart City and Security market segment includes the application of:
    a. Military surveillance
    b. Geology and Archaeology
    c. Service robot
    d. Intelligent Transportation System
25. Lidar is not used in:
    a. Printing
    b. Agriculture
    c. Mapping
    d. Security

Module Review Questions

1. The round trip time for light to travel to a target at a distance of 250 m and back is:
    a. 1.67×10^{-6} s
    b. 1.67×10^{6} s
    c. 8.33×10^{-6} s
    d. 8.33×10^{-7} s
2. How many measurements can be done in one second if the round trip time to the target and back is the one in the previous problem?
    a. 1.2×10^{6}
    b. 6×10^{5}
    c. 1×10^{6}
    d. 2×10^{5}
3. Calculate the pulse duration needed to achieve a range resolution under 3 cm.
    a. Less than 2 ms
    b. Less than 0.2 ns
    c. More than 2 s
    d. Less than 1 ns
4. Calculate the change in the wavelength of the laser light emitted by a VCSEL across a temperature range from -20°C to 55°C if the thermal wavelength shift is 0.065nm/K.
    a. 6.50 nm
    b. -13.0 nm
    c. 55.0 nm
    d. 4.88 nm
5. When the range increases from 50 m to 150 m, the power received by the photodetector (assuming all other factors remain the same) will:
    a. Increase 2x
    b. Decrease 3x
    c. Decrease 9x
    d. Increase 9x
6. Research a company producing MEMS based Lidar and describe its Lidar's characteristics.
7. Research applications of Lidar in robotics, such as in service, industrial, delivery, and agricultural robots. Write a 1+ page paper describing one such application including information about the Lidar used and its related performance.
8. Research the Unmanned Aerial Vehicle (UAV) application of Lidar and write a 1+ page paper describing it, including information about the Lidar used and its related performance.
9. Review the list of list of YouTube videos provided at the end of the Bibliography section and discuss one of the applications mentioned in a one-page paper.

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YouTube videos on how Lidar works and its applications

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Lidar Laboratory

Objective

The objective of this lab is to demonstrate in practice how an industry grade commercial Lidar device works. Students will analyze the 2D depth and 3D point cloud images of an environment in the lab captured by the Lidar device to get insight into its features and performance.

Safety Precautions

The Lidar in this experiment includes a Class 1 eye safe laser emitting an infrared wavelength. As with any laser, never look directly into the laser for any period of time. For more information about laser safety in educational institutions see the References section at the end of the Lab.

Equipment

- Intel RealSense LiDAR Camera L515
- Software development kit RealSense SDK 2.0
- Computer with USB 3.1 connection
- Several objects of various sizes and shapes, not exceeding 2 ft in any dimension
- Ruler or tape measure

Background

The Intel RealSense LiDAR Camera L515 includes a high resolution solid-state Lidar, an RGB (color) camera, and an Inertial Measurement Unit (IMU). The device is designed for indoor applications. The Lidar is based on MEMS mirror scanning technology, and has a range of operation from 0.25 m to 9 m in ideal conditions. Typical applications for L515 are in pick and place for warehouse robotics, volumetric measurement, and room scanning. The small and light device shown in Figure 1 has a puck shape with a diameter of 61 mm, thickness of 26 mm, and a mass of only 100g. The Datasheet for the device is included in the References section at the end of the Lab.

Fig. 1. Intel RealSense LiDAR Camera L515.

The open source software for the device is freely available at https://www.intelrealsense.com/sdk-2/. If not already installed on the computers in the lab, download and install the latest version of the software. The current version for Windows 10 is 2.47.0.

Procedure

Look for sentences in Italic font throughout this lab. Follow the instructions given in these sentences to complete your lab report.

Pre-lab Activity: To create a 3D environment, gather three or four small objects or boxes of different sizes and shapes on a large table in the lab. A good size for the objects is around 1 ft, not exceeding 2 ft in any dimension. The support table should be flush to a wall painted in a light color that will serve as the background, with the objects located 1-2 ft from the wall. Figure 2 shows an example of a 3D set of objects that can be imaged with the Lidar sensor.

Fig. 2. Example of 3D environment for imaging with Lidar.

Establishing "Ground Truth": Position the camera directly in front of the wall at a distance of 3 - 4 ft, without any objects in the camera field of view. The camera puck should be oriented vertically. It is helpful to define an XYZ coordinate system we will refer to in the remaining of the lab as follows. The face of the puck is in a vertical plane defined by the horizontal axis X, and the vertical axis Y. The third axis Z is perpendicular to the face of the puck and points towards the wall. The origin of the coordinate system is at the location where the laser beam is emitted from the puck.

The distance measured along the Z axis between the sensor and an object in front of it is called depth. Please note that this is the perpendicular distance from the object to the vertical plane of the puck, not the distance corresponding to a straight line connecting the two.

Start the RealSense Viewer software. If the camera is not yet connected to the USB port, the software will ask for it. Once the camera is connected, dismiss the message to the right of the screen.

At the top right of the screen you will see two options, 2D and 3D. Make sure the 2D option is selected at this time. You will also see a Menu on the left side of the screen. Because we are looking at objects that are within 3 to 6 ft (1 to 2 m) of the camera, we need to change the Preset value from Max Range to Short Range.

Before toggling the L500 Depth Sensor on, look at the menu options under the L500. Keep the resolution at 640 x 480. In order to prevent an infrared image to appear side-by-side with the depth image, unclick the Infrared option on the left.

Now turn the L500 Depth Sensor on. A color image of the table and wall portions in the field of view of the camera will appear. This 2D image, called the depth map, contains the depth information for the objects in the field of view of the Lidar. As discussed above, we refer to the XYZ coordinate system defined to have the origin at the location where the emitted laser beam exits the puck. The depth measured by the Lidar is the perpendicular distance along the Z axis from the plane of the puck to the point of interest.

