Technical Note on:

Echo Detection

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1 Introduction

One of the essential features of laser-scanning is its capability to penetrate vegetated areas and to measure the ground elevation. This feature is often associated with the term „last echo mode“ meaning the recording of the last echo if several echoes are resulting from a single laser pulse. Last echo mode is taken frequently as a synonym for ground measurement. But this assumption is not always correct.

This note shall clarify

- how echoes are detected and registered,
- what detection of multiple echoes means and
- how the shape of the surface influences the measurement.

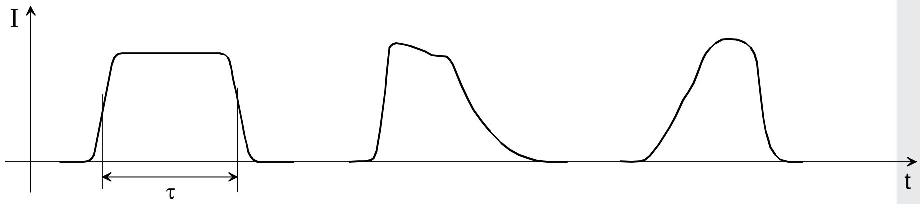
At the end the difference between “first echo” and “last echo” mode should be more clear. It is the intention of this paper to provide a general background but not to describe all effects precisely in mathematical terms.

Over the past years the terms Last Pulse and First Pulse have become widely used. There is only one pulse emitted by the laser but several echoes are returned from the surface, thus the terms “First Echo (FE)” and ”Last Echo (LE)” are more appropriate and describe the effects more precisely.

2 Echo

First we should shortly define what an echo is and how it is detected.

A laser pulse is very short but not infinite small. Its intensity raises within a short time up to a certain level, remains there for some time and decreases. The next figure shows how the waveform of typical laser pulses might vary depending on the laser used.



For simplicity we will use the first of the three shown pulses. Due to its duration (or length) the leading edge of the pulse reaches a target somewhat earlier than the trailing edge.

Let us now assume that a laser pulse is a „Packet of Light“ (PoL) traveling from the sensor down to the earth. This packet is defined by three parameters:

- length
- width (or diameter)
- intensity

The length of the packet corresponds to the pulse duration

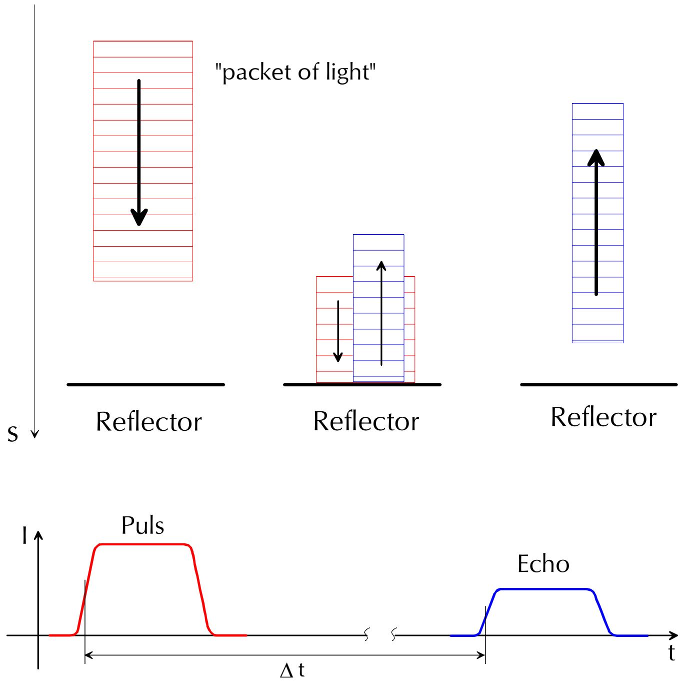
$$\delta[m] = c[m/\sec] \cdot \tau[\sec]$$

where δ is the packet length in meter, c is the speed of light and τ is the pulse duration in seconds.

