Higher Surveying
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Module – 7
Lecture – 23
LiDAR (LiDARgrammetry)

Hello, everyone. Welcome back, in the course of Higher Surveying and today, we are in the new module on LiDAR. In this module, we are going to talk about the LiDAR grammetry or LiDAR, ok. So, this module has four lectures.

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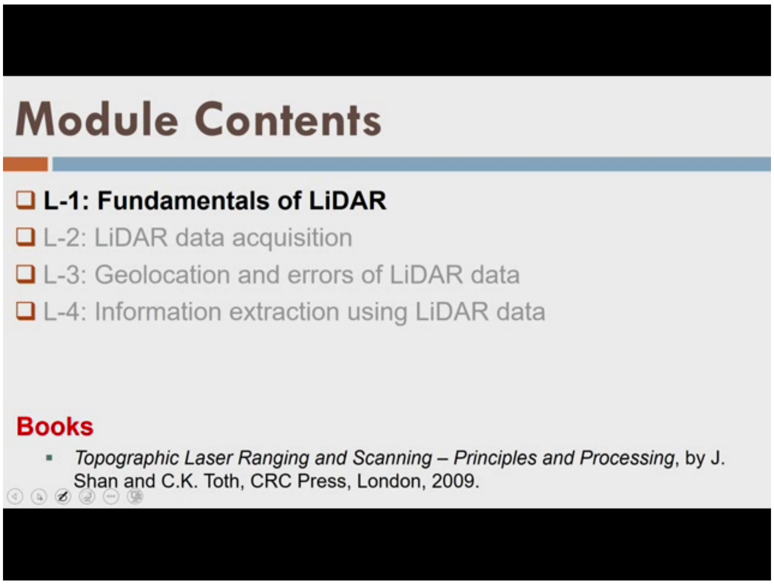

Module Contents

- ☐ **L-1: Fundamentals of LiDAR**
- ☐ L-2: LiDAR data acquisition
- ☐ L-3: Geolocation and errors of LiDAR data
- ☐ L-4: Information extraction using LiDAR data

Books

- *Topographic Laser Ranging and Scanning – Principles and Processing*, by J. Shan and C.K. Toth, CRC Press, London, 2009.

The first lecture that we are going to cover today is about the fundamentals of the LiDAR. So, these are the four lectures and this is the book we recommend for the this module and that is book is Topographic Laser Ranging and Scanning – Principles and Processing by J. Shan and C. K. Toth. Again, I urge you to join some library to avail this book.

So, let me give you an historical perspective why LiDAR has emerged as a new and alternative technology to the existing technologies, like photogrammetric or RADAR or will be some any other technology, right. In 1990s when photogrammetry or analytical photogrammetry was on its peak, but still it was facing some problems on limitations. The first limitation was related to the high photographic resolution.

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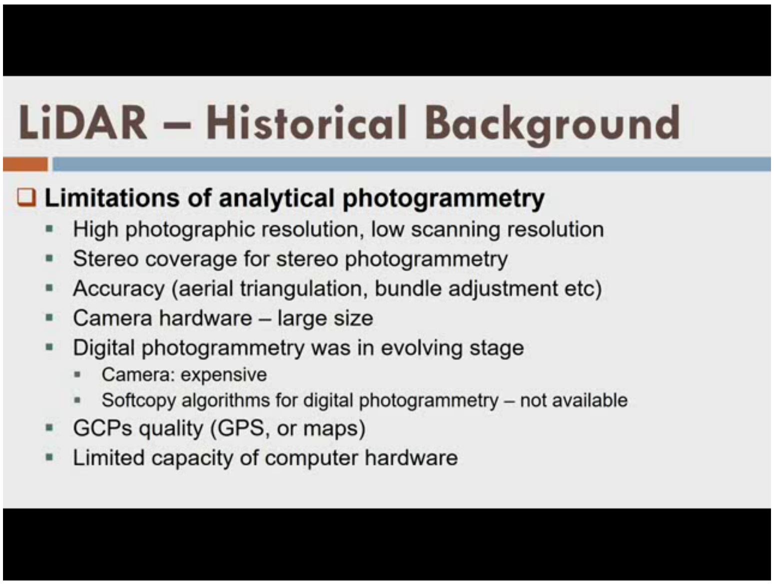

LiDAR – Historical Background

- **Limitations of analytical photogrammetry**
  - High photographic resolution, low scanning resolution
  - Stereo coverage for stereo photogrammetry
  - Accuracy (aerial triangulation, bundle adjustment etc)
  - Camera hardware – large size
  - Digital photogrammetry was in evolving stage
    - Camera: expensive
    - Softcopy algorithms for digital photogrammetry – not available
  - GCPs quality (GPS, or maps)
  - Limited capacity of computer hardware

That means, although the photographs were acquired at very high resolution 150 lines per millimeter or 250 lines per millimeter; however, when these photographs were converted to the soft copy images by scanning that scanner resolution was the real limitation.

So, I remember when I was a student the maximum resolution which was easily available was 2400 dpi of a scanner. In 1990 2400 dpi was very high resolution in those days that was the first limiting factor. For photogrammetry we have to have the stereo photographs. For the sterio coverage the lot of planning was required and it was a combustions process and secondly, the logistics of the aerial photography was always there in place, right. Apart from that after processing the 2D images we used to get the 3D data.

Moreover the accuracy whether the aerial triangulation or the bundle adjustment that was not so excellent the way it is today and that was one of the limiting factor that the accuracy of aerial triangulation was around 2.5 pixel best something and pixel size as very high or poor or the pixel size was very poor some few meters and even, what about digital photogrammetry was, yes the digital photogrammetry was in the place, but it was in the evolving state and that is why none of the algorithms like SIFT or SURF or any other algorithm was not in place. And, further we say that the cameras which were using the films they were very expensive as well as large in the size. Moreover, digital camera they were in the evolution stage in those days that is why they were also very expensive. Secondly, they were large size also.

So, these were the all limitations that give rise to an opportunity that we should have some technology that can give us the direct 3D data without GCPs, because even the GCPs that we use in photogrammetry they were collected by the GPS or maps and GPS and maps both for very low accuracy. You remember GPS was having selective availability, similarly maps which were very old. So, this, but the limitations and it was a natural opportunity to emerge a new technology. LiDAR is one of such technologies that emerge due to some limitations of other technology, ok. It is not like that it has not it was not developed, but yes, there was an opportunity also.

So, let us go ahead and try to see how LiDAR works, ok.

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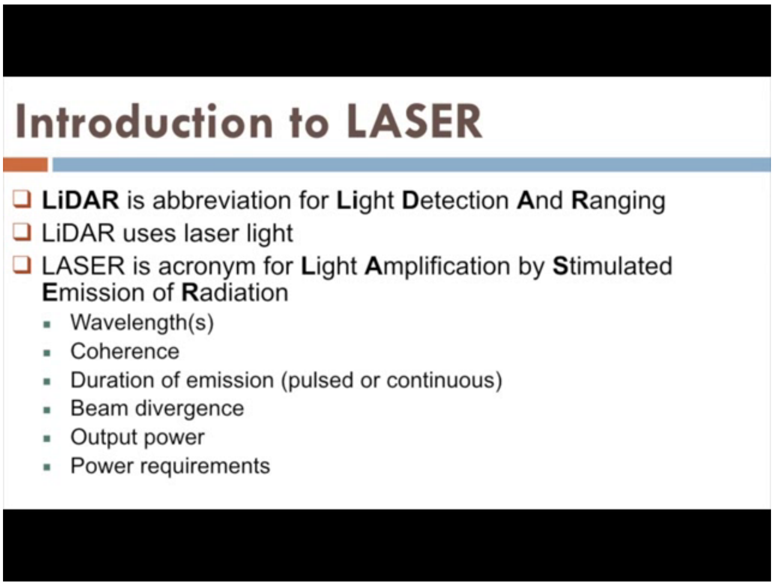

Introduction to LASER

- ❑ **LiDAR** is abbreviation for **L**ight **D**etection **A**nd **R**anging
- ❑ LiDAR uses laser light
- ❑ LASER is acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
  - Wavelength(s)
  - Coherence
  - Duration of emission (pulsed or continuous)
  - Beam divergence
  - Output power
  - Power requirements

So, LiDAR is an abbreviation for Light Detection and Ranging ok. LiDAR uses the laser light, ok. Why laser light? So, let us first try to understand what is the LASER and how is it useful in order to do the ranging and detection, ok. So, LASER is an acronym for Light Amplification by Stimulated Emission of Radiation, right. So, it has some certain characteristic like wave length, coherence, duration of emission, beam divergence, output power and power requirements.

So, we are going to talk about all this thing in order to learn the laser in a very comprehensive manner today, but before that let us first understand what do you mean by stimulated emission ok. Now, let us talk about the spontaneous emission.

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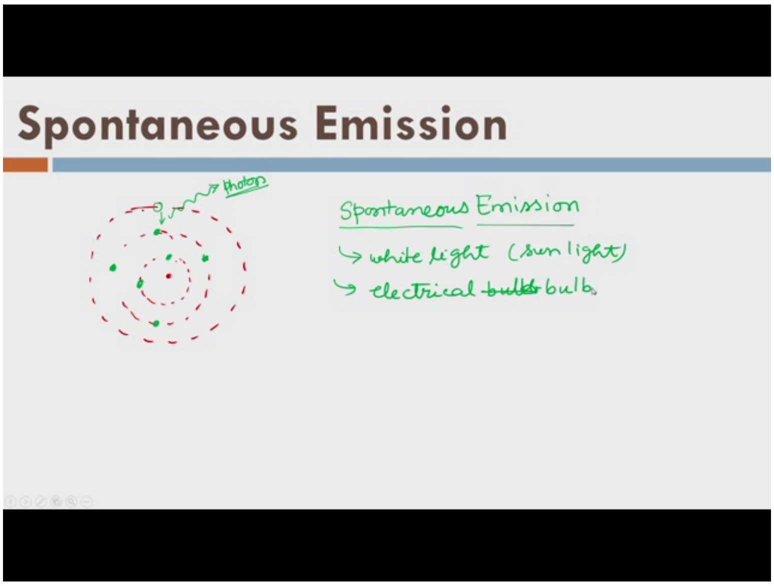

Spontaneous Emission

Spontaneous Emission

↳ white light (sun light)

↳ electrical ~~bulb~~ bulb

What is spontaneous emission? We know by the quantum physics that if there is a nucleus of a atom and there are some orbits of electrons like this. So, their fixed level of energy, this could be let us say electrons which are moving in this orbit, fine. Now, what happens is because these electrons get some energy and they go to this level and later on they release the energy and again come back to the their original state and during this process they releases energy.