In the 2D image you see on the screen, the colors correspond to depth values. You can select Show Color Map Ruler from the icons shown at the top right of the image. When you do, a vertical color strip will appear in the image at the right. Moving the cursor along the vertical color strip you can see what value of depth corresponds to each color in the image.

To find the depth for specific points in the image, move the cursor over the image and stop at a point of interest, for example a point on the wall. At the bottom left of the image you will see the coordinates of the pixel you are pointing to, and the corresponding depth measured by the Lidar in meters.

Measure 2 or 3 depth distances from the camera to the wall and write them down. If the puck is vertical and the camera is parallel to the wall, the way it should be, these distances should be very close to each other. You might need to make slight adjustments in the camera orientation until it is in the proper position. When this is found, measure the 2 or 3 points again with the depth sensor. Verify these distances are accurate by doing a measurement of the same distances with a tape measure.

Capture the image you obtained with the L515 in the lab at this time to include in your lab report. Add a caption explaining the content of the image in the lab report. Include the results of all measurements with comparison of the Lidar depth and tape measured distance in the lab report.

Once you found the appropriate orientation for the camera, keep the camera fixed in place. Instead of moving the camera, move the objects of interest around until they are fully in the camera field of view.

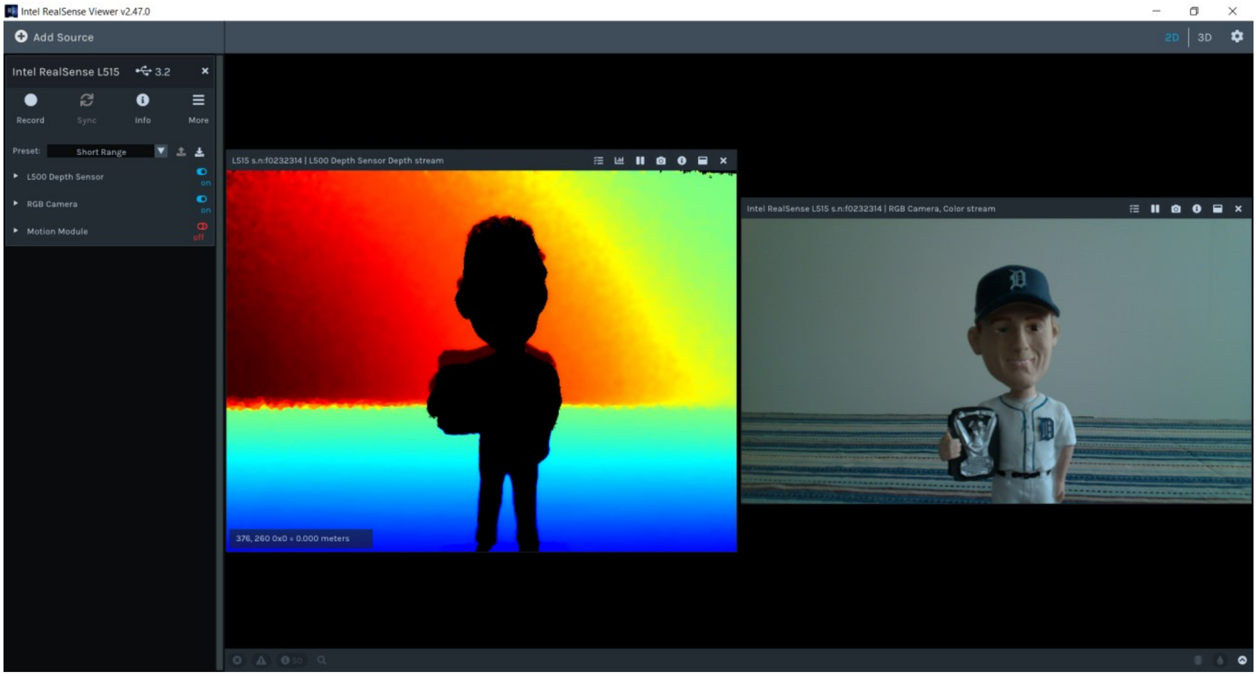
<u>Verifying the Lidar Minimum Range:</u> Bring in an object and position it in front of the camera to get its 2D depth image. First, place the object very close to the camera, at a distance less than 20 cm approximately. What do you see in the viewer? Now gradually move the object farther from the camera, until its color depth image appears. When the color image has appeared, record the depth for a few points on the object. Measure these distances with the tape measure also. How accurate is the depth data?

Capture the image you obtained with the L515 in the lab at this time to include in your lab report. Add a caption explaining the content of the image in the lab report. Include the results of all measurements with comparison of the Lidar depth and tape measured distance in the lab report.

Move the object a bit farther, repeat the measurements and determine the accuracy again. Did the accuracy improve in this latter case?

Lidar devices have a minimum range under which they cannot perform a measurement. For the L515 the minimum range is guaranteed as 0.25 m or 250 mm. However, the sensor can capture depth data even at distances slightly less than 250 mm under favorable conditions or depending on the environment as shown in Figure 4 below.

As Figure 3 illustrates, when the sensor is not able to determine the depth, black areas will appear in the image. This can be because the object is closer to the camera than the minimum range, or they correspond to points at the back of the object where the Lidar cannot penetrate.