The width of the packet (i.e. the diameter of the laser beam) depends on the beam divergence and the distance from the sensor.

The intensity means the power density within that packet. As the beam widens with distance and due to attenuation of the light in the atmosphere, power density decreases with distance.

The first figure overleaf shows the principle of a PoL traveling to ground, illuminating an object and traveling back to the sensor's detector. Usually the object is not a mirror or corner reflector directed towards the sensor and so the object reflects only part of the light back to the sensor. The backward PoL is much weaker than the forward PoL. This characteristic of a reflector is called its reflectivity or directional reflectivity (if reflectivity depends on viewing or illumination angle). The figures depict the weaker signal as a narrower packet.



The figure is related to distance (s) and assumes a flat reflector.

The figure to the left shows this simple example in the time domain:

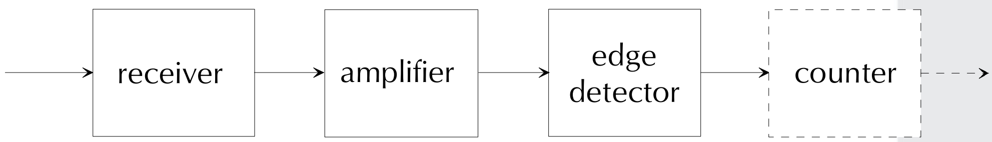
The laser pulse is emitted from the sensor, reflected and received by the sensor's detector. The time difference between the leading edge of the pulse at emission and the leading edge of the echo at reception corresponds to twice the distance to the object:

$$\Delta t = 2 \cdot s/c \quad .$$

So, e.g. 1 nsec (10^{-9} sec) traveling time corresponds to 0.15 m in distance.

Detection of the echo can be considered as a three stage process

- reception of the reflected portion of light (by a photo sensitive diode or transistor)
- amplification of this weak signal
- detection of the leading edge

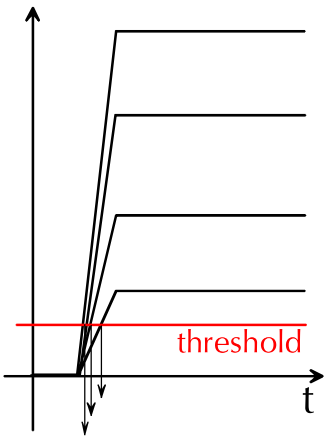


The task of receiver and amplifier is to detect the echo at all, the edge detector's task is to determine the leading edge. The performance of receiver and amplifier primarily define the range of the system, while the performance of edge detector and time counter define resolution and accuracy of the distance measurement.

Technical note on

Echo Detection

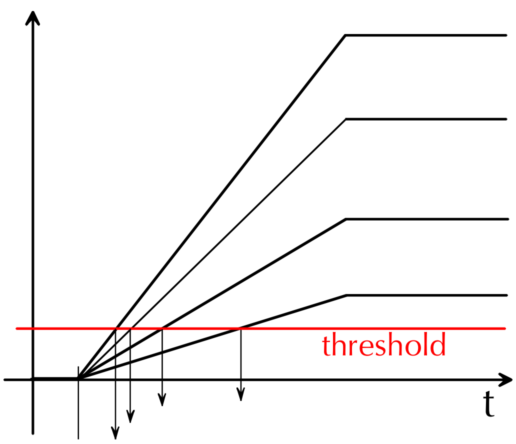
There are several methods to detect the edge of a sharply raising signal.



The most frequently used method is to apply a threshold. If this threshold is exceeded by the echo a signal is derived which stops the counter.