So, energy is released as photon and this process is called the spontaneous emission. The surprisingly this photon is having some wavelength. So, you will be surprised how a photon which is a kind of energy particle how can it have a wavelength. Now, remember that light has dual nature. So, light when travels in the space it behaves like a wave, but when it interacts with the surface it behaves like a particle. So, that is why we can say that the photon when it travels it has some wavelength. So, when he interacts with some surface it is like a particle, right. So, with his idea we say that the spontaneous is releasing some energy at certain wavelength.

So, now, we can see that this photons they have different wavelengths and that is why we see the white light. The first example is the white light you see, because it has the photons of all wavelengths. So, when all wavelengths lights are mixed the create the white light. Similarly, the another example is electrical bulb where, yes, in case of electrical bulb when the electricity supplied to the filament photons which are emitted by that filament material that is an another example of the spontaneous emission.

So, what is the effect of the spontaneous emission? So, whatever color we see of any material quantum physics explain that is because of the spontaneous emission. Well, let us go ahead to the stimulated emission.

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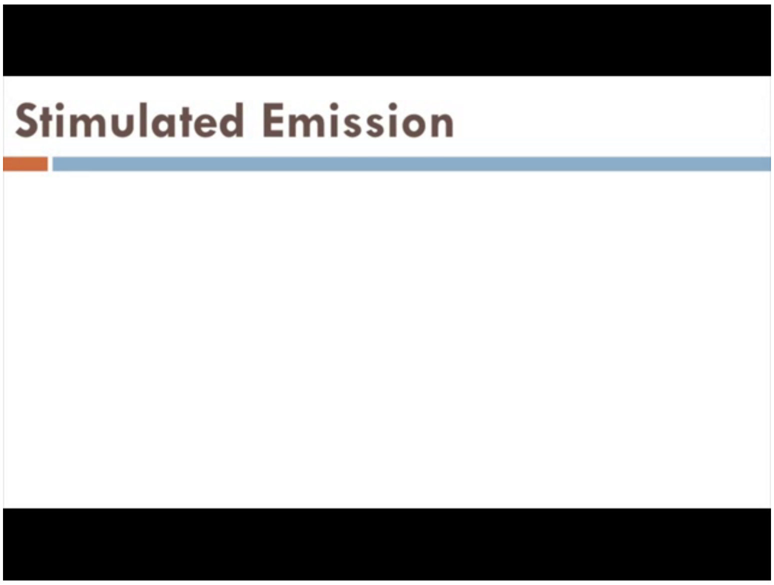

Stimulated Emission

Now, in case of a stimulated emission what happens, when we deliberately stimulate some of the atoms by giving energy and that energy when it is released in form of photon then it will have certain wavelength. Now, imagine that all the photons which are released by many atoms are in the same wavelength, right and because of that what will happen they will give the same color, right. I hope you understand because wavelength is same and we characterize the color by the wavelength. So, they are giving the same color all the photons. So, that is the first thing about the stimulated emission.

Now, what do you mean by stimulation. So, we are stimulating the atoms, so that they are excited and in the excited state the one photon is released by one atom and that photon will trigger another atom. So, now we have two photons these two photons these two photons will trigger two more atoms then we have four photons and that is why it is called the process of amplification in case of stimulated emission. So, now, we have first of all a stimulation then we have the amplification. So, now, because of that we have a stream of photons available to us after certain duration and that creates the LASER.

So, now you can understand what do you mean by stimulated emission and what is the must condition. The must condition is first of all that I should have the photons of the same wavelength. One more condition it is required here that these photons should be of the same phase; that means, the wavelength are not only same, but the waves are also having in the same face and we will talk about this two characteristics in coming slides. So, we generate the laser by the stimulated emission. First of all let us go to the wavelength, ok.

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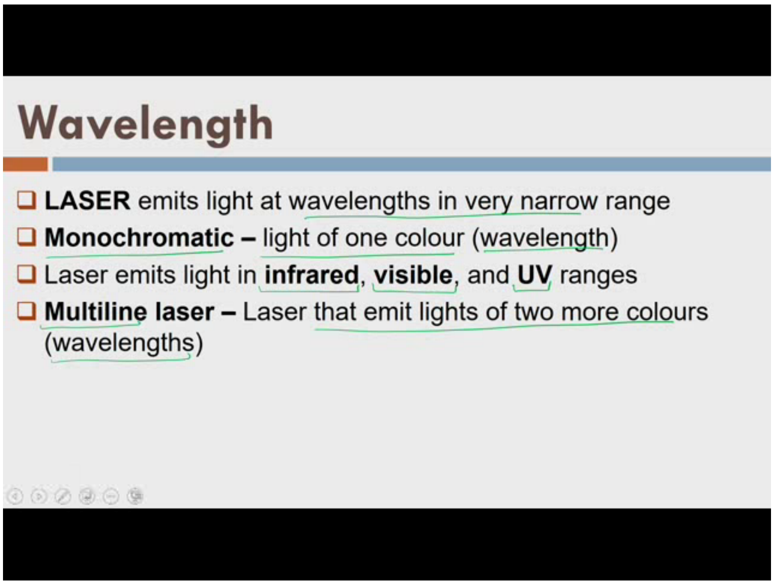

Wavelength

- ❑ **LASER** emits light at wavelengths in very narrow range
- ❑ **Monochromatic –** light of one colour (wavelength)
- ❑ Laser emits light in **infrared**, **visible**, and **UV** ranges
- ❑ **Multiline laser –** Laser that emit lights of two more colours (wavelengths)

So, as I told that all the photons which are triggered by the stimulated emission, they have the same wavelength, fine. As a result they are monochromatic; that means, they have they produce the light of one color or light of one wavelength, right. The reason is that it is not that exactly all the photons have the same wavelength, but they wavelength are in a very small range that is written here, the laser in the infrared, visible and ultraviolet ranges, ok. What about the other ranges, for example, gamma ray, x-rays, or micro wave? Yes, we do have the lasers in these ranges also.

However, especially we gamma rays and x-rays laser are very harmful for the human and that is why we do not prefer those. At the same time micro wave which is having very higher wavelength even laser can be generated in that range. However, that will not be so accurate for the topographic mapping and that is why we also avoid the micro wave laser ok. What next? We have the laser that emits lights of two or more colors it is called multiline laser; that means, it is having certain wavelength at those wavelength it is a emitting the light, ok. So, that is my wavelength.

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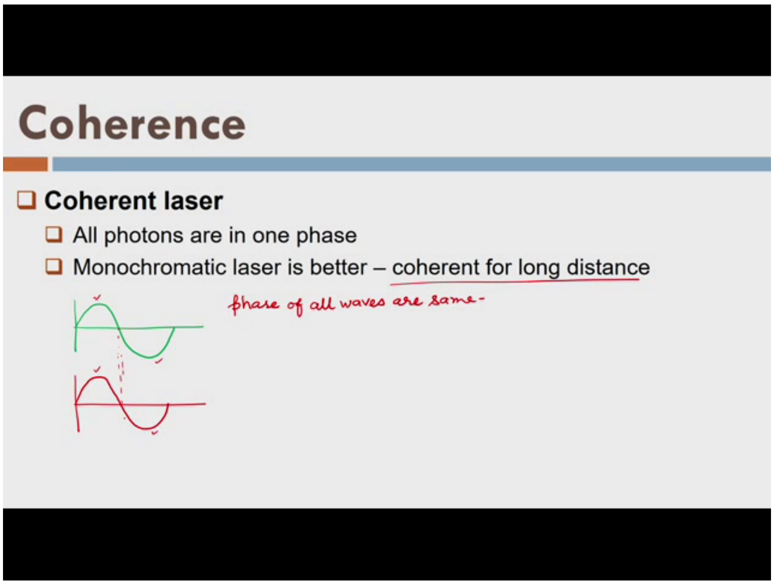

Coherence

- ☐ **Coherent laser**
  - ☐ All photons are in one phase
  - ☐ Monochromatic laser is better – coherent for long distance

phase of all waves are same-

Now, coming to the next property called coherence as I told that all the photons in laser those photons are having the same face. Here before explaining you the coherence, I would like to the give an simple example, right. So, now, you see that the soldiers are moving their hand during the march past in one rhythm; that means, when all the soldiers moving, so, they will either raise their hand or they will low down their hands, similarly their legs also there. So, for each and every soldier I can say that all the soldiers are moving in a rhythm or in a same pace, right and their moving along a certain direction on a straight track or may be convenient track. So, that you can assume that their movement is like a wave and their hand movements is like having the same phase.

So, that means, a wave is moving with photons are. So, if you assume that each soldier is a like a photon now you got the concept what is the wave and how photons are moving in same phase. So, what does it mean you already said they have the same wavelength. So, let us see I am drawing the wavelength of a wave like this ok, let us draw another one. So, if they have same wavelength and same phase. So, wavelength this is same wavelength I have here, but they have the same phase also because peaks are matching or the valleys are matching here, right and because of this we say that in case of coherence the phase is same. and that is what the laser has. All the photons are all the waves are having the same phase.

What is the advantage here? The advantage is first their monochromatic and so, they have the same color they have same wavelength, ok. Not only that once they are in the same phase and so, that travel for the long distance they show the coherence for the very long distance and I can give you a simple example here.