Intel RealSense Viewer v2.47.0

Intel RealSense L515 3.2

Preset: Short Range

L500 Depth Sensor on

RGB Camera on

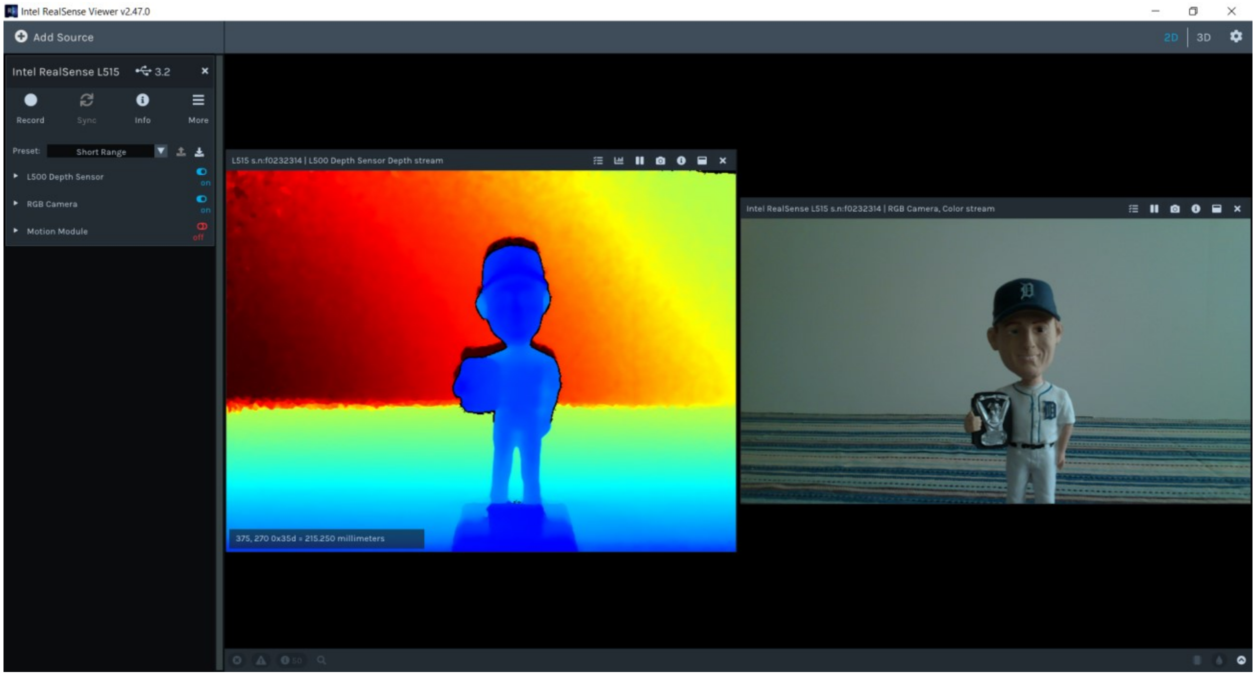
Motion Module off

L515 s.n:f0232314 | L500 Depth Sensor Depth stream

Intel RealSense L515 s.n:f0232314 | RGB Camera, Color stream

376, 260 0x0 = 0.000 meters

Fig. 3. If an object is too close to the Lidar, its depth image cannot be obtained and instead a black area will appear in the image. The additional image on the right is obtained with the RGB Camera, which was turned on from the menu on the left together with the L500 Depth Sensor.



Intel RealSense Viewer v2.47.0

Intel RealSense L515 3.2

Preset: Short Range

L500 Depth Sensor on

RGB Camera on

Motion Module off

L515 s.n:f0232314 | L500 Depth Sensor Depth stream

Intel RealSense L515 s.n:f0232314 | RGB Camera, Color stream

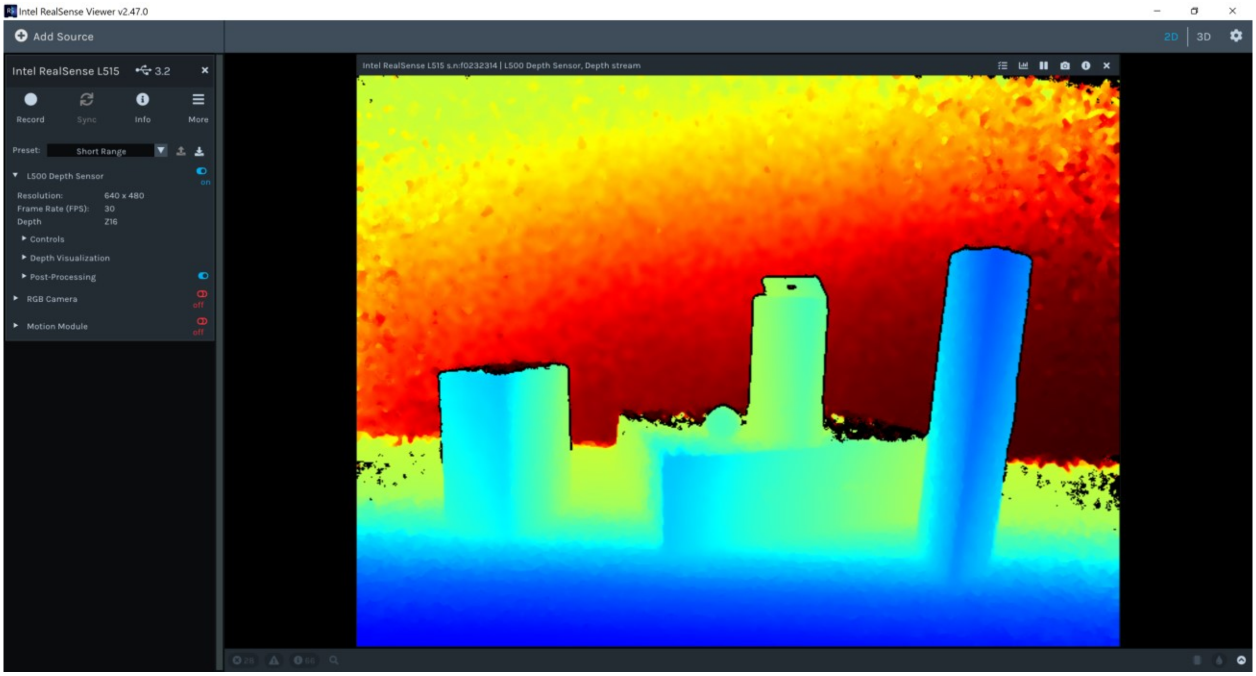
375, 270 0x35d = 215.250 millimeters

Fig. 4. Lidar determined depth information for the object. The 215 mm measured from the camera in this experiment is less than the 250 mm minimum range specified.

