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LIDAR

TAF OPE – AMRC

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LECTURE PLAN

- Introduction. What is Lidar ? Basic Principle
- Different Lidar types and applications
- Anatomy of a Lidar – main components
- Basic Lidar equations
- Lidar and light-matter interactions
- **Atmospheric** Lidar and its applications
- **Topographic** Lidar and its applications
- **Automotive** (robot, drone …) Lidar
- Conclusion

LIDAR = LIght Detection And Ranging

(LAser Detection And Ranging)

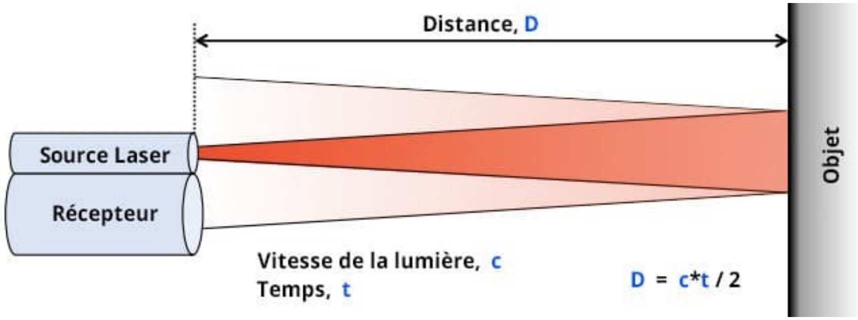
Same idea as RADAR but with different wavelengths (250-1000nm vs 3-100mm).

Basic Principle

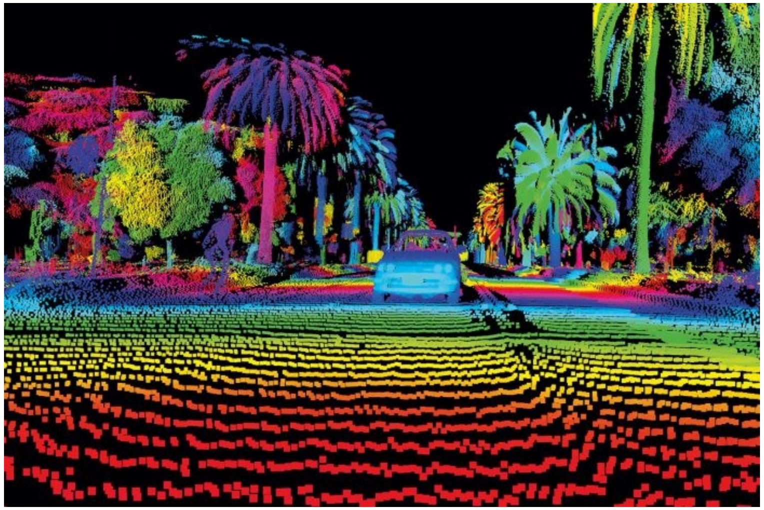
- A laser pulse is emitted towards a target
- The target reflects part of this light pulse back towards the receiver
- A high-speed photodetector measures the time for the return trip
- This is converted into a distance to the target
- The beam is scanned in 2D to build up a 3D distance map
- Detailed analysis (spectrum, polarisation …) of the returned light allows the determination of some specific target properties (e.g. atmospheric Lidar)

Historical timeline: Sonar (WW1), RADAR (WW2), LIDAR (1971, Apollo 15)

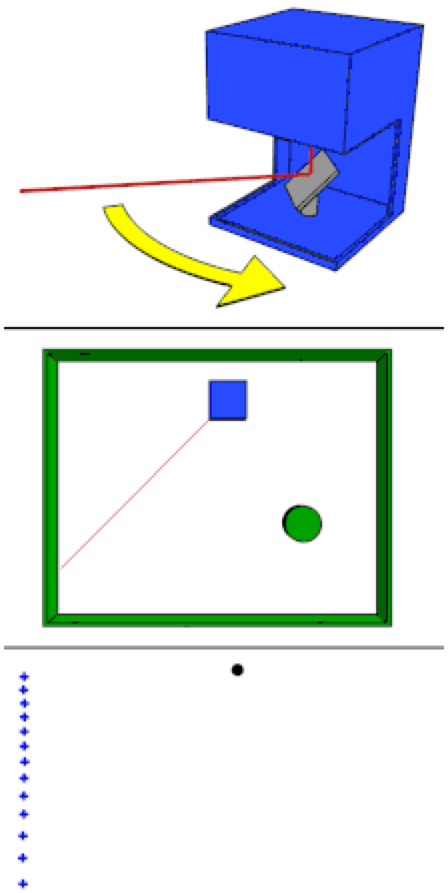
INTRODUCTION – BASIC LIDAR PRINCIPLE ?