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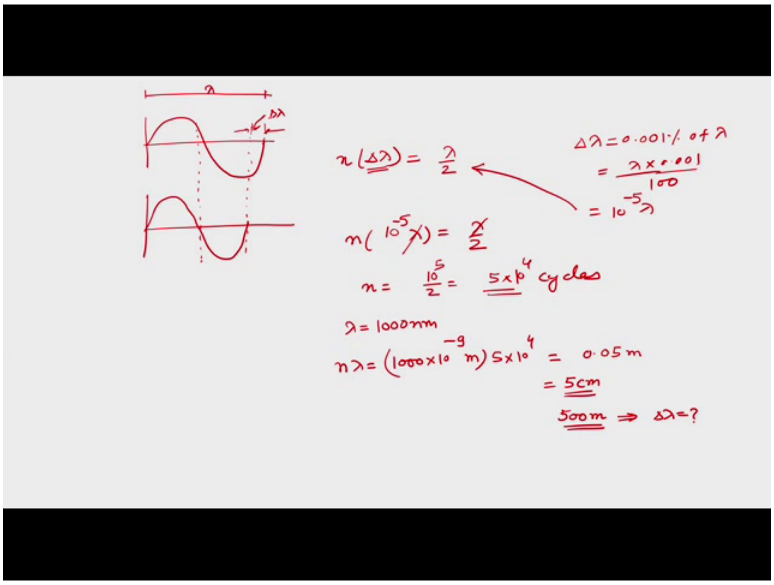

$n(\underline{\underline{\Delta\lambda}}) = \frac{\lambda}{2}$

$\Delta\lambda = 0.001\%$ of λ

$= \frac{\lambda \times 0.001}{100}$

$= 10^{-5}\lambda$

$n(10^{-5}\cancel{\lambda}) = \frac{\cancel{\lambda}}{2}$

$n = \frac{10^{5}}{2} = \underline{\underline{5\times10^{4}}}$ cycles

$\lambda = 1000 nm$

$n\lambda = (1000\times10^{-9} m)\, 5\times10^{4} = 0.05 m$

$= \underline{\underline{5 cm}}$

$\underline{\underline{500 m}} \Rightarrow \Delta\lambda = ?$

Let us see that we have 2 wavelengths which I shown in the last slide. Let us say there is some wavelength difference. So, this is my first wavelength and the second wave is which is slightly different we can say here. So, it is like this, this is my we can say the difference of the wavelength here delta lambda I call it. Remember, this is my total lambda. So, this is my delta lambda, right. Now, you can see here that as these two wavelength are propagating what will happen at every one cycle they will accumulate the difference of delta lambda. So, after n number of cycle they will accumulate some amount of lambda, the same amount of difference of face and let us say that face as change after n cycles. So, what will happen, it becomes lambda by 2, right. I hope you agree.

Now, let us take that delta lambda is 0.001 percent of lambda which means lambda into 0.001 divided by 100 or I can say 10 is to power minus 5 lamda. Now, if I put this value here what will I get n into 10 is to power minus 5 lamda equal to lamda by 2, lamda by cancel and n is equal to 10 is to power 5 divide by 2 which is nothing, but 5 in to 10 is to power 4 cycles, right. So, after this minutes cycle this two wave they start showing the destructive interference because their phase are completely changed right and with that we do not want and hence you can see that if my lamda which is the typical value is of laser is let us say this value 1000 nano meter.

So, what will happen n into lamda is nothing, but 1000 into so many meter into an what will call here test power 4 and that gives me 0.05 meter; that means, by within 5 centimeter these two waves or these two photon waves of laser will become completely uncoherent, right and that is why now we can say that what is the tolerance of delta lamda now? That means, how delta lamda is very small extremely small such that the coherence is achieved in case of laser.

Now, think that if this 5 centimeter is 500 meter or 5 kilometer you can think you can find out what should be the delta lamda value. Try it yourself, try to find out, right, ok. So, I hope that I have explained you what is the coherence and what is the meaning of the monochromatic or what is the meaning of same wavelength that is monochromatic and what is the meaning of coherence the waves having the same phase, right. Let us go ahead.

Now, one more property comes hear the duration of emission. Now, let us assume that you have a laser torch like that this is laser torch, fine. So, the laser torch is here turn it on and keep it turning on. As a result the laser photons are been emitted by the laser torch and so, they are emitted and they are travelling. So, the continuous stream of that laser photons will create a wave, right ok. So, what will happen? So, this continuous stream of the photos they will go, they will interact to the surface come back and what we call the reflected one and then we measure it again and we try to measure some kind of attribute in the space, maybe the distance or maybe some other characteristic or maybe some other attribute. So, that is the idea here how to use the laser, right.

Now, there is another concept called pulse. Let us say you again you have a torch and you click it turn it on and turn off. So, during that short duration of turn on to turn off, the torch will emit certain number of photons for a very short duration and that is what we call the pulse. Those number of photons will travel now again they will also interact to the surface and comes back and again will measure those and, so, we are meeting the pulses now.

So, best example of pulse is our heartbeats, right our heart vibrates like this. So, it gives 72 pulses in a minute. Sometimes you might have seen some medical experts they measure the pulses on the wrist of a patient, what does it mean? Basically they are trained to count that how many pulses are coming or how many you know signals are coming into that small duration of 1 minute. If it is around 72, well, patient is ok, it heart is working well. However, if it is otherwise they take the cognizance of that, they notice it, right. The idea here is the heart is also creating some pulses or heart is vibrating. So, it is kind of creating a pulse; that means, it is on off on off.

So, that is the idea about the pulse, ok.

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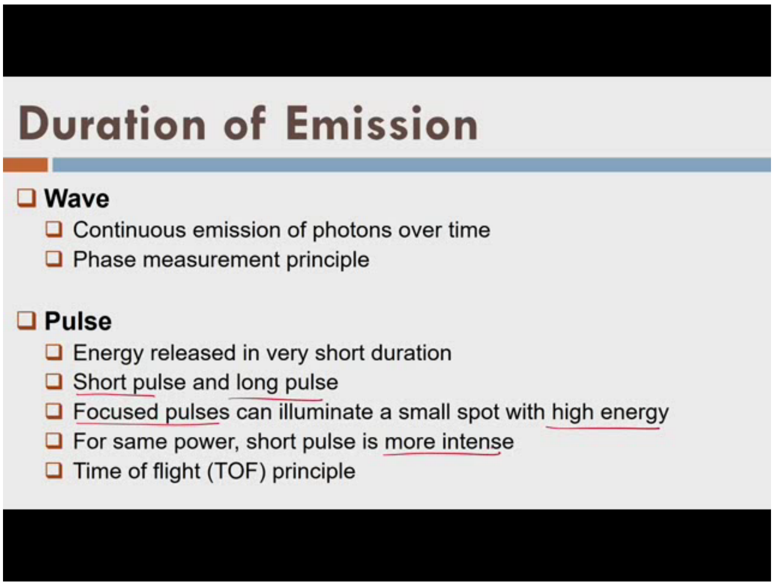

Duration of Emission

- ☐ **Wave**
  - ☐ Continuous emission of photons over time
  - ☐ Phase measurement principle
- ☐ **Pulse**
  - ☐ Energy released in very short duration
  - ☐ Short pulse and long pulse
  - ☐ Focused pulses can illuminate a small spot with high energy
  - ☐ For same power, short pulse is more intense
  - ☐ Time of flight (TOF) principle

So, we can see here that they are some short pulses and long pulses. What is the short pulse? A plus which is triggered in a short duration is called short pulse and comparatively if the same number of photons are triggered in a slightly longer duration, it is called long pulse. But, there is a condition here that in general when we call there is a pulse which means it should be triggered with in a second and that is why we have more number of pulses triggered in 1 second at least more than one pulse we have always, right, ok.

What about the focused pulses? So once pulse is triggered it travels in the space, it interacts with the surface it interacts with the some surface area of the object and if it interacts with the larger area of a object what will be happen the number of photons will be divided over that surface and the returned signal will be weaker. Why, because it the number of photons are fixed and they are interacting with large area. However, if the pulse is focused it will interact with very small area and number of photons that will be responded back will give a better information or rather it will give the pinpointed information. So, we say that focused pulses can illuminate a small spot with high energy. I hope these concepts are now becoming clear to you ok.

Also, since the short pulse is the short duration over which we trigger the some photons. Hence they are more intense. Why because you can understand that over the short duration we are triggering the same number of photons they are travelling, they are interacting with the surface and they are reflected back. So, they will be definitely more intense because they are interacting in a small duration or the short duration compared to a longer duration, right ok. There are two things now, one is wave and one is pulse we have understood both, ok.

In case of pulse what happens is since we trigger the photons in a very short duration those photons travels in the space interacts with the surface come back. And so, we measure the time difference between the triggered pulse and the received pulse and, so, we try to measure the distance based on the time of flight or what we call it time difference between the triggered and received pulse and this is called the time of flight principal.

On the other hand, in case of wave since we are continuously triggering the photons over the time so, what happens is wave goes interacts with the surface comes back and we try to measure the phase of the two waves one is triggered and another is received. So, the difference of phase gives us the information about the distance from the laser emitter or receiver and the object. The wave based principal we have already seen in the basic surveying course where we have learnt all modulation technique and so on about the total station.

So, this are the same thing, but the time of flight principle is different and will see that for topographic mapping time of flight principle is more popular for longer distances which are in kilometers and that is specific to the LiDAR, right.

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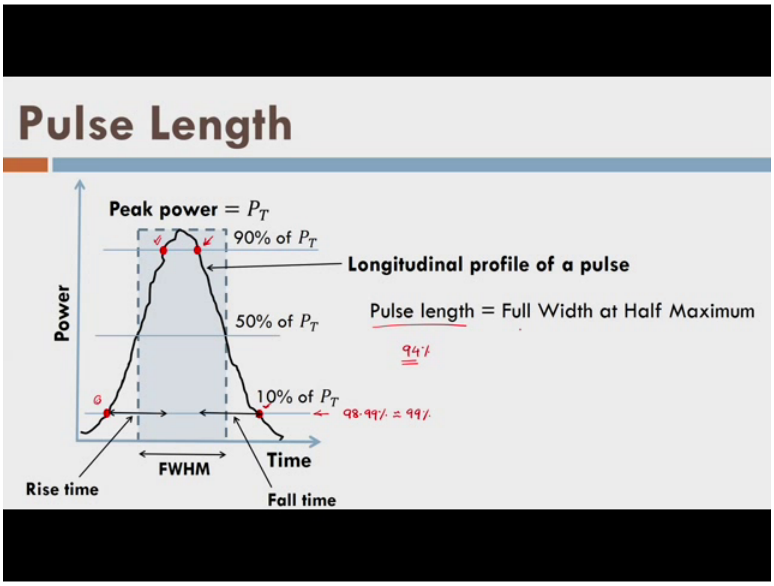

Pulse Length

Pulse length = Full Width at Half Maximum

Now, for a pulse let us try to understand how pulse is or what are the attributes of a pulse that helps us to do the topographic mapping. So, let us see this a power and time curve and this is my pulse. So, that is the longitudinal profile of a pulse, right and it looks like a normal curve the normal distribution curve and we can moderate also like that, fine, but suppose if I moderate like a normal distribution curve first try to see this is my peak power pt ok. So, this is my 10 percent of the peak power and now I draw this are the two points this point and this point, right.