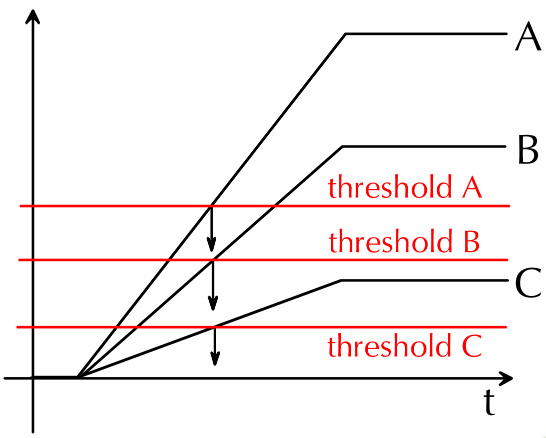
If the echo has a very short and steep edge as shown in the graph to the left, the amplitude of the echo has a negligible effect on the time the counter is stopped.

Practical echoes are not such steep but take some time to reach the maximum level (or amplitude). As shown in the next graph to the left, the stop signal to the counter comes later as weaker the echo becomes.



If one does not apply reasonable corrections it means that the low reflective asphalt of a runway and the white painting on the runway will cause different distances and thus different elevations. The white lines will always be above the runway.

This method is very useful if the signal's amplitude does not vary widely but stays in a narrow region. With airborne laser-scanning the signal strength varies over a wide range and thus this method is not recommended.



TopoSys implies a more sophisticated method which applies a dynamic threshold. The threshold is calculated from the amplitude of the echo and thus ensures that the trigger signal for stopping the counter will be always in the middle of the raising edge.

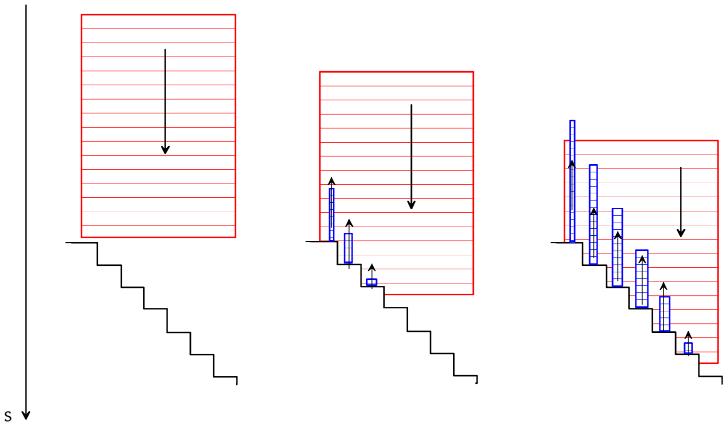
Variations of the trigger time and thus on the measured distance will be caused by very noisy echoes or by echoes having a very strange shape as shown in the next section.

3 Echo Shape

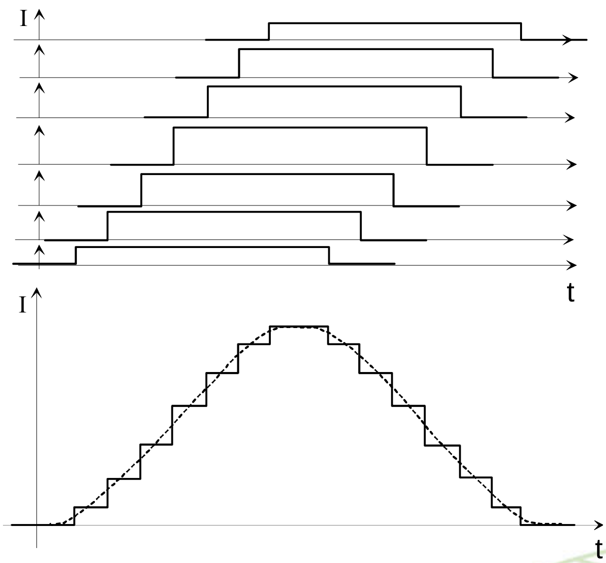
In the previous section we have always assumed a flat reflecting surface causing an echo having the same shape but lower amplitude than the emitted laser pulse. The shape of an echo is influenced by the reflecting surface(s), its slope or roughness.. The shape specifically of the raising edge of an echo influences the ability to detect an echo and the accuracy of the distance measurement. The principle effects are outlined below for three frequent surface shapes.