<u>2D Depth Image:</u> In many applications, for example robot navigation, the interest is in determining depth distances to objects located in front of the sensor. These distances can be represented as a depth map,

an image where each pixel has an associated value indicating the depth. In addition, the depth information is color coded on the map.

Place the objects you gathered at the beginning of the lab on the table, at a distance 1- 2 ft from the wall, and in the field of view of the camera. Turn the L500 sensor on and observe the 2D depth image. You should see something similar to Figure 5, which shows the 2D image corresponding to the objects in Figure 2.



Preset: Short Range

L500 Depth Sensor on

Resolution: 640 x 480

Frame Rate (FPS): 30

Depth Z16

Fig. 5. 2D depth image for the objects in Fig. 2.

As before you can choose to display the color map to the right of the image by activating the Show Color Map Ruler from the icons shown at the top right of the image.

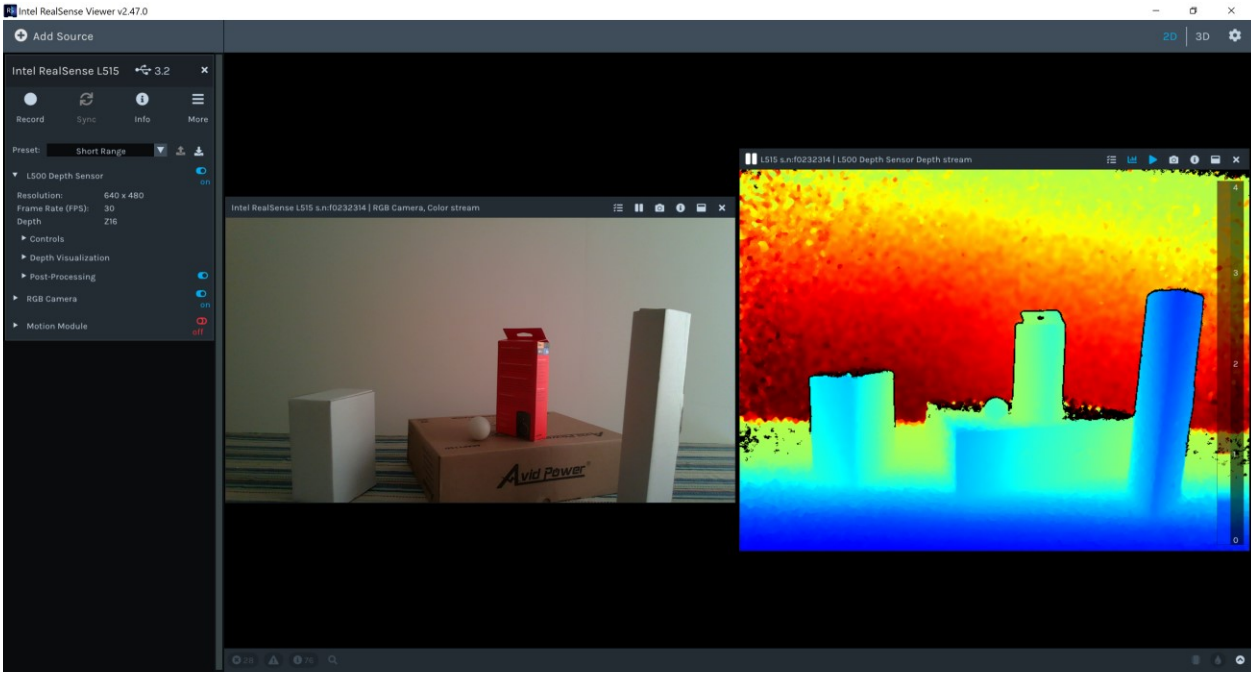
Perform several depth measurements for points located on each of your objects and verify the actual distances with a tape measure tool. Remember the actual distances must be measured along the Z axis that points into the wall. If there is a lot of movement in the image, you can pause the data collection by pressing the Pause button and restart it when needed.

Capture the image you obtained with the L515 in the lab at this time to include in your lab report. Add a caption explaining the content of the image in the lab report. Include the results of all measurements with comparison of the Lidar depth and tape measured distance in the lab report.

If you want to see the RGB camera image side-by-side with the depth image, turn the RGB Camera on from the menu on the left. The images will look similar to Figure 6 below.

You can also experiment with changing the image resolution in the 2D depth image from 640 x 480 pixels to 1024 x 768 pixels. The higher resolution format comes with a loss of maximum range from 9 m to 6.5 m under 95% reflectivity conditions.

The 2D depth map is useful in a variety of applications, but Lidar is capable of also generating high resolution 3D maps of its environment. By contrast, a regular camera can only create 2D pictures which lack the depth information.