If I take this level here and try to find out the curve, area of the curve this power time curve you will be surprised that the area under this curve if I assume it to be normal it is approximately 98.99 percent area of the total area all we can I can say 99 percent apart from that if I see the 90 percent of the peak power. So, I have marked these two points, right ok. So, the time from this point here to this point here longitudinal profile is rising up and so, we call it the rise time of laser pulse. Similarly, from this point here to this point laser longitudinal profile will fall, so, we call it the fall time and this rise time and fall time are very small because we are triggering the number of photons in very short duration. So, it reaches to the peak power comes back very fast, that is a concept here. So, rise time and fall time are very small.

Now, I want to model this laser pulse on the longitudinal profile of the laser pulse in a very easy manner. So, what can I do here? We defined a third level which is 50 percent or what we call is the half of the maximum then withdraw this rectangular box. If I calculate the area of this rectangular box then it is equal to the almost 94 percent of the total area under this curve or under the longitudinal profile of a pulse and that is why we say that that is a good approximation this rectangle box. And, the corresponding time length which is shown by the arrow here on the screen it is called full width at half maximum, right. Again I repeat, full width which is this width at half maximum because we are considering only 50 percent which is half of the maximum, right.

So, now, this FWHM is known as pulse length, ok. So, that is my pulse length here. So, full width at half maximum.

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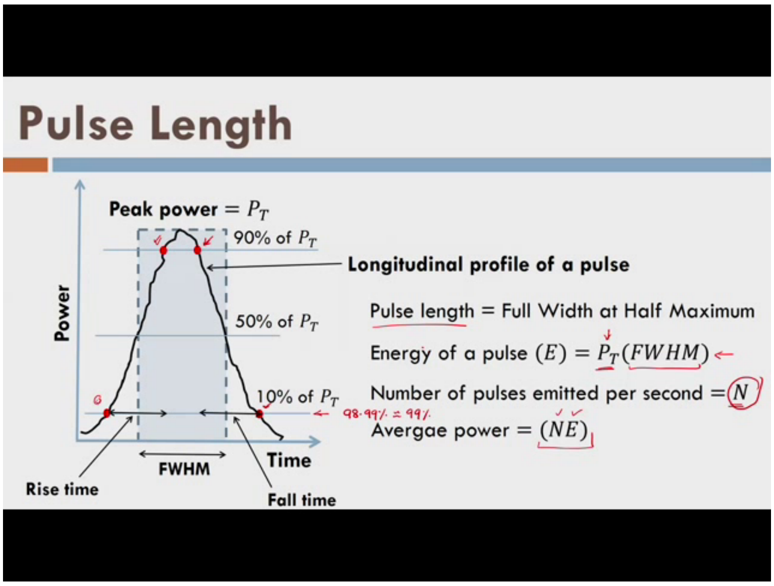

Pulse Length

Pulse length = Full Width at Half Maximum

Energy of a pulse $(E) = P_T(FWHM)$

Number of pulses emitted per second $= (N)$

Avergae power $= (NE)$

And, now we can say that what is the energy of a pulse is equal to the peak power into FWHM; that means, energy content within a pulse is equal to peak power peak power into pulse length, right. So, now, I have approximated my laser pulse which is normally distributed by a rectangular box. It is easy to deal or make any estimates with the rectangular pulse now.

So as I told already that short pulses are there. So, we are triggering more than one pulse in a second and suppose we trigger N number of pulse in one second how much energy do I need to trigger N number of pulses and each pulse is having this much of energy, ok. So, that is my average power I need in order to trigger N number of pulses each having e energy. So, now, we can see that since we are triggering our pulse over a very short duration which is FWHM my P T is very high sometimes 2 kilowatts. Why because the 2 kilowatts is concentrated over very short duration and that is what we call pulse and that is why we can have and very high; that means, I can you know release sometimes 10 is to 5 pulses in 1 second and that is somehow advantage of the laser and that is why we want to use it in order to do the topographic mapping we want to use the laser, so that we can acquire the data at very fast rate with high accuracy.

Now, try to understand the beam divergence which I just named in the last slide what is the beam divergence, ok. As I told that the laser is a light it behaves like a wave also ok. So, it deflects, it refracts, it reflects it get polarized and so on.

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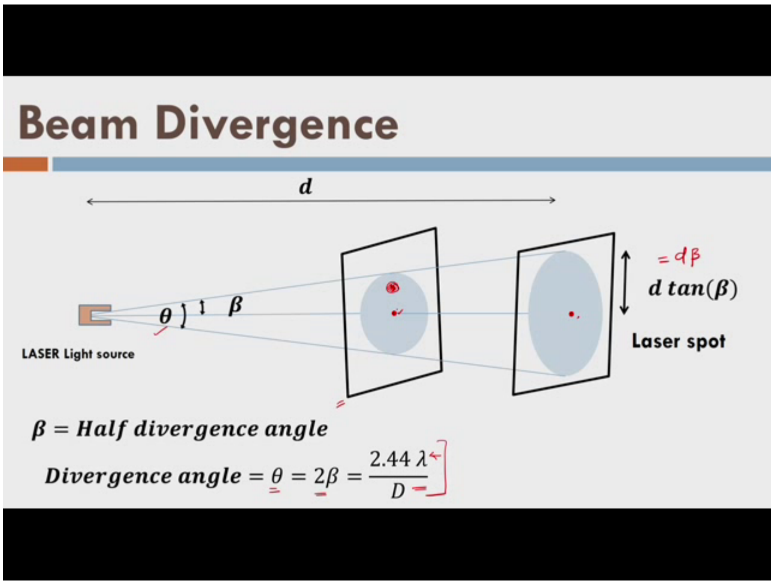

Beam Divergence

$\beta = Half\ divergence\ angle$

$Divergence\ angle = \theta = 2\beta = \frac{2.44\,\lambda}{D}$

So, now we see there is a laser light source and it has some opening and because of that opening the laser light is deflecting at the corners of that opening and as a result it will create and spot or it will illuminate some area not a point it will illuminate some area on the object surface which is this. Let us see how does it do. So, this is distance d the from the laser light source and the object surface and now, this is spot is created by the laser pulse my area of interest is this point the center right, point. However, a spot is created by laser pulse.

So, the laser spot is basically ambiguity because I am thinking that I am the laser pulse is reflected back from this point. However, this is reflected from this whole area and I do not know which part is more reflective with in this foot print let us say that this part is reflective more reflecting and it is reflecting more energy compared to the remaining part of the footprint or the spot. So, what will happen I will assume that this red part is located here at the center. So, basically the my laser spot is a ambiguity or the uncertainty in the position of my point, ok.

So, this is my beta angle which is call half beam divergence and now increase the distance the what will happen definitely because of the distance increase because of the increase in the distance d what will happen the a spot the laser spot size will increase and now you can understand that as we increase the distance from the light source to the object ambiguity will increase, right. Now, the radius of the laser spot is given by d tangent beta you can just do it a simple mathematics, moreover if beta is very small what will happen I can make it equal to d beta, right.

So, the beta is my half divergence angle and the divergence angle or the beam divergence is called theta which is equal to 2 beta and shown here is given by 2.44 lamda divide by D. D is my size of the aperture of the transmitter or size of the opening of my transmitter and lamda is wavelength of the laser. Now, you can understand that if I want to reduce the ambiguity or uncertainty in the position of this point on maybe this point what can I do I can reduce the lamda. Again, remember few slides back I told that reducing lamda has some limitation because it is not good for the biological life or human life and that is the reason we always have some limitation on the laser pulse or laser wave because there will be some uncertainty.

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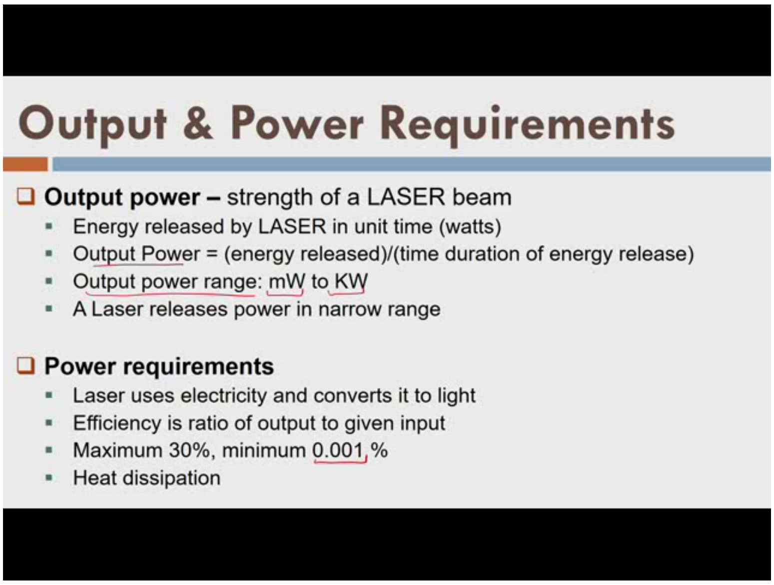

Output & Power Requirements

❑ **Output power –** strength of a LASER beam
  - Energy released by LASER in unit time (watts)
  - Output Power = (energy released)/(time duration of energy release)
  - Output power range: mW to KW
  - A Laser releases power in narrow range

❑ **Power requirements**
  - Laser uses electricity and converts it to light
  - Efficiency is ratio of output to given input
  - Maximum 30%, minimum 0.001 %
  - Heat dissipation

So, now we have learned many properties and again try to understand the property output, ok. As I told that we give some energy to atoms and atoms are stimulated and as a result they gives us the laser, right. So, the output power is nothing, but the strength of a laser beam; that means, the number of photons which are released in short duration or as a continuous wave, but they are released in certain time. So, the amount of energy released by the photons in that time duration it is creating the concept of power, which is a usual concept so, I will say what is output power energy released divided by time duration of energy release. So, that is the power of the laser pulse or laser wave.

Now, what is the output power range for laser it is in the range of milli watt to kilo watt, but a particular laser has only certain level of power. It can be milli watt, it can be kilowatt or it can be intermediate value, but it will be certain value, right. Now, compare the pulse and the wave since wave is a continuous emission of the photons. So, it has low power; on the other hand in case of pulse we trigger the number of photons in very short duration and as a result we get the peak power and the peak power is very high in case of pulse, right. So, remember these things. They are very simple things, but they are very useful in terms of distance measurement concepts.

Because if a pulse since which is having very high power over a short duration it can travel to a long distance because having the high power at the same time the continuous wave although it having it is having the continuous stream of the photons, but average energy is very less as the result what will happen. So, it will travel for shorter distances compared to the pulse and that is why for topographic mapping where the distances are very high 1 kilometer, 2 kilometer we prefer the pulse or we prefer the time of flight principle or we do measurement by time of flight principle in case of last distances, right ok.