3.1 Slope

Instead of taking a slope we will use steps of equal heights from which one can easily deduce the real behavior at a slope. For simplicity we assume that the laser beam illuminates a circular surface with a constant intensity.



As the laser pulse travels down, it illuminates several steps, each of them producing a partial echo. As the illuminated areas at the border of the laser beam are smaller (only the outer section of a circle) than in the middle, the amplitudes of the partial echoes decrease with the distance from the middle of the beam.



The seven partial echoes of this example are depicted in the time domain in the figure aside. For simplicity of the drawing the echoes are shown with vertical edges.

The partial echoes are delayed against each other by the height of each step (upper diagram). Superposing all seven echoes results in the stepwise curve depicted in the lower diagram. The dotted line shows how the real echo from a roof might appear.

What happened? The resulting echo has got a slow raising edge and became longer than each single echo.

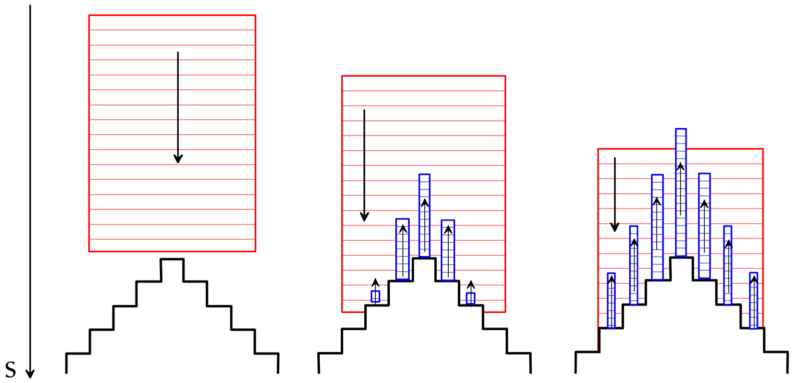
The resulting amplitude is about the same as if the reflecting surface would have been flat. The duration of the rising edge can be determined by the delay of the last partial echo compared to the first partial echo. In this example it is about six times of a step's height.

If d is the diameter of the laser beam and α is the slope angle of the reflecting surface then the duration of the rising edge t_r becomes

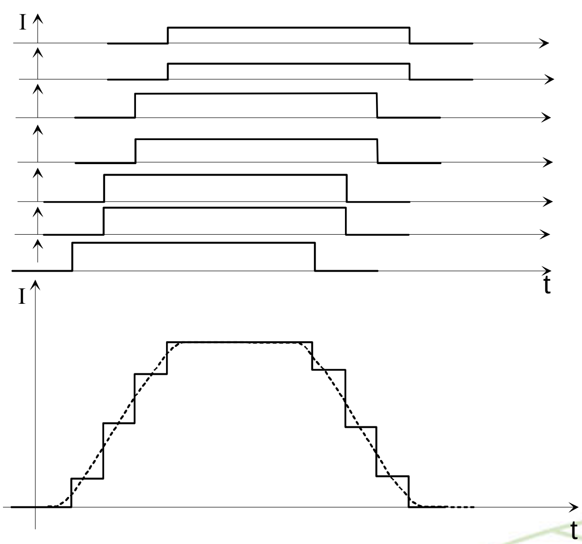
$$t_r \approx d \cdot \sin\alpha \quad .$$

As said in section 2, the "adaptive threshold" method applied by TopoSys will detect approximately the center of a rising edge. In the example this center corresponds to the forth partial echo which is associated with the center of the laser beam. Thus the measured distance relates to the center of the laser beam and to the center of the illuminated slope.

Measuring directly the top of a roof, things look somewhat different. The diagram shows a laser pulse hitting a roof top at the center. A number of small echoes get reflected.