Preset: Short Range

L500 Depth Sensor on
Resolution: 640 x 480
Frame Rate (FPS): 30
Depth Z16

Controls
Depth Visualization
Post-Processing
RGB Camera on
Motion Module off

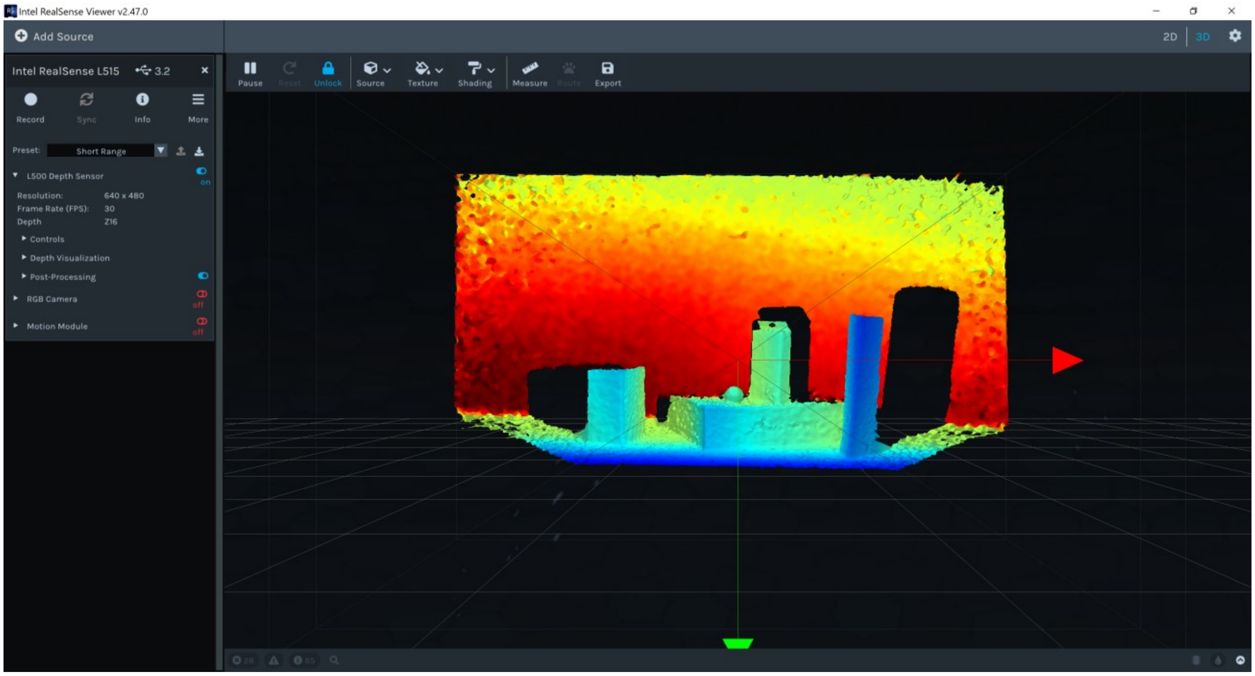
Fig. 6. RGB camera image side-by-side with 2D depth image with color map on.

<u>3D Point Cloud Image:</u> From the top right of the screen select 3D. The image you will see will appear somewhat similar to the one in the 2D depth image, but will also include an XYZ coordinate system having the origin at the location where the emitted laser beam exits the puck. All coordinates are measured with respect to this origin. The difference between the 2D and 3D images is that in the latter we have access to all three coordinates that completely locate the position of an object in space.

Figure 7 shows the 3D image corresponding to the objects in Figure 2. The image is seen from the vantage point of the sensor looking straight ahead at the scene. The X horizontal axis is shown in red, and the Y vertical axis is shown in green. The Z axis is shown in blue, but in this orientation it is not visible because it points straight into the screen. The positive direction for the X axis is to the right, and for the Y axis is down. The Z coordinate will always be positive as the sensor can only detect objects positioned in front of it.

In addition to zooming in and out, the 3D image can be rotated to change the vantage point. By rotating the image, the Z axis will become visible. Experiment zooming in/out and rotating the image to better understand it. It is also possible to change the shading of the image from the Shading chevron at the top of the screen. The default option shown in Fig. 7 is With Diffuse Lighting.

The 3D image shows black areas, or shadows, associated with each object. These correspond to the back of the objects, where the sensor does not “see”. If a 360° view is needed, like in autonomous vehicles for example, the sensor must be rotated or multiple sensors need to be used.



Preset: Short Range

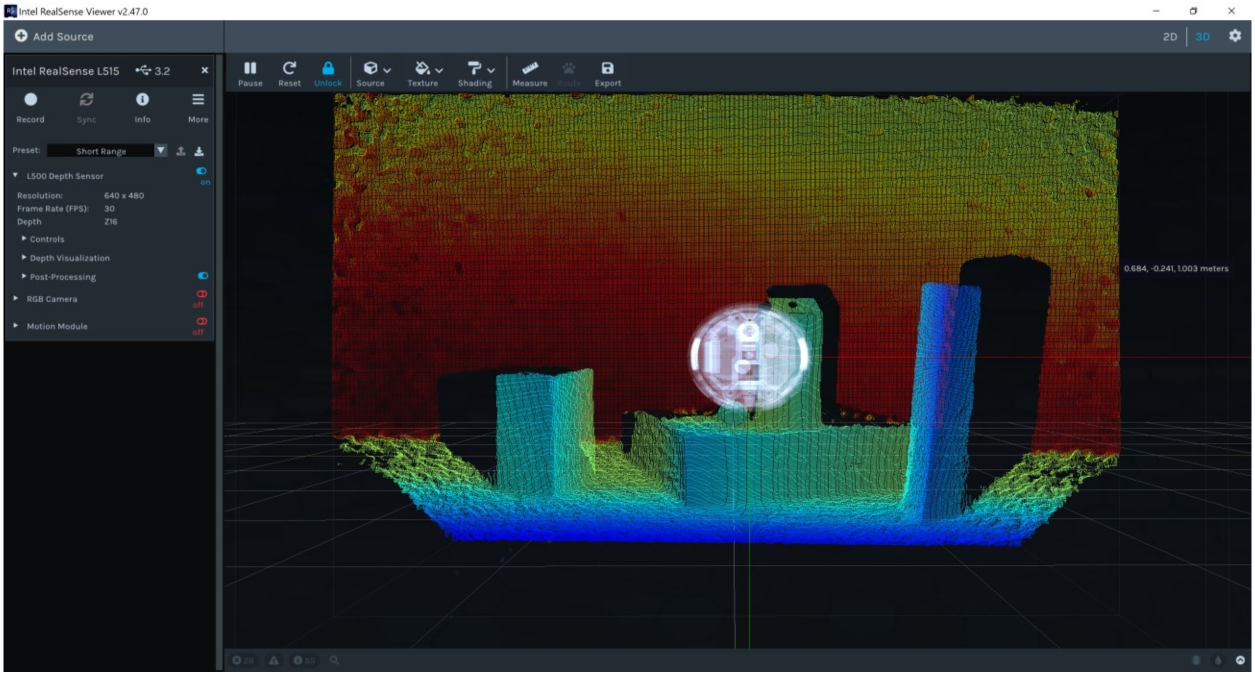
Resolution: 640 x 480

Frame Rate (FPS): 30

Depth Z16

Fig. 7. 3D image. Default shading is With Diffuse Lighting.