Now, what is the power requirement, right? So, laser is using electricity. So, efficiency is somewhere very slow the minimum efficiency is 0.001 percent; that means, if I give you 100 watts you multiply by one 0.001 percent that will be the output of the laser pulse of wave. At the same time the maximum energy is 30 percent. So, what about the remaining energy? So, generally the remaining energy goes into the heat generation, right. So, that is somehow a limitation also; that means, we have to do continuous cooling.

So, now, we have learnt what is a laser and what are it is characteristics, ok. I want to do the range measurement or the distance measurement using the laser pulse or maybe the laser way, but now let us first start with the laser pulse. So, let us understand how do we measure the distance between the transmitter or receiver of a laser and the object surface, right. This distance could be inclined; this distance could be vertical or anything, right.

Now, it is very important to understand that what we are doing by triggering the laser pulse or a wave we are sending some energy that energy is the energy photons are interacting with surface reflecting back and they are coming to the receiver. So, we are again mirroring some kind of energy there, right. So, we should be able to measure the energy again that is the idea here. So, once we trigger we will note down the time or will note down the phase and once that laser pulse or wave comes back to receiver we will measure the time again or the phase again, whatever and then we measure the difference of time or face in order to determine the distance between the receiver transmitter assembly and the surface and the object surface.

So, let us see how do we measure the energy right, ok.

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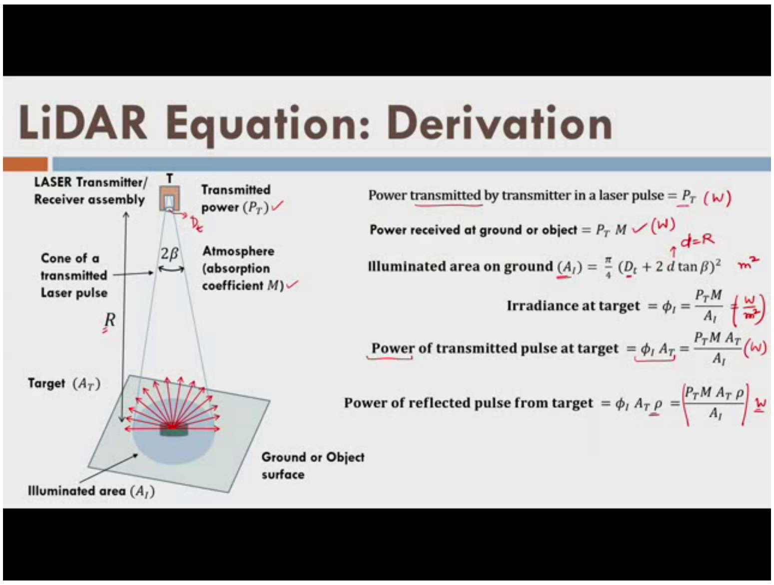

LiDAR Equation: Derivation

Power transmitted by transmitter in a laser pulse $= P_T$ (W)

Power received at ground or object $= P_T\ M$ ✓ (W)

Illuminated area on ground $(A_I) = \frac{\pi}{4}\,(D_t + 2\,\overset{\uparrow d=R}{d}\tan\beta)^2$ m^2

Irradiance at target $= \phi_I = \frac{P_T M}{A_I}$ $\left(\frac{W}{m^2}\right)$

Power of transmitted pulse at target $= \phi_I\ A_T = \frac{P_T M\ A_T}{A_I}$ (W)

Power of reflected pulse from target $= \phi_I\ A_T\ \rho = \left(\frac{P_T M\ A_T\ \rho}{A_I}\right)$ W

So, that is my transmitter here and it has some aperture there is range R. So, this is the illuminated area and this is my laser spot which is shown here by illuminated area and we also call it footprint, this is cone of the transmitted laser pulse, ok. So, now, this is my divergence angle 2 beta, ok. So, we have 2 R tangent beta as my foot print or laser spot diameter. Well, we call it footprint in case of topographic mapping ok, right. So, I can approximate it by 2 R beta, fine.

So, now, we can see here that transmitted power of a laser is P T here it is passing through the atmosphere and it is getting patinated; that means, its power is reduced by the atmosphere and. So, we define coefficient called M, it is absorption coefficient of atmosphere. So, we have the transmitted power as P T and then we have power received at ground or object here through the atmosphere is this much and M is less than 1, that is why we receive energy less than or the we receive the power of the laser at ground surface less than P T.

Now, you can see this is the illuminated area A i because we can see here D t which is nothing, but the opening of transmitter and then d is my nothing, but the distance or we can see the range R here; so, here d equal to R, right. So, we have 2 R tangent beta, right. Now, what is irradiance, ok? So far this is the area in meter square and here it is a power in watts and here it is power in watts. So, now, if I divide this power over this illuminated area so, I can find out what is the power available at unit area. So, we call it the irradiance and irradiance is measured in watt per meter square, fine, ok. Now, you can see that how much power is received on the unit area of the illumination or the unit area of illuminated area, fine.

So, within the illuminated area let us assume there is a target and it has an area A T, right. What will happen? That the power received or the power of the pulse at the target it will be this much. So, again it will be in watts, fine and we are just multiplying here terms. Now, that will reflect this target within the illuminated area is reflecting the pulse. So, that if reflectance is row which is again less than 1, it will allow this much energy this much power to be reflected back, right like this. So, now, target is reflecting the power in all the directions fine, ok.

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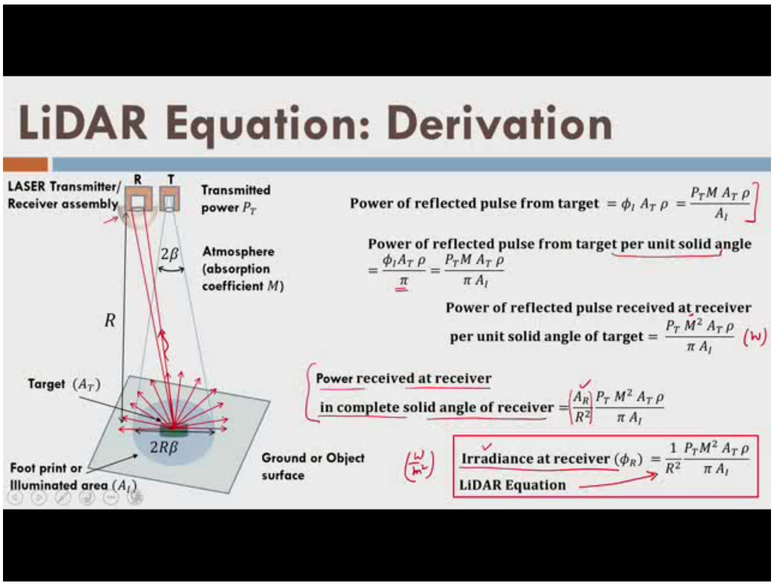

LiDAR Equation: Derivation

Power of reflected pulse from target $= \phi_I A_T \rho = \frac{P_T M A_T \rho}{A_I}$

Power of reflected pulse from target per unit solid angle $= \frac{\phi_I A_T \rho}{\pi} = \frac{P_T M A_T \rho}{\pi A_I}$

Power of reflected pulse received at receiver per unit solid angle of target $= \frac{P_T M^2 A_T \rho}{\pi A_I}$ (W)

Power received at receiver in complete solid angle of receiver $= \left(\frac{A_R}{R^2}\right) \frac{P_T M^2 A_T \rho}{\pi A_I}$

$\left(\frac{W}{m^2}\right)$

Irradiance at receiver $(\phi_R) = \frac{1}{R^2} \frac{P_T M^2 A_T \rho}{\pi A_I}$

LiDAR Equation

Again coming same thing, right. So, this is this, ok. Now, if I assume a hemisphere around the target we can say that in the solid angel the unit solid angle of the hemisphere how much energy or how much power is being reflected by the target. So, this is the power reflected by pulse in the per unit solid angle of my target because we are dividing it by pi which is a solid angle of hemisphere, right.

Now, the power of the reflected pulse received at the receiver because again here it is travelling to atmosphere. So, again we are multiplying with M. So, it becomes M square and now this is the power that is reflected and that is received at the receiver, fine. Now, if I consider hemisphere around the receiver. So, receiver also is having a opening and in that opening all the energy or the power will be detected, right.

So, now consider the solid angle frame at the receiver also is having opening and in that opening only energy or the power will be detected, right. So, now, consider the solid angle frame at the receiver this is the angle and in this angle only water power reflected that will be reaching to the receiver. So, I can say here the power received at the receiver in complete solid angle of receiver this is the solid angle of the receiver and so, now, we can say what is the irradiants at the receiver with this phi R. So, I divide it power divided by this A R. So, I will get this term and this is what we call the LiDAR equation.

So, we have just seen that how to derive the LiDAR equation and that says that if I have a laser pulse of P power peak power, I will have this much irradiance in watt per meter square at the receiver and if I can measure this much amount of laser power I can do the range measurement from the transmitter receiver assembly of laser instrument to the target, ok.

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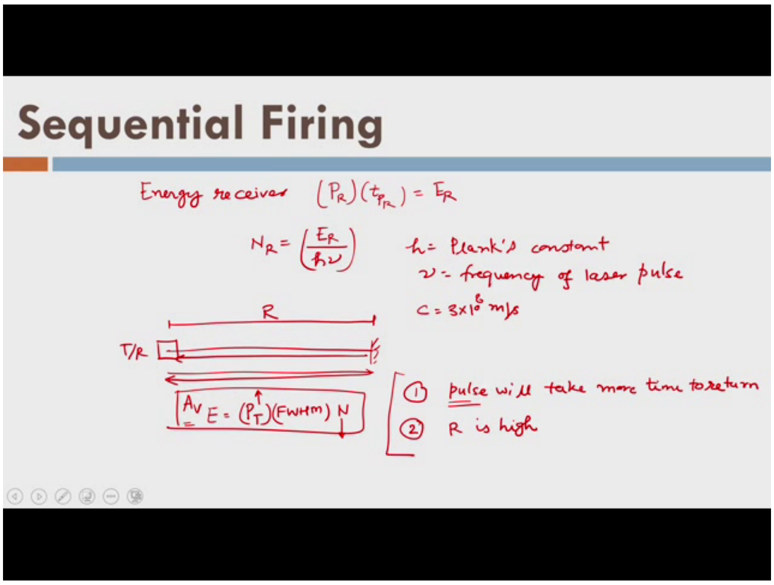

Sequential Firing

Energy receiver $(P_R)(t_{p_R}) = E_R$

$N_R = \left(\frac{E_R}{h\nu}\right)$

h = Plank's constant

ν = frequency of laser pulse

$c = 3\times10^8$ m/s

$\boxed{\underline{A}_V \; E = (P_T\uparrow)(FWHM)\, N\downarrow}$

① pulse will take more time to return

② R is high

So, what about the energy at receiver? Let us say there is a pulse which is reflected and which is having P R as a peak power and if we say that the t p is a pulse length of the received pulse. So, that is my total energy of the received pulse fine, ok. What about the number of photons of the received pulse I can find out E R divided by h nu, where h is plank constant and nu is the frequency of laser pulse, ok. Now, what happens here let us say we have a laser transmitter it h as fired some number of pulses together, ok. So, they are all coming back.