Basic Lidar operation and distance calculation



Example colour-coded 3D point cloud map from an automotive Lidar



Illustrative animation of a 1D Lidar scan and output for a simple target

LIDAR – EXAMPLES AND APPLICATIONS

Initial Lidar systems were bulky and so ground based

- Large, low efficiency lasers – required lots of power
- Main application → study of the **atmosphere** from the ground
  - Metrological studies (cloud height, composition)
  - Chemical pollution (smoke, ash …)

As laser technology improved, Lidars became more compact and efficient

- Portable ground Lidar used for surveying
  - cartography, archaeology, agriculture, volcanology ...
- Aeroplane mounted, downward looking Lidar allowed large areas to be mapped very quickly.

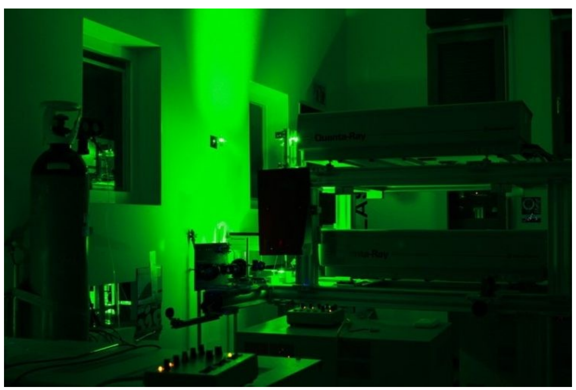
Further, recent, advances in laser and computing technology

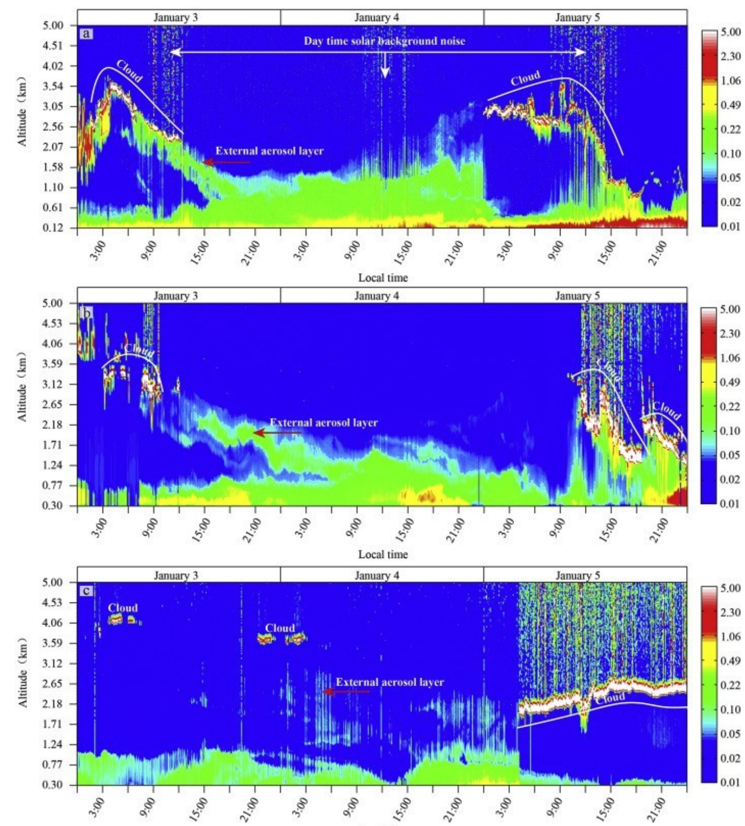
- Higher power, smaller, faster and especially lower cost Lidar available
- Mounted on vehicles/drones/robots for autonomous vehicles

LIDAR EXAMPLES – ATMOSPHERIC

Used to monitor meteorological and air pollution parameters

- Fixed, ground based installations … up to 300W light power (eye safety)
- High power visible/UV lasers (Nd:YAG, Excimer: 532nm, 355nm, 308nm)
- Large collecting optics for return signal (telescope) – ranges up to > 20km
- Spectral, polarisation … analysis of returned signal.