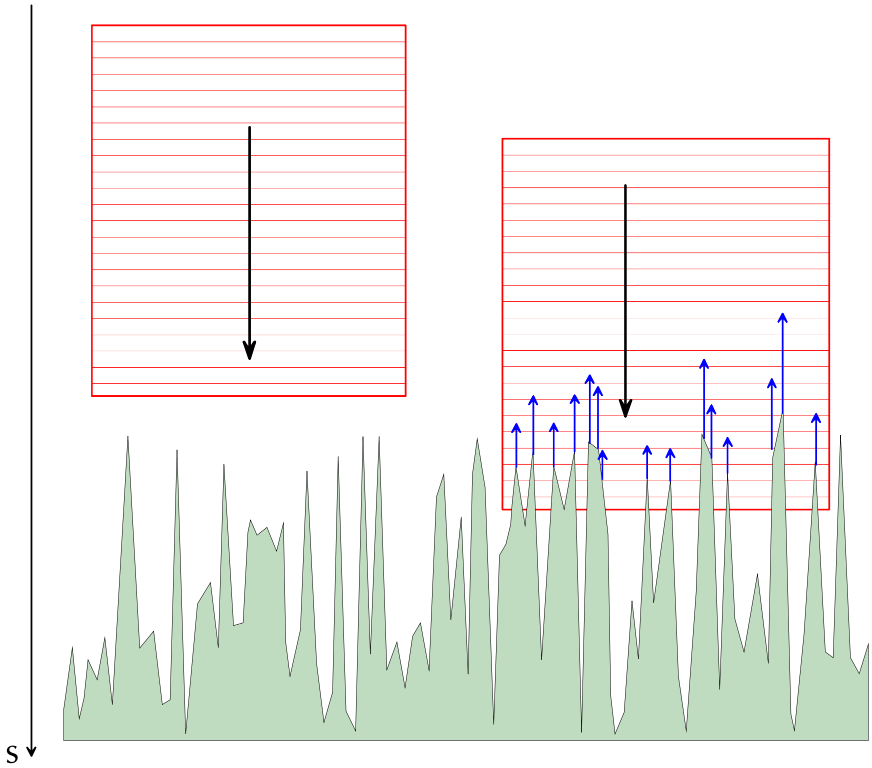


As for the previous example there are seven steps and echoes, but here always two echoes at each side of the roof are identical and arrive at the same time. So the edge of the combined echo is steeper and this edge will be detected between the third and forth individual echo. The distance measurement associated with the center of the beam will not relate to the top of the roof, but to a middle elevation of the illuminated area.
In other words the precise top of a roof can not be directly measured at all.



3.2 Vegetation

Somewhat different thoughts are necessary to give an answer on how a very rough surface will be measured. Assuming a high grown meadow, a young spruce stand or the like whose cross section looks as shown in the following figure.

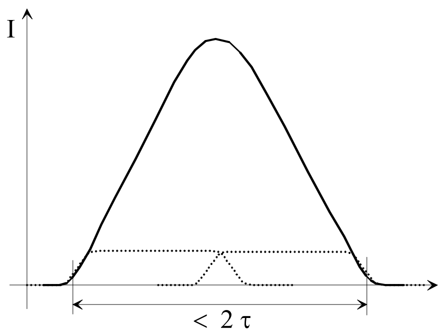


The contour of the green shaded area is defined by the highest leafs or blades or branches. The light traveling down illuminates the vegetation. First the highest branches will reflect the light resulting in a weak echo (indicated by the upward arrows). As the light goes further down, more and more branches or leaves will reflect light.

The resulting echo is composed of a lot of very weak echoes. The echo starts at the highest branches and will end at the lowest point the light could reach (which is not necessarily the ground surface). Assuming that the reflecting surfaces are evenly distributed between the highest and the lowest point, the resulting total echo looks very similar to that of a slope.