Another shading option is Raw Point-Cloud, which produces the image in Fig. 8. This image looks like the familiar 3D point cloud image discussed and illustrated throughout the module. The image includes a representation of the puck in white, showing the origin of the XYZ coordinate system mentioned above.



Preset: Short Range

Resolution: 640 x 480

Frame Rate (FPS): 30

Depth Z16

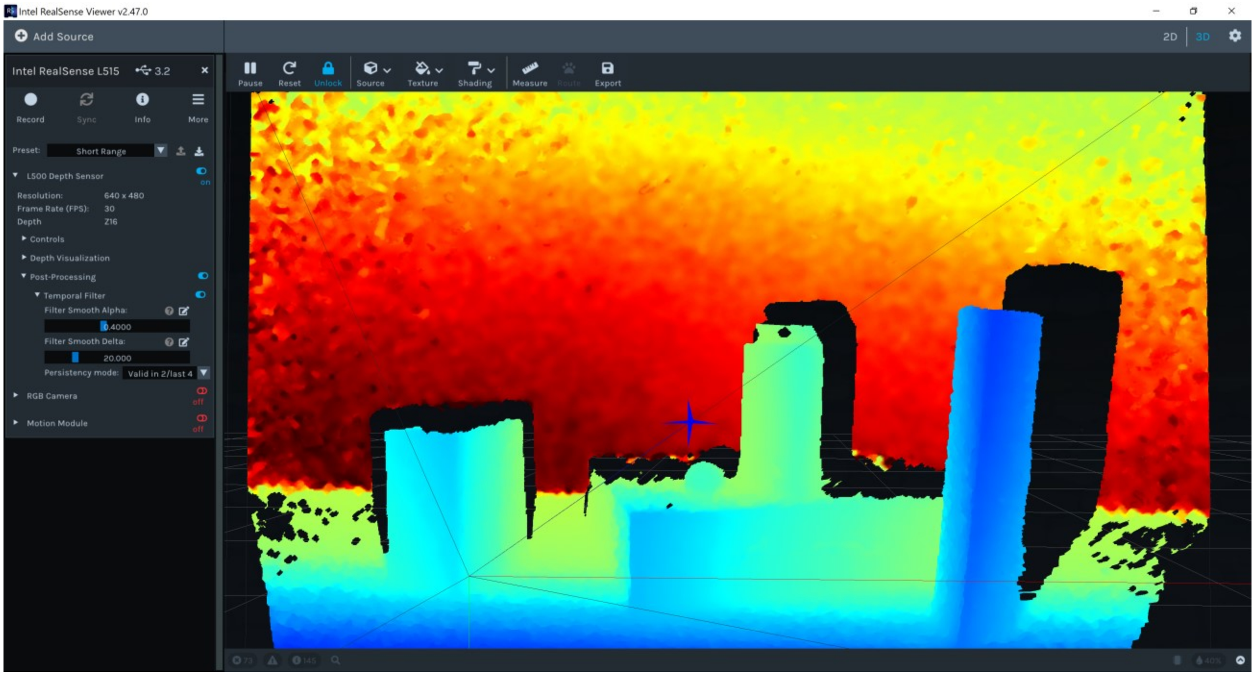
0.684, -0.241, 1.003 meters

Fig. 8. 3D image with Raw Point-Cloud shading.

When moving the cursor across the image, the XYZ coordinates of the chosen point are shown using dimensions of meters. Remember that the positive direction of the Y axis is down, so points above the horizontal plane going through the origin will have negative Y coordinates. Choose one or more points for which to show the XYZ coordinates. Remember not to change the position or orientation of the sensor throughout, which would change the XYZ coordinates values.

Capture the image you obtained with the L515 in the lab at this time to include in your lab report. Add a caption explaining the content of the image in the lab report.

A third option for shading is the Flat-Shaded Mesh, which eliminates some of the color variation in Figure 7, resulting in a solid aspect of the objects. This is shown in Fig. 9.