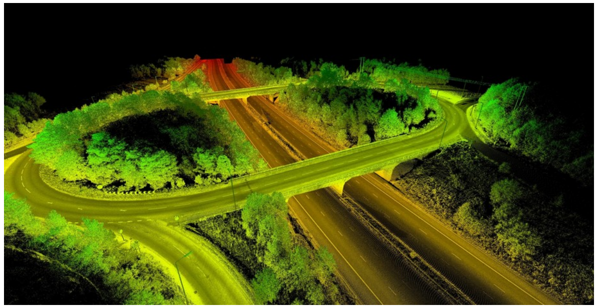


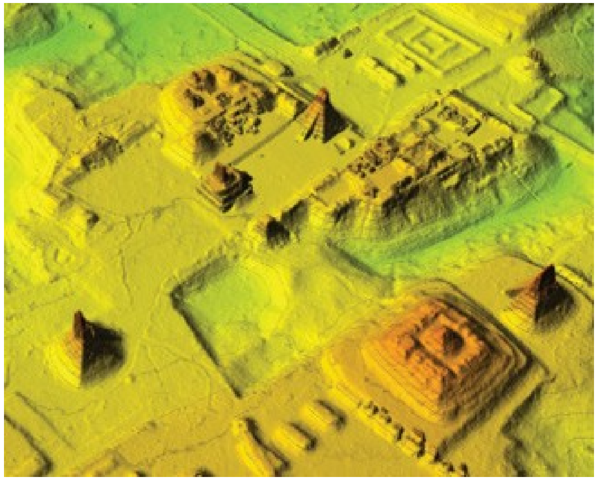


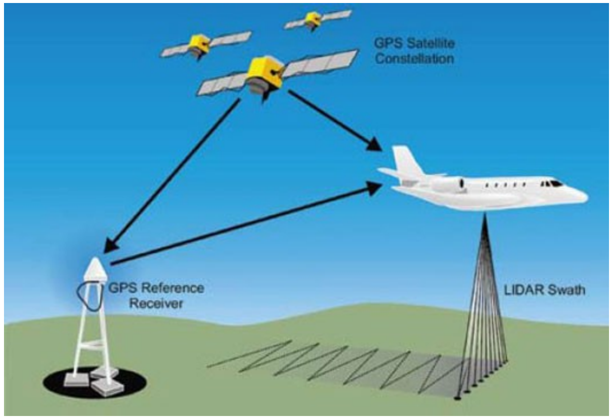
LIDAR EXAMPLES – SURVEYING

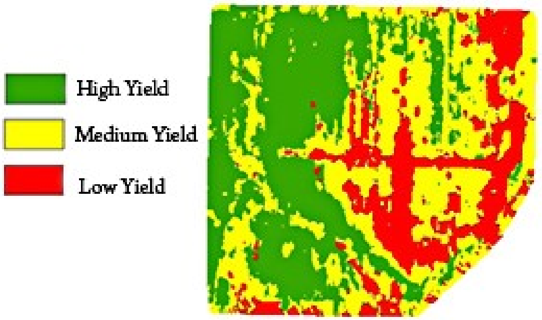
High efficiency compact lasers (e.g. laser diodes) → portable LIDAR

- Visible wavelengths (532nm) limited by eye-safety regulations so low range
- Tendency to move to IR wavelengths 903nm, 1064nm, 1550nm …
- 532nm used for bathymetric LIDAR (minimal water absorption)
- Aeroplane/drone mounted, LIDAR allow large areas to be mapped very quickly.
- Applications in cartography, archaeology, agriculture, volcanology, mining ...