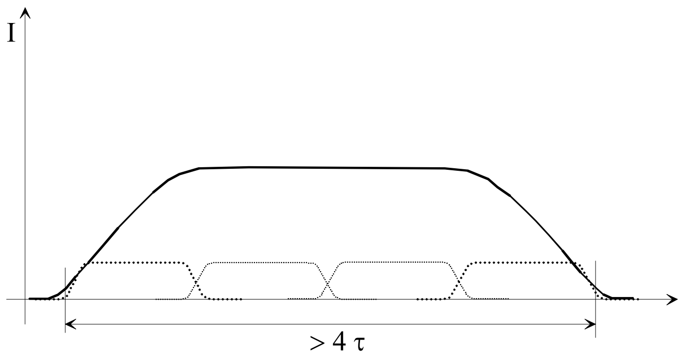
There will be some differences in the measurements for a corn field of 1.5 m height or a dense spruce stand of 5 m height. So we will analyze two different cases.

If *h* is the distance between the highest and the lowest reflecting surface and δ is the length of the laser pulse (pulse duration τ), then there are two very specific cases:



$h \approx \frac{\delta}{2}$:

The leading edge of the echo from the lowest point reaches the sensor at the same time as the trailing edge from the highest point (left diagram). This means that all partial echoes will sum up forming a peak-shaped echo.



$h \approx \delta$:

The last partial echo has to travel at least twice the pulse length longer than the first partial echo. Therefore, the distance between the trailing edge of the first partial echo and the leading edge of the last partial echo is larger than the pulse length. As all other partial echoes are in between, the resulting echo is plateau-shaped (left diagram).

Assuming the same total reflectivity for both cases, then the energy of both echo types is the same; but because of the longer duration, the amplitude of the second echo is smaller.

The partial echoes (dotted lines) are oversized in amplitude. As one can see, the raising edge in both cases takes about the duration of the laser pulse. The “adaptive threshold” method will trigger the distance measurement in the center of the raising edge, thus in both cases the measured distance defines an elevation half the pulse length lower as the top.

The assumption of evenly distributed reflectors over the height *h* is an ideal case. Usually it will be a random distribution and thus the shape of the resulting echo will vary.

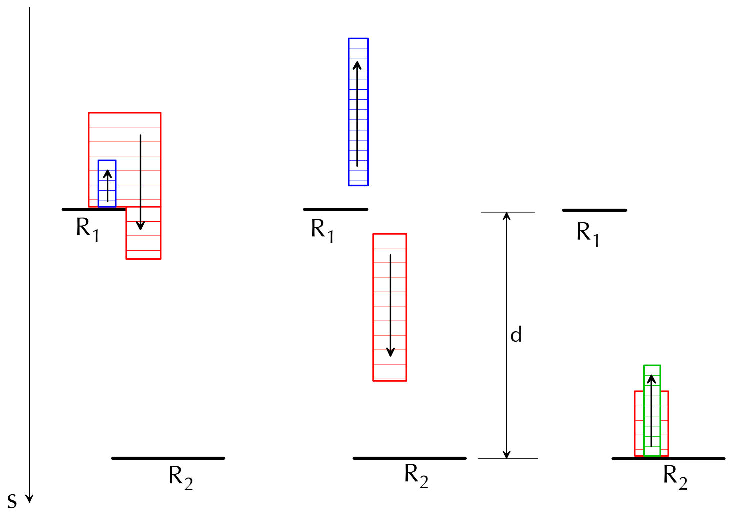
4 Multiple Echoes

One laser pulse can produce multiple reflections if the light traveling to ground illuminates several objects at different distances. Multiple reflections can occur when

1. objects are at different elevations (trivial)
2. the laser beam has a chance to partly illuminate other objects
3. objects are large enough and have a sufficient reflectivity to generate echoes
4. the laser beam is large enough (in diameter) to illuminate several objects (if the beam diameter is only a few centimeters, then already one leaf may hide all lower objects)

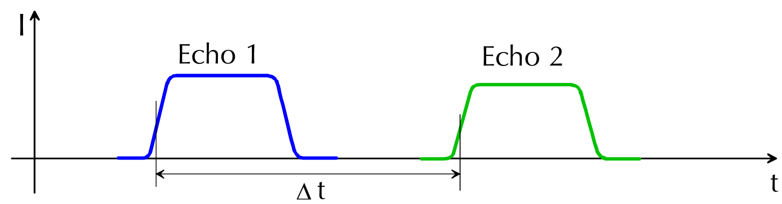
4.1 Separated Echoes

The figure shows a laser pulse illuminating two reflecting surfaces on its way down:



Part of the light is reflected on surface R1 and the remaining light is traveling further till it illuminates surface R2. Obviously the resulting two echoes are separated in time as shown in the second figure:

For simplicity it has been assumed that both surfaces are flat and thus the echoes have the same shape as the transmitted laser pulse (naturally the echoes' amplitudes are much smaller). The time separation directly corresponds to the distance of the two reflecting surfaces



$$\Delta t = \frac{2d}{c} \quad \text{or} \quad d = \frac{c \cdot \Delta t}{2}$$

4.2 Overlapping Echoes

As the example shows, echoes can only be separated if Δt is larger than the pulse duration τ. Therefore the minimum requirement for detecting two echoes from surfaces at a distance *d* becomes:

$$d > \frac{c \cdot \tau}{2}$$

Usually the detection electronic needs some recovery time, before the next echo can be detected. Taking this into account, the requirement for echo separation might become

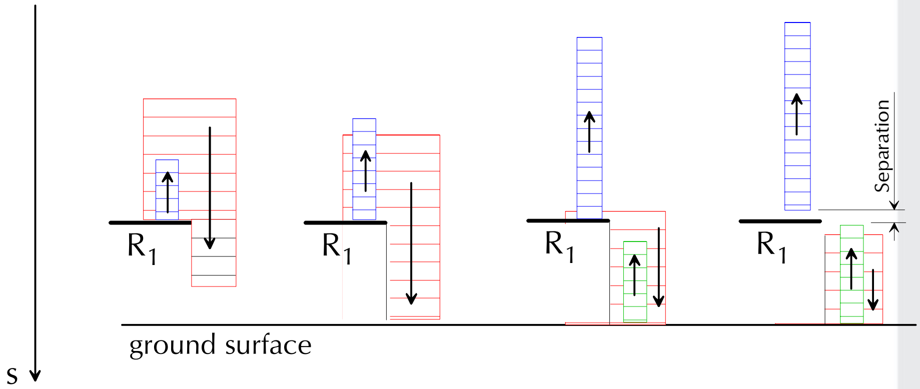
$$d > c \cdot \tau \ .$$

Taking *d* and realistic figures for pulse durations, the minimum distance becomes

$0{,}75m < d < 1{,}50m$ for $\tau = 5\ nsec$

$1{,}50m < d < 3{,}00m$ for $\tau = 10\ nsec$

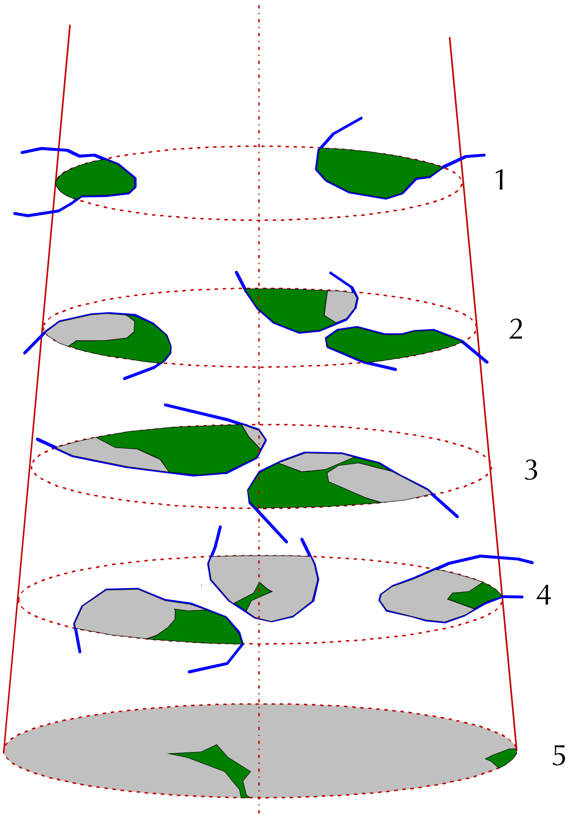
What does this mean for the measurability of the ground surface?