So, we are not even to distinguish because the laser pulse are travelling with the speed of light and speed of light of you know, right because of this high speed what is the consequence? We cannot fire all the pulses in a single moment. So, what do we do if fire these pulses sequentially one by one. So, one pulse is fired by a transmitter receiver assembly here interacting with surface coming and then fire the next pulse it interacts comes back and so, this process is called sequential firing.

Now, be I would like tell one thing here because of the sequential firing we have certain limitation the first limitation is that [vocalized-voice] if I increase this distance which is d or range R, right what will happen a pulse will take more time to return back number – 1, and the result what will happen I can fire some limited number or less number of pulses if distance is high or the range is high between the transmitter receiver assembly and the surface right,. What next?

Since R is high; that means, a pulse has to travel a long it needs more energy; that means, I have to increase the peak power of the pulse and movement if I increase the peak power of the pulse for given constant power in input remember we have the average power E here or average energy which is P T into FWHM right into N that is my average power or the average energy I have, right.

So, the movement I increase the P T what will I do automatically number of pulses fired per second will be less and automatically I will have less details because I am firing less number of pulses, right. So, that is a kind of concept we should understand; that means, if my distance is higher what will happen, pulse will take more time and the result less number of pulses during 1 second or during my operation of the range measurement right, fine. At the same time in order to travel long distances we need to give more energy to each pulse and as a result the number of pulses will reduce for a given average energy which is available towards in the form of battery power. I hope that you understand this concept of sequential firing now.

So, we have learnt how to measure the reflected signal after triggering a pulse or maybe wave, right. So, now, let us see the time of flight principle, how do we do it exactly; that means, how to measure the time difference of the triggered and reflected pulse.

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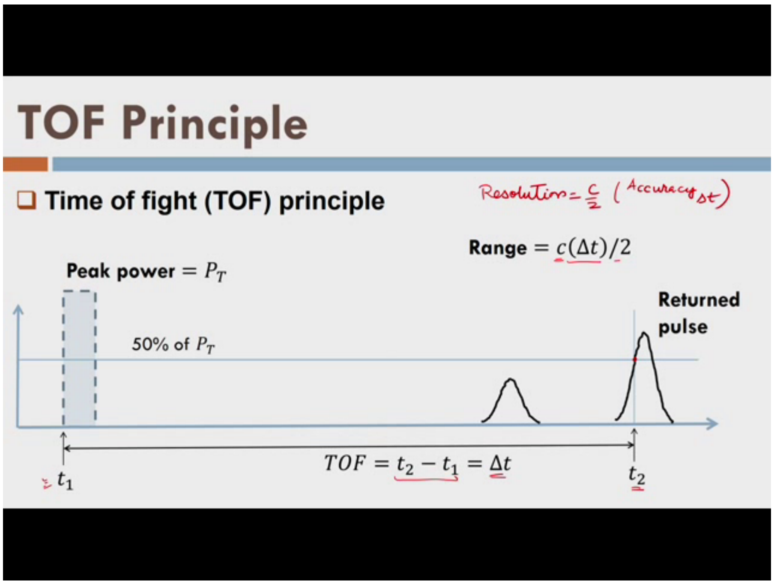

TOF Principle

❑ Time of fight (TOF) principle

Resolution $= \frac{c}{2}$ (Accuracy$_{\Delta t}$)

Range $= c(\Delta t)/2$

So, let us see this a power and time curve again. So, this is my peak power my modeled laser pulse which is rectangular in shape. So, this is my peak power and now I see that if the reflected pulse is having some threshold I will assume that the signal has been received or the reflected pulses has been received and it is a valid signal, right. So, if this is the reflected pulse I will assume that it is not being received. At the same time if this is the laser pulse I will say this is my return pulse, and it is crossing certain threshold. So, I will mark this as my point here. So, this is my t 2 time and this is my t 1 time, so, this is my time of triggering the pulse and this is the time of return pulse.

So, now, if I measure the time difference between the two t 2 minus t 1 it will be delta t right and now, I can find out the range c which is velocity of the light into delta t into divided by 2 this time difference t 2 minus t 1 is equivalent to the 2 times of the range because it is going and it is coming back and that is why I will be divided by 2 and that is my range between the transmitter receiver assembly and the object surface. So, what about the accuracy of this measurement or what about the resolution of this measurement and this resolution of this range is given by c times divided by 2 into the accuracy of delta t. So, that accuracy of the time measurement or time of flight measurement will decide my resolution that is the minimum distance we can measure by a laser pulse ok, fine. I hope you got the idea.

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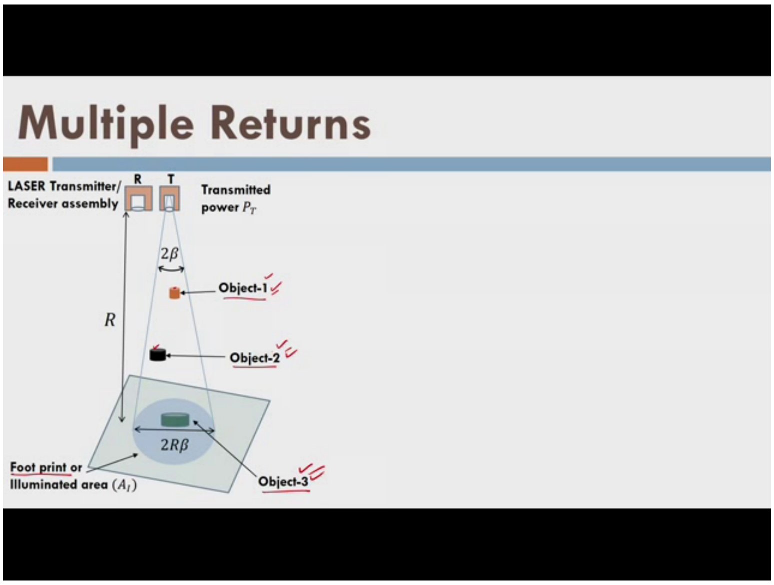

Multiple Returns

Now, multiple returns what happens in case of LiDAR. This is the illuminated area or what we call footprint, fine. What happened here is let us say there are three objects that is object 1, object 2 and object 3 which are located in one footprint. What will happen that energy which is passing through the atmosphere first it will interact with this object 1 here then the energy which is not interacting with object 1 will pass through and it will interact with object 2 and later the remaining energy or the remaining power will interact with object 3. And, as a consequence of that we will get multiple return pulses first from object 1, then from object 2 and then from object 3.

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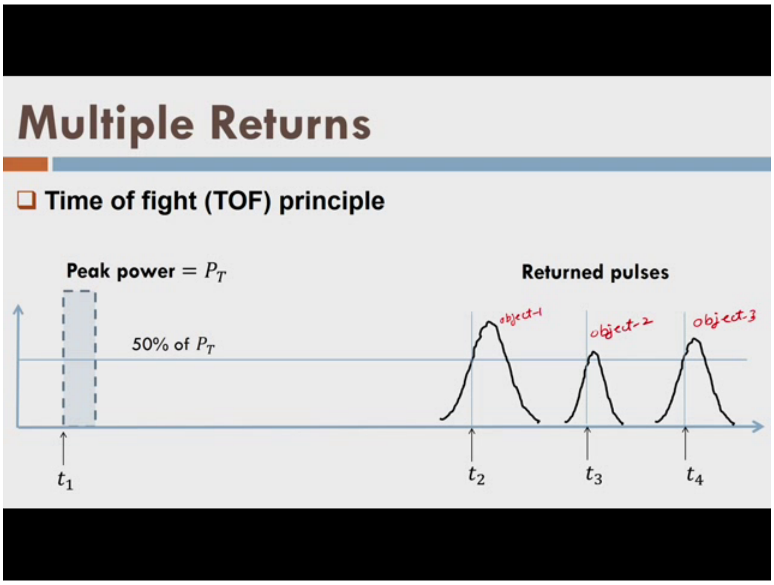

Multiple Returns

❑ Time of fight (TOF) principle

Let us see like that this is my peak power P T and this laser pulse which is triggered one. So, this my time stamped even this is my threshold value and now, for object 1 this is the written pulse, for object 2 this one, object 3 this one and all these three objects are considered to be in one footprint; that means, they are along the one line. Although in the last slide we are shown them slightly here and there with in one footprint; however, the laser pulse will report that all three are in one line along the centre point of the laser pulse, right and that is what we call somehow the limitation.

But, no doubt it is giving us one advantage we are getting multiple returns why because there is a space available between the object 1 and object 2 and object 3 and through that space the laser pulse travelling it is passing through atmosphere and so, it is giving the multiple returns. And, as a result you will be surprised this is the only reason we get the tree structure because the tree canopy has some voids and those through those voids the laser pulses passes; that means, they partly interact at certain level of leafs and then the partly pulse will pass through the void and again it will interact with the another layer, again it will pass through that only and so, we get multiple returns and by using the multiple returns we can completely understand or we can completely map a 3D structure of a tree and that is a beauty with the LiDAR.

I hope now you can appreciate why do we have LiDAR in place today and it is been extensively used by the researches now, by industry also. So, now see these are the my return pulses, so, this is my time stamps t 2, t 3 and t 4. So, if I take the time difference of t 1 and t 2, I will find out what is my first return distance or range. Secondly, for the second object I can find out what is the range of second object from the transmitter and similarly, I can find out for the object 3. And, now I am map those objects along the particular line I can find out what is the height of particular tree leaf second tree leaf and the third tree leaf or may be the ground surface. So, today it is possible to receive four returns, right.