Intel RealSense L515 3.2

Preset: Short Range

L500 Depth Sensor on

Resolution: 640 x 480

Frame Rate (FPS): 30

Depth Z16

Post-Processing

Temporal Filter

Filter Smooth Alpha: 0.4000

Filter Smooth Delta: 20.000

Persistency mode: Valid in 2/last 4

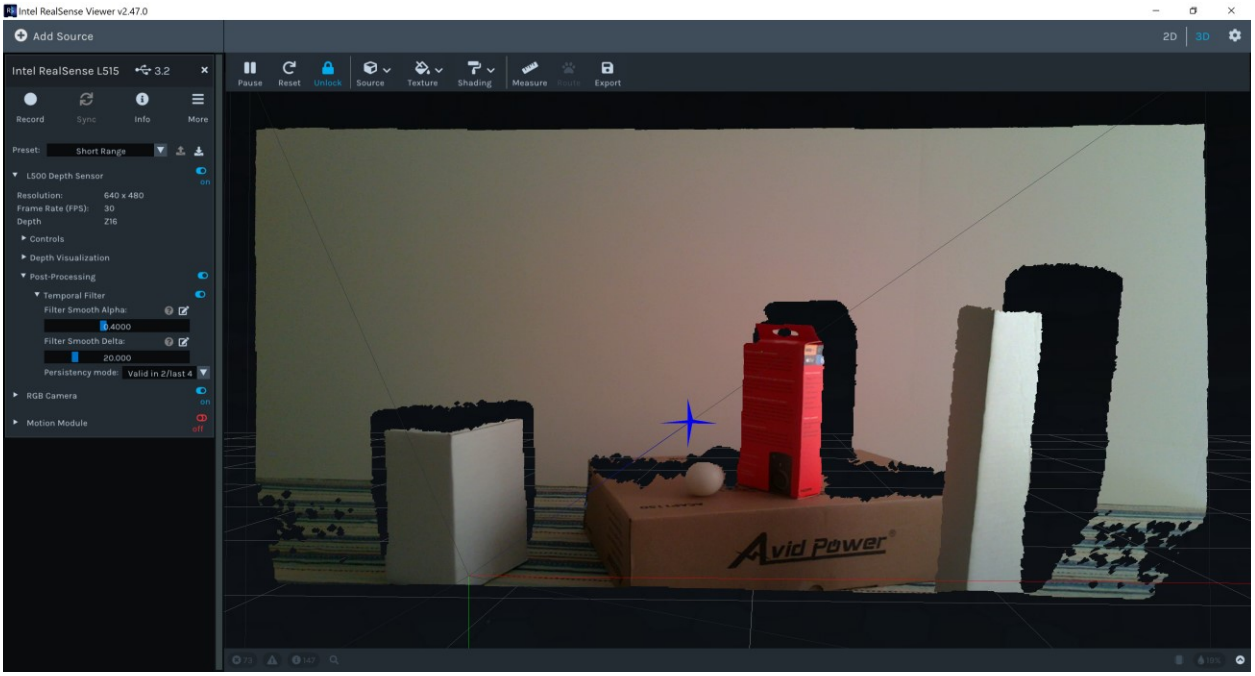
RGB Camera off

Motion Module off

Fig. 9. 3D image with Flat-Shaded Mesh shading.

The SDK 2.0 software allows saving the information from the 3D image in a PLY extension or Polygon File Format file, the same format as the files generated by scanners. Many software programs can read and work with PLY files for further processing of the information.

Finally, it is interesting to superimpose the image from the RGB camera on top of the 3D Lidar image. This can be done by turning the RGB camera on at the same time as the L500 sensor. An example of the resulting image is shown below. As the fields of view of the two sensors are not the same, the superposition requires complex calculations in software.



Preset: Short Range

L500 Depth Sensor on

Resolution: 640 x 480

Frame Rate (FPS): 30

Depth Z16

Post-Processing

Temporal Filter

Filter Smooth Alpha: 0.4000

Filter Smooth Delta: 20.000

Persistency mode: Valid in 2/last 4

Fig. 10. Superimposed 3D image and RGB image.

<u>Measuring Object Sizes in 3D:</u> An important feature of the L515 and associated software is the ability to measure distances between two points in the image directly on the viewer screen. These measurements can be used to determine the dimensions of objects and to calculate their volumes, which is very useful in logistics and robotics applications.

To measure the distance between two points we can use the Measure icon at the top of the screen. By experimenting with this we can quickly see that the Flat-Shaded Mesh type shading works best for measurements, while the Raw Point-Cloud does not work very well. This is because an accurate measurement depends on carefully choosing the two points and making sure they are actually located at the desired positions on the object. If we happen to click on a black portion of the object, the measurement will give an incorrect result. By rotating the object you can ensure that the points selected are the intended points.

An example of the object size measurement is shown in Figure 11.

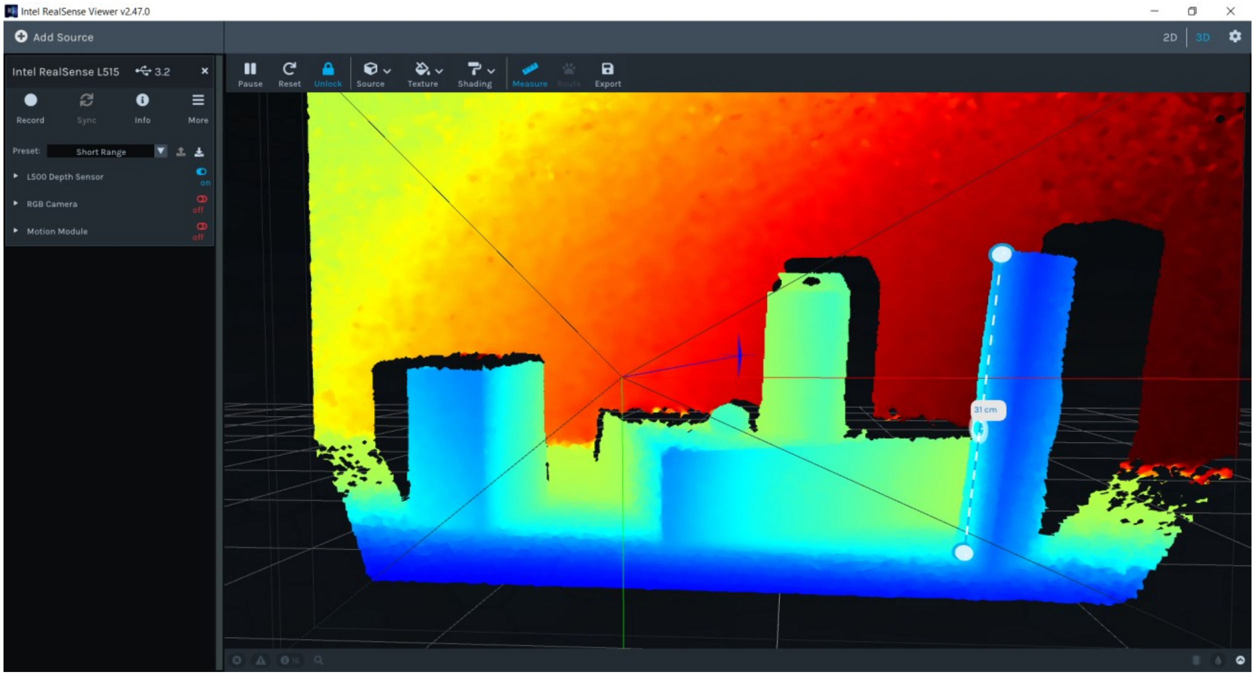


Fig. 11. Measuring the height of an object using the Measure feature.