The figure above shows a reflecting object close above the ground. The separation of the two echoes is too short for the detector to separate them. This means for the ground surface that it can only be measured, if no reflector is present in the minimum distance *d* from ground. Reflector in this context means any object capable of reflecting sufficient light to form a detectable signal. Tiny leafless branches of a scrub usually do not belong to that type of object.

4.3 Detecting multiple Echoes

Multiple echoes mean that some of the illuminating laser light has been reflected and that the light traveling further will be reflected by lower obstacles.



The graph to the left shows some principles of multiple echoes. All obstacles (or reflectors) are arranged at dedicated levels (1 to 5) separated such that each level will produce a detectable echo. The blue lines indicate the reflectors reaching into the laser beam shown by red lines and circles.

At the first level the two objects are illuminated and reflect the laser light indicated by the two green areas.

At the second level there are three objects of which only one is illuminated completely. The two others are partially shadowed by the objects at the first level (gray areas).

At the fourth level the three objects are largely shadowed by all the objects at a higher level. And at the last level the illuminated areas have become marginal.

It becomes obvious that detecting more than two or three echoes will become rare cases. Specifically if one considers that reflectors are not arranged at specific, clearly separated levels. Taking into account that tree branches are often such close together that they create overlapping echoes which can not be separated, such simple levels as used in the example do rarely exist.

Assuming a minimum distance of 1.0 m for echo separation (valid for a TopoSys scanner) then 6 echoes would require 6 levels and a minimum height of an object of 5 m. If the minimum distance is at least 3 m (as for competing scanners) then the minimum height of an object becomes 15 m. Considering that the simple leveling of reflectors does not be reality, it becomes clear that recording of more than 4 echoes will have a probability of about zero.

4.4 First and Last Echo

The TopoSys LIDAR system measures up to nine echoes but records only the first and the last echo. As shown in the section above intermediate echoes are rare and not of general use. There might be some very specific applications where reflectors are arranged at specific levels (e.g. power lines) and where recording of more than two echoes would be worthwhile. On special request TopoSys can customize the scanner system accordingly.

The terms First Echo (FE) and Last Echo (LE) are usually associated with high objects and low objects respectively. This is not completely true. If there is a street lamp and a street there will be two echoes one from the lamp (FE) and one from the street (LE). If there is only one surface (roof, road, meadow) there will be only one echo.

5 Conclusions

Multiple echoes can be measured only if reflectors are further apart than the pulse duration (or its equivalent length in meters). Otherwise “First echo” mode and “last echo” mode data will not differ.

A number of surfaces will reflect only one detectable echo, resulting in that FE and LE are identical:

- Flat vegetation (lawn, wide crown of a deciduous tree, ...)
- Low structured surfaces (road, roof, ...)
- Dense vegetation (spruce, corn, ...)

On the other side there are a number of surface shapes which will always provide multiple echoes, just to take a few examples:

- power cables
- leafless deciduous trees
- edges of buildings or of high trees

A distance measurement represents the surface properly only if the surface is even (independent whether flat or tilted). It represents a larger distance (or lower elevation) if the surface is structured (top of a roof, corn field, ...)

If the ground surface has to be measured, survey flights should be performed preferably during the leafless season, or when all fields have been harvested.