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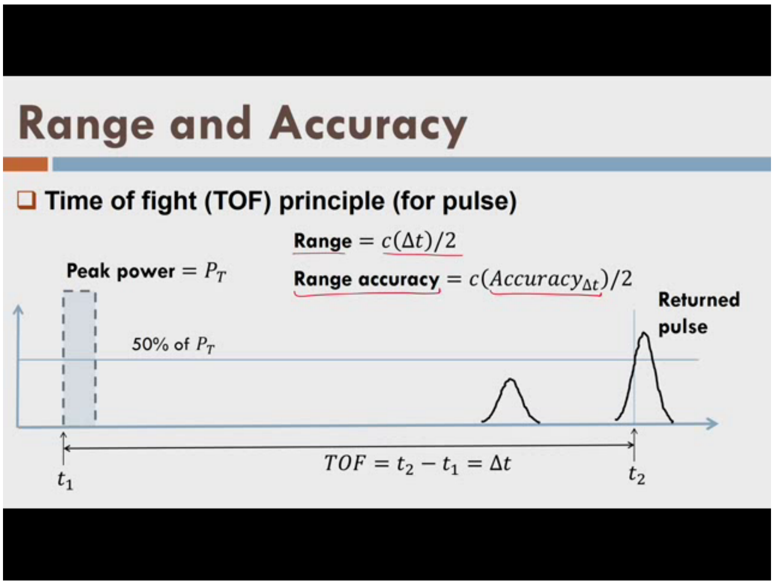

Range and Accuracy

- ☐ Time of fight (TOF) principle (for pulse)

Range $= c(\Delta t)/2$

Range accuracy $= c(Accuracy_{\Delta t})/2$

So, let us further what is the range and accuracy as I already told the range is c times delta t and. So, we have the accuracy of the delta t and that is the time measurement that decides my range accuracy or the resolution of the laser pulse.

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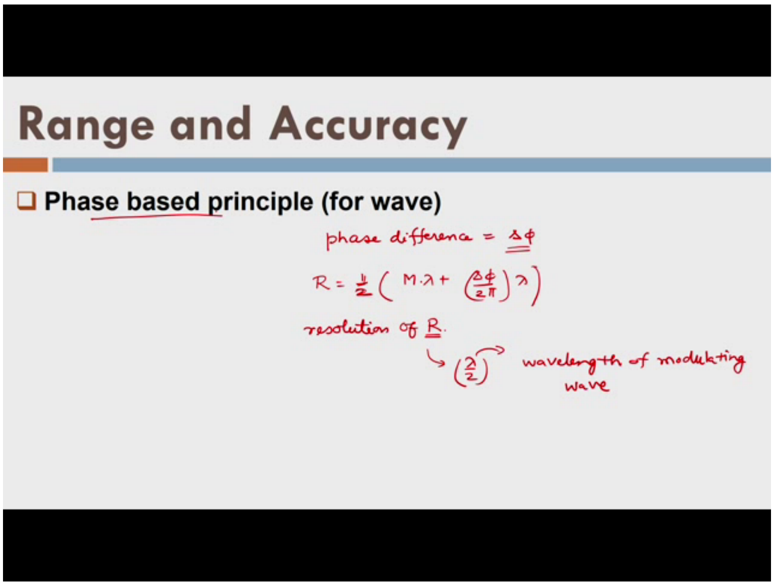

Range and Accuracy

- ☐ Phase based principle (for wave)

phase difference = $\Delta\phi$

$R = \frac{1}{2}\left(M\cdot\lambda + \left(\frac{\Delta\phi}{2\pi}\right)\lambda \right)$

resolution of R.

$\hookrightarrow \left(\frac{\lambda}{2}\right) \rightarrow$ wavelength of modulating wave

Similarly, if I see in case of phase based principle the measure the phase difference equal to delta phi and we right one think here that distance is R is given by 1 by 2 M number of cycles so, M lamda plus two phi into lamda, that we have already seen in case of total station and the same expression I am writing here.

So, what about the accuracy or the resolution of R as we have seen in case of basic surveying we can of achieve and desolation of R as lamda by 2 where lamda is the wave length of my modulating wave not the laser wave, right. So, they are the same concept when phase based principle are there.

So, let us talk about the dependencies; that means, if I consider the factors which are going to affect the response or the return pulse, what are those factors, right.

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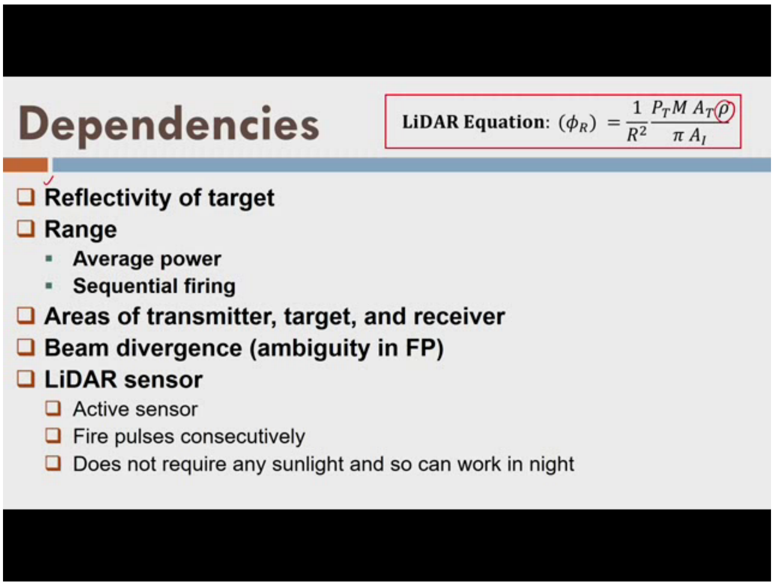

Dependencies

LiDAR Equation: $(\phi_R) = \frac{1}{R^2}\frac{P_T M\, A_T \rho}{\pi\, A_I}$

- ☐ **Reflectivity of target**
- ☐ **Range**
  - **Average power**
  - **Sequential firing**
- ☐ **Areas of transmitter, target, and receiver**
- ☐ **Beam divergence (ambiguity in FP)**
- ☐ **LiDAR sensor**
  - ☐ Active sensor
  - ☐ Fire pulses consecutively
  - ☐ Does not require any sunlight and so can work in night

This is my LiDAR equation now you see the reflectivity of pulse or reflectivity of the target which is here. So, the reactivity of the target is the most influencing factor. I will give you certain example of those what does it mean basically, ok. Let us see as we told it is possible within one foot print we are able to detect multiple returns.

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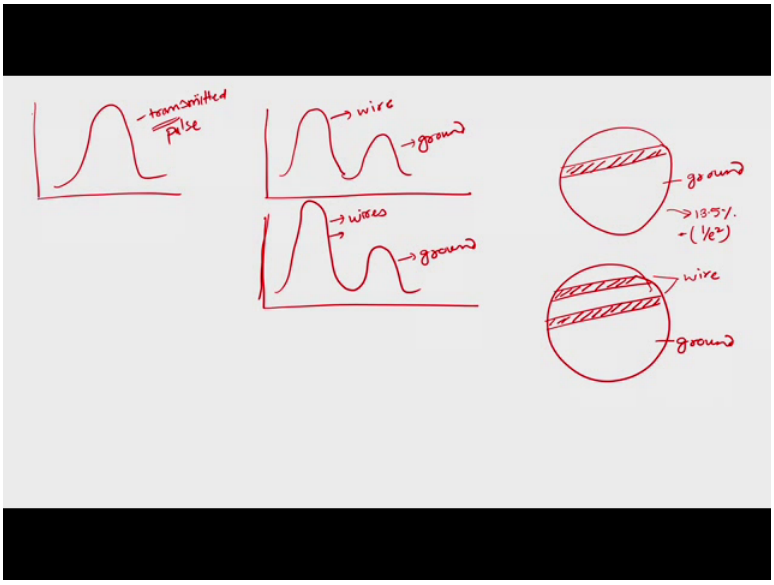

So, let us see these in area on the ground surface and this is my one footprint or I can see here that is 13.5 percent or 1 by e square size at certain distance, right. Now, with in this we have a wire line which is at some height from the ground and because of this wire line what will happen I will get this is the let us say transmitted one transmitted pulse and I will get two responses first is from the wire which is more reflecting I assume here and this from the ground. This is my ground response and that is from the wire, ok.

What next? What if I have two wires in one footprint, let us say this and this is my ground, this is my ground here since the both wire at are at the same height what will happen they will give this we cannot distinguish between the heights of the two wire or we cannot distinguish between the two return from the wires. So, now, they will get the one return from two wires and one return from the ground, but my return will be higher. But, remember this is for the wires and this is for the ground because now two wires contributing towards the reflections remember this return pulse will be less than the transmitted one, right ok.

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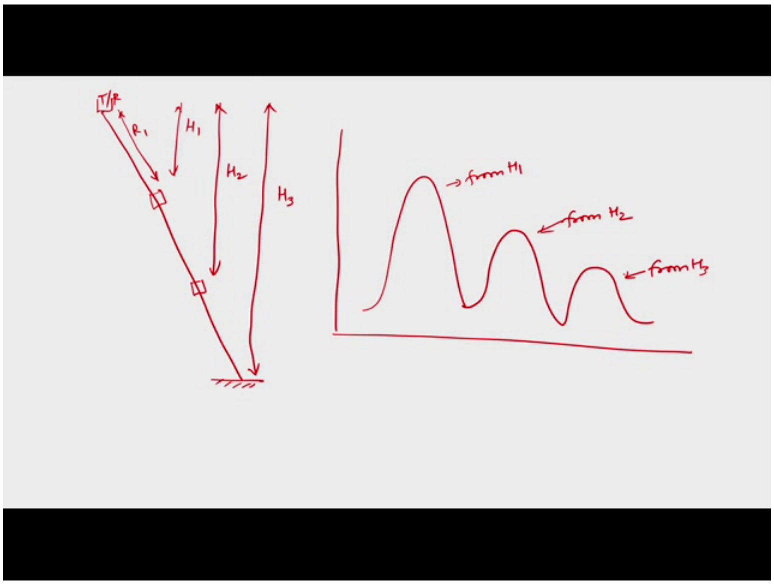

What is the third possibility now? Assume that we have this is my transmitter or receiver assembly and along this line we have couple of objects let a one is here, one is here, one is here and so ok. So, if I say that if this is the range R 1 or if I say this is height H 1, this is the height H 2 and this is the height H 3; that means, my heights are increasing from this one what will happen I will get responses that high reflectance like this, like this and like this right from height H 1, from H 2, from H 3 you can assume that all the factors are their atmosphere height and everything.