Determine at least one of the dimensions of each object in your image. Check that you selected the correct endpoints and verify your result using a tape measure.

Capture the image you obtained with the L515 in the lab at this time to include in your lab report. Add a caption explaining the content of the image in the lab report. Include the results of all measurements with comparison of the Lidar distance and tape measured distance in the lab report.

Lab Report and Additional Questions

Assemble your lab report from the images captured throughout the lab with captions explaining what they represent. Provide measured data and calculated accuracy as indicated throughout. Additionally answer the questions below in your report. To help answering the questions it is helpful to review the L515 Datasheet in the References section.

1) What is the wavelength of the laser in the L515?

2) What is the field of view of the Lidar in the L515?

3) What is the maximum range of the Lidar at 15% reflectivity?

4) What are the pulse duration and repetition rates for the laser in the L515?

5) What is the field of view of the RGB camera in the L515?

6) What are some of the applications of the L515 sensor? Describe each application in a short paragraph.

References

[1] American National Standards Institute – Z136.5. Safe Use of Lasers in Educational Institutions. https://www.lia.org/resources/laser-safety-information/laser-safety-standards/ansi-z136-standards/z136-5, accessed 07/26/2021.

[2] Intel_RealSense_LiDAR_L515_Datasheet_Rev003.pdf, https://www.intelrealsense.com/lidar-camera-l515/, accessed 07/26/2021.

Answers to Self-Tests

1. b 2. c 3. c 4. a 5. d

6. b 7. a 8. c 9. d 10. b

11. b 12. d 13. c 14. d 15. d

16. b 17. b 18. d 19. c 20. c

21. d 22. b 23. d 24. d 25. a

Appendix
Module Review Questions Solutions

This appendix includes the solutions to questions 1 - 5 in the Module Review Questions on page 26. These solutions are for instructor use only.

1. The round trip time is calculated using equation (2).

$t = 2R/c = 2*250\ \text{m}/(3 \times 10^8\ \text{m/s}) = 1.67 \times 10^{-6}\ \text{s} = 1.67\ \mu\text{s}$. The correct answer is a.

2. The number of measurements that can be done in one second is the inverse of the round trip time.

$N = 1/1.67\ \text{e-6} = 600{,}000 = 6 \times 10^5$. The correct answer is b.

3. The pulse duration is calculated using equation (3).

$\Delta t = 2\Delta R/c = 2*0.03\text{m}/(3 \times 10^8\ \text{m/s}) = 2.0 \times 10^{-10}\ \text{s} = 0.2 \times 10^{-9}\ \text{s} = 0.2\ \text{ns}$. The correct answer is b.

4. The change in the wavelength is equal to the temperature change times the thermal wavelength shift. Because 1°C = 1K, when looking at temperature differences, the temperature change in °C is the same as the temperature change in K.

$\Delta\lambda = \Delta T \times d\lambda/dT = (55 - (-20))\ \text{K} \times 0.065\ \text{nm/K} = 4.875\ \text{nm} = 4.88\ \text{nm}$. The correct answer is d.

5. From equation (4) the received power is proportional to the inverse of the range squared, $1/R^2$. When the range increases by a factor of 3 from 50 m to 150 m, the received power is proportional to $1/3^2 = 1/9$, which means the received power decreases 9 times. The correct answer is c.

Glossary of Terms

Altimeter: an instrument for determining altitude attained, especially a barometric or radar device used in an aircraft.

Bandwidth: a range of frequencies within a given band, in particular that used for transmitting a signal.

Coherence: a fixed relationship between the phase of waves in a beam of radiation of a single frequency. Two beams of light are coherent when the phase difference between their waves is constant.

Designator: laser light source that is used to designate a target. Laser designators provide targeting for laser-guided bombs, missiles, or precision artillery munitions.

Duty cycle: fraction of one period in which a signal or system is active. Duty cycle is commonly expressed as a percentage or a ratio. A period is the time it takes for a signal to complete an on-and-off cycle.

Interference: the combination of two or more electromagnetic waveforms to form a resultant wave in which the displacement is either reinforced or canceled.

Jitter: slight irregular movement, variation, or unsteadiness, especially in an electrical signal or electronic device.

Lidar: method for determining ranges (variable distance) by targeting an object with a laser and measuring the time for the reflected light to return to the receiver.

Linewidth: spectral width of the laser light beam.

MEMS: the technology of microscopic devices, particularly those with moving parts. Device sizes are generally between 20 μm^2 and 1 mm^2.

MOEMS: optical MEMS; integrations of mechanical, optical, and electrical systems that involve sensing or manipulating optical signals at a very small size.

Mode locking: optical technique by which a laser can be made to produce pulses of light of extremely short duration, on the order of picoseconds (10^{-12} s) or femtoseconds (10^{-15} s). The basis of the technique is to induce a fixed-phase relationship between the longitudinal modes of the laser's resonant cavity.

Monochromatic: electromagnetic radiation of a single frequency or wavelength. No source of electromagnetic radiation can be purely monochromatic, however the term is used to specify narrow linewidth lightwaves such as those emitted by a laser.

Pixel: the smallest element of an image that can be individually processed in a video display system.

Point cloud: A set of data points in space that may represent a 3D shape or object. Each point position has its set of Cartesian coordinates (X, Y, Z).

Q-switching: technique by which a laser can be made to produce a pulsed output beam with extremely high peak power, much higher than would be produced by the same laser if it were operating in a continuous wave mode.

Range: distance to a target.

Rangefinder: any of various instruments for determining the distance from the observer to a particular object, as for sighting a gun or adjusting the focus of a camera.

Repetition rate: the pulse repetition rate (or pulse repetition frequency) of a regular train of pulses defined as the number of emitted pulses per second, or more precisely the inverse temporal pulse spacing.

Time-of-flight principle: method for measuring the distance between a sensor and an object, based on the time difference between the emission of a signal and its return to the sensor, after being reflected by an object.