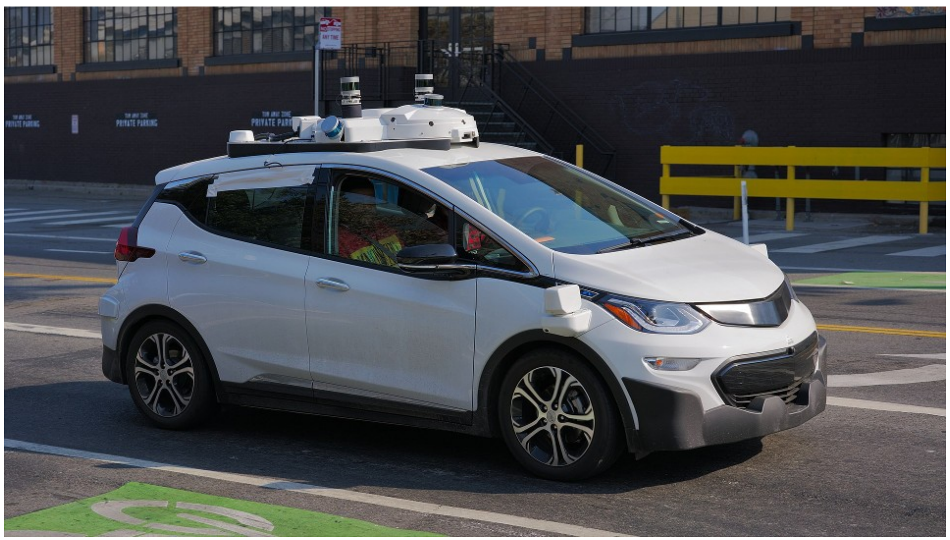




LIDAR EXAMPLES – AUTOMOTIVE / ROBOT

Recent advances in laser and computing (data processing) technology

- Smaller, lighter and especially lower cost Lidar available ("scanfree" solid state)
- Autonomous vehicles – complement to Radar and 2D camera images
- Robot, drone guidance (huge cost reductions obtained)



TeraRanger Evo64px

- 8x8 pixels
- 12g
- 125€

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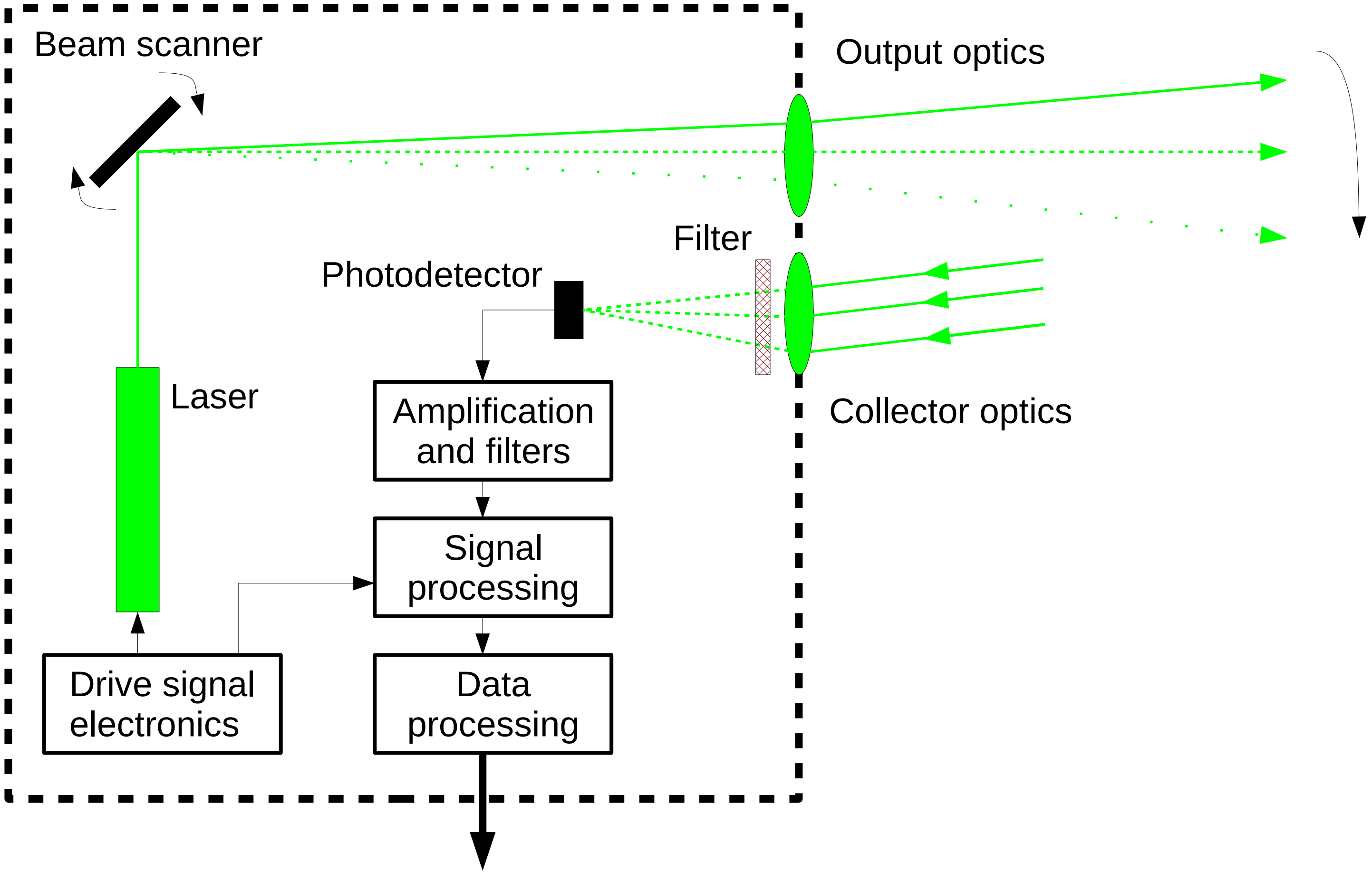
- **Automotive** (robot, drone …) Lidar
- Alternative, competing techniques
- Conclusion

ANATOMY OF A LIDAR

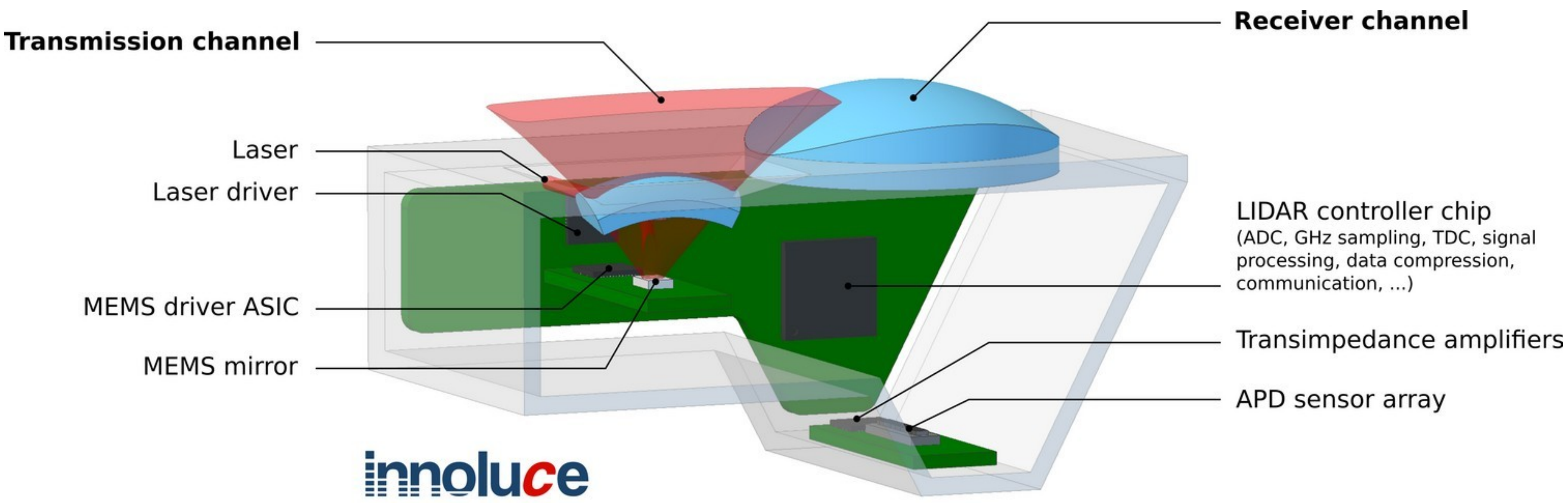
Main LIDAR components:

- Directive, pulsed **light source(s)** – almost always a laser
  - wavelength, power, repetition rate, pulse length … adapted to the application
- Emission optics
  - optimise beam size and divergence
- **Beam scanning** system
  - scan the target field area – scan step (resolution) and speed adapted to application
- **Reception optics**
  - Collect as much light as possible – optimise SNR
- **Optical filters**
  - Remove background light (noise) – optimise SNR
- **Photodetector**
  - Sensitivity/bandwidth compromise
- GPS/Inertial Guidance system
  - To precisely geo-localise each measured data point
- **Signal processing electronics**
  - Amplify and filter to improve SNR
- Data processing hardware and software
  - Post-processing with GPS data to create human (or robot) readable data

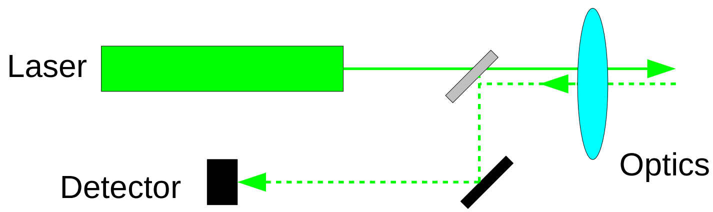
BASIC LIDAR SCHEMATIC

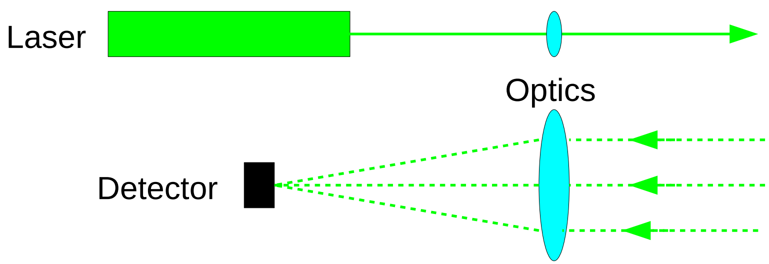


EXAMPLE SCHEMATIC – AUTOMOBILE LIDAR



MONOSTATIC AND BISTATIC GEOMETRIES





Monostatic

- Outward/Return paths share same optics
- Filters (polarisation, wavelength ...) isolate return signal from output signal

<u>Advantages</u>

- Can be cheaper as optics are shared
- No parallax errors – close objects
- More compatible with coherent detection

<u>Disadvantages</u>

- Isolation imperfect – noise on return signal
- Can't optimise optics simultaneously for laser and detector.

Bistatic

- Outward/Return path use separate optics
- Paths can be parallel or at an angle

<u>Advantages</u>

- Optimised optics (eg larger for return path)
- Can be cheaper as optics more specific
- Easier to use multiple detectors
- Better path isolation

<u>Disadvantages</u>

- Parallax errors for close objects.

LIDAR LASER CHARACTERISTICS

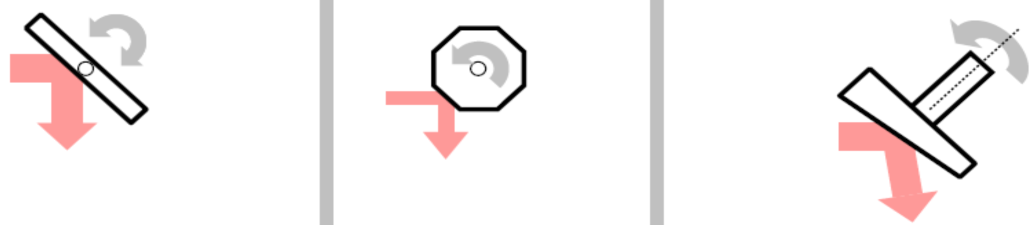
Laser characteristics vary with the application – some typical values:

- **Wavelength**:
  - Atmospheric lidar near UV (355nm) and near IR (**905**; 1064; **1550**nm)
  - Underwater lidar visible (**532**nm) – best penetration of water
  - Automotive/robot/drone – near IR (905, **1550**nm …) - eye safety.
- **Power**: 2mW (robot/drone) → kW (high power atmospheric Lidar station)
- Pulse **repetition rate** ~1-100 kHz
- **Pulse duration** (typically ~10 ns)
- **Beam divergence** – typically ~mrad (scanned lidar, "flash" Lidar much wider)
- **No. beams** : 1, 16, 32 ... 64 … more beams → faster data point acquisition

BEAM SCANNING SYSTEMS

System mechanics

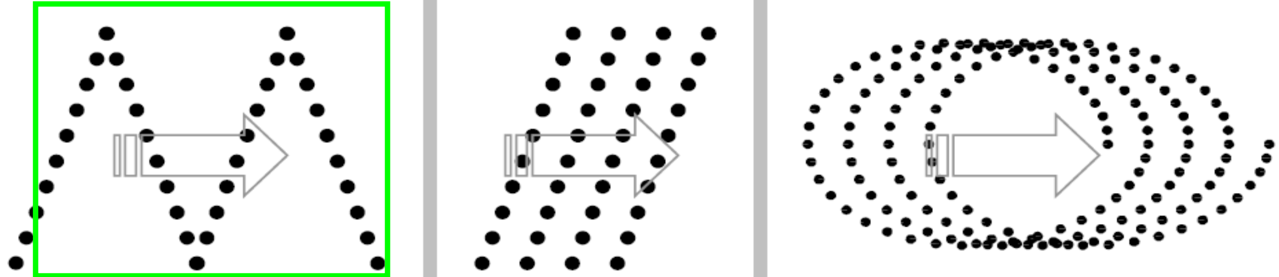
Oscillating mirror | Rotating polygon | Nutating mirror (Palmer scan)



Sawtooth

Z-shaped, sinusodial | Parallel lines | “Elliptical”

Scan pattern

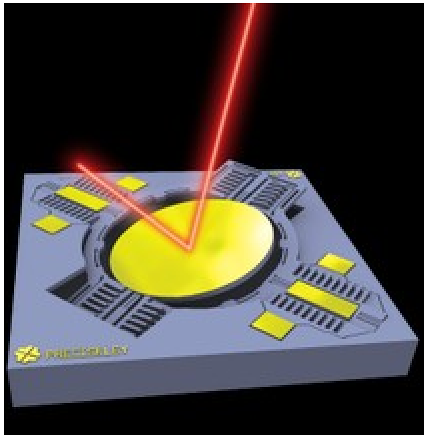


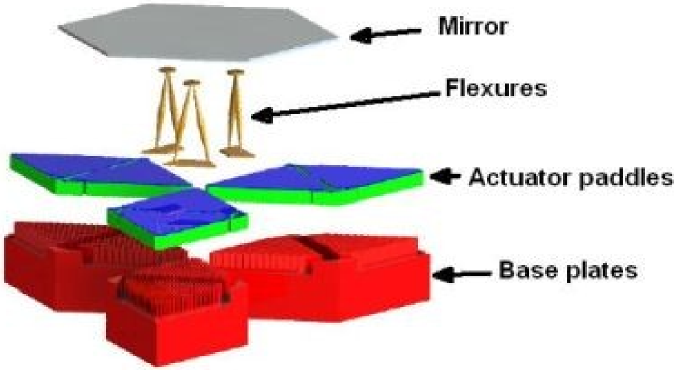
Most common pattern (Leica, Optech)

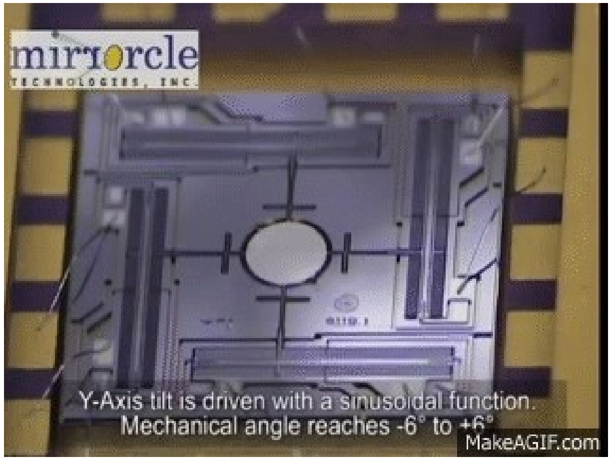
Figure adapted from: Nikolaos 2006

MEMS SCANNERS

- Mechanical systems (rotating mirrors etc) are bulky, expensive and wear out
- Many, modern, compact Lidars use **MEMs** (Micro Electro-Mechanical Systems)
  - “Solid state” device – no moving parts to wear out ?
  - Small, low-weight devices (1x1mm or less)
  - Batch fabrication on wafer (micro-electronics) → low cost
  - Small mirror size can limit beam size and power

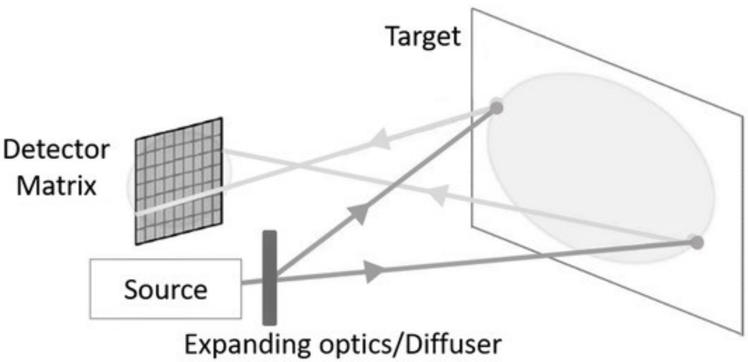


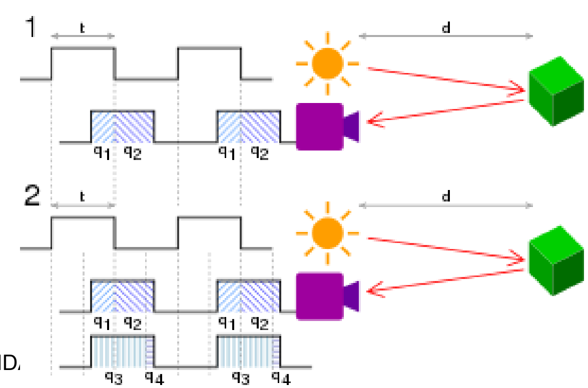




« FLASH » LIDAR

- **“Flash” Lidar simultaneously illuminates a whole scene (vs single scanned beam)**
  - Use of a divergent laser beam, multiple beamlets … or a LED (short range)
  - Eye safety constraints limit beam power and hence range
- **No scanner mechanics so compact, reliable, fast and potentially cheap**
- **Requires an array detector which can precisely measure the return flight delay for each pixel (complex high-speed parallel electronics)**
- **Such “TOF” (Time Of Flight) detectors currently have low pixel counts (eg 640x480) compared to scanned systems – hybrid systems proposed.**





LUMOTIVE

	Flash	2D Raster-Scan	1D Line-Scan
Illumination pattern	Entire FoV simultaneously	Sequentially by pixel (120°)	Sequentially by column (25°)
Returned signal per pixel	Low	Highest	High
Range	Too short (< 50 m)	Longest (> 250 m)	Long (250 m)
Frame rate	Fastest (> 30 fps)	Too slow (2 fps*)	Fast (30 fps)
Suitability	✗	✗	✓

* Frame rate limited by 300 k pixels / frame (1,200 x 250) and 2 µs minimum time-of-flight per pixel (2 x 300 m / 3x10⁸ m/s). 300 k pixels / frame x 2 µs / pixel = 600 ms / frame. ∴ Max frame rate < 2 fps.

LeddarTech Video: https://www.youtube.com/watch?v=R57488zI-hk

LIDAR RECEIVERS

- **Collection optics**
  - Larger optics – more light signal collected and better theoretical reolution
  - Long distance atmospheric and satellite Lidar use large mirror telescopes

- **Optical Filters**
  - Narrow bandwidth (<1nm) thin film interference filters at laser wavelength
  - Strong rejection of background light (sunlight) (T>30%, block 10^{-7})
  - If required, operation at night to maximise SNR