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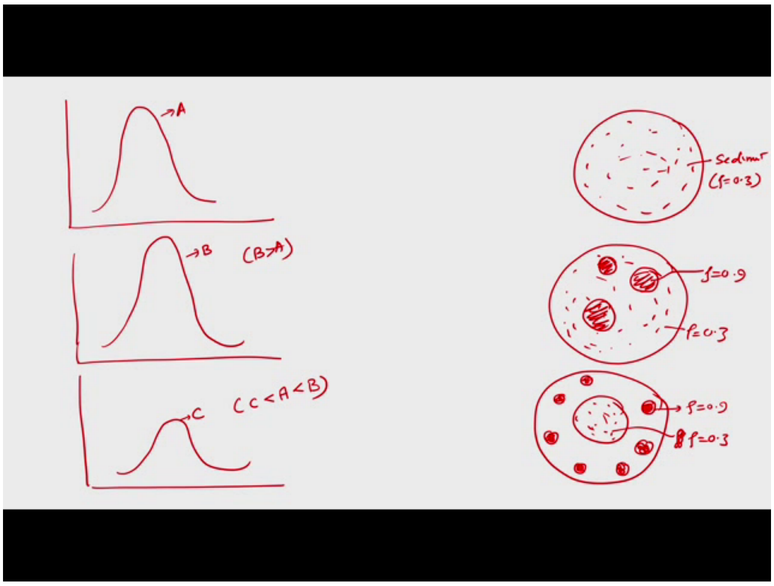

Now, take one more case, ok. Let us see there is some footprint. There is a footprint here and there some material here which is of uniform nature let us say sediment and sediment has row equal to 0.3, reflectance of 30 percent, ok. So, I will response like this right call it A, ok. Now, let us assume another case where in a footprint we have sediment like this at the same time we also have some kind of more reflecting areas like this which is having very high reflectance that is rho is equal to 0.9, ok. What will be consequence? I will get response which is slightly higher an I called b. So, the B is more than A, right for the same laser pulse, ok.

Let us take one more case and try to understand what is the effect of reflectivity. I have very small areas here which are having high reflectivity, but they are area an very small and they are also not concentrate to one their away from each other as well as very small in the size, but here there is a big area of sediment here they are the reflecting particles, but they are very small in area. So, what will happen I will get this kind of response let us say C and C is no doubt less than B or A which is no doubt less than B. So, this is the way we explain the effect of reflectivity on my return pulse.

What about the other factors, for example, range which is affected by the average power as well as sequential firing we have already discussed it before. Then we have the areas of transmitter target and receiver, if I put all the factors and order they are on the third order; that means, they are on the third rank they can affect the range measurement, ok. The fourth one is beam divergence because it is creating the ambiguity in the footprint and finally, these are the total factors which effect the range measurement by laser Now, we have seen that here, it can fire the pulses consecutively and it does not require any sunlight so, it can work in the night.

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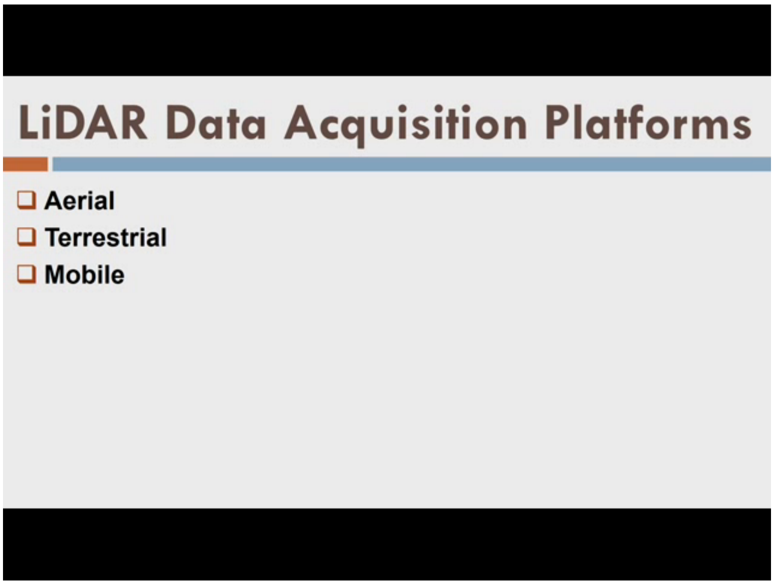

LiDAR Data Acquisition Platforms

☐ Aerial
☐ Terrestrial
☐ Mobile

And, as a result now we can use the laser in a three fashion. That means using different-different platforms we can use the LiDAR or the light detection and ranging technique in aerial fashion; that means, I am mounting the laser scanner on a aircraft and aircraft is caring that in the air and then we are acquiring the data or what you call airborne LiDAR data acquisition similarly if I use some tripod or any terrestrial platform which is which is not moving we called the terrestrial platform. So, I can use it like tripod and I can mount my laser scanner over there and I can acquire the data

Similarly, what if I mount the laser scanner on a vehicle and vehicle is moving on the roads and it is acquiring the data. So, that is called the mobile laser scanning or mobile LiDAR scanning. So, these are the three ways we do in order to acquire the LiDAR data.

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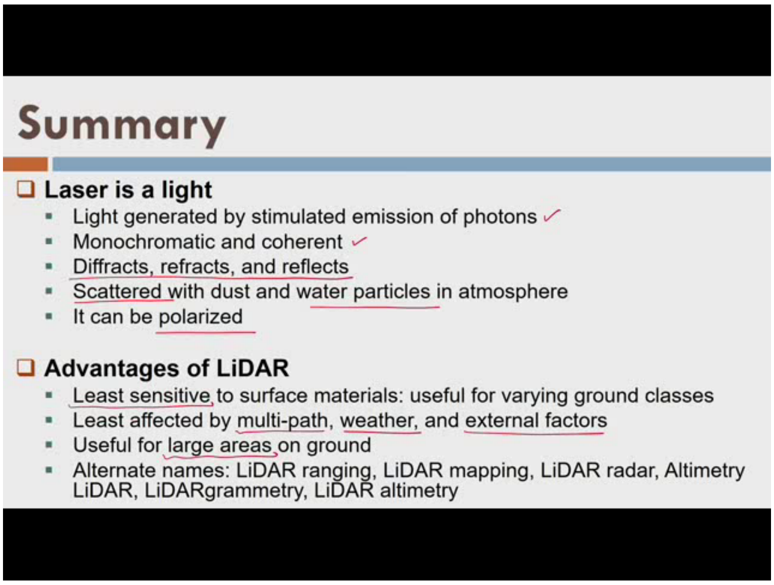

Summary

- ❑ **Laser is a light**
  - Light generated by stimulated emission of photons ✓
  - Monochromatic and coherent ✓
  - Diffracts, refracts, and reflects
  - Scattered with dust and water particles in atmosphere
  - It can be polarized
- ❑ **Advantages of LiDAR**
  - Least sensitive to surface materials: useful for varying ground classes
  - Least affected by multi-path, weather, and external factors
  - Useful for large areas on ground
  - Alternate names: LiDAR ranging, LiDAR mapping, LiDAR radar, Altimetry LiDAR, LiDARgrammetry, LiDAR altimetry

So, I would like to make a summary of what we have learnt today about laser as well as LiDAR first thing is that laser is a light; that means, it behaves like a light, it get diffract, it get reflect, it gets refract, it get polarized also right it also create interference, destructive as well as constructive, fine. But, it is a monochromatic having the same wavelength and coherent having the same phase. Again as I told it has diffracts refracts and reflects it is also scattered with the dust and water particles in the atmosphere and it can be polarized, fine.

So, now, using laser we develop the LiDAR that is light detection and ranging and light detection and ranging is or LiDAR is an active sensing technology, right. So, it does not require any external source of energy like sun. So, I can use it night also like radar, ok. Moreover if you see carefully it is least sensitive to the surface material; that means, if I am having different land classes for example, ground for example, grass for example, tree or road or any other surface like buildings given in the same area I can still use the LiDAR in order to detect all those, right.

So, then we have it is least affected by the multipath whether and external factor, ok. So, it is very useful for the large areas on ground, right and you may find in the literature it is named by different-different names one is LiDAR ranging, LiDAR mapping, LiDAR radar, altimetry LiDAR, LiDAR grammetry and LiDAR altimetry.

Well, with this I can say that today we have learned fundamentals of the LiDAR, ok. In the next lecture, we are going to talk about the how to use the LiDAR in order to acquire the data or the topographic data and what we called the data acquisition, topographic data acquisition and mostly since LiDAR is an active sensing technology it is expensive also. We prefer to acquire for the large areas or large areas can be easily covered by the airborne data acquisition. Does not mean it does not mean that do not use it terrestrial platforms, we use it. However, with the airborne we can cover large areas. So, we will look into these things in the next lecture, fine.

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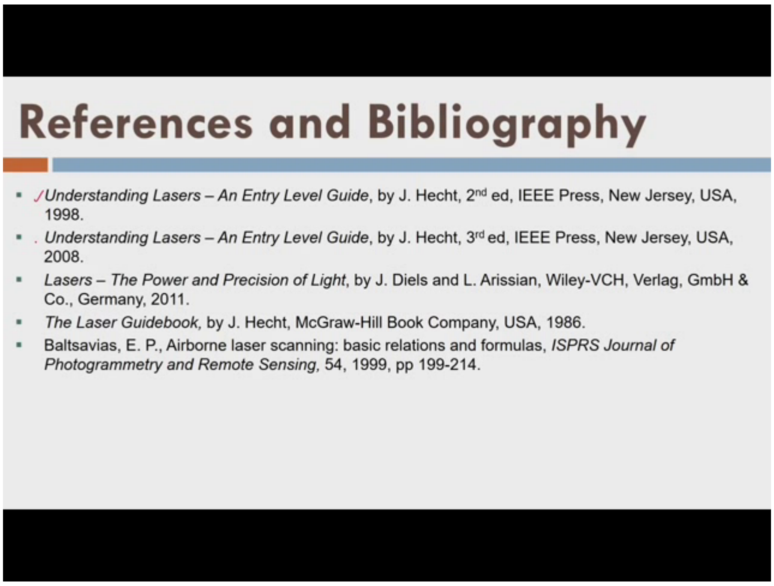

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Here I would like to say that whatever discussion I had today with you in this lecture, I have refer this books also which are excellent resource.

Thank you very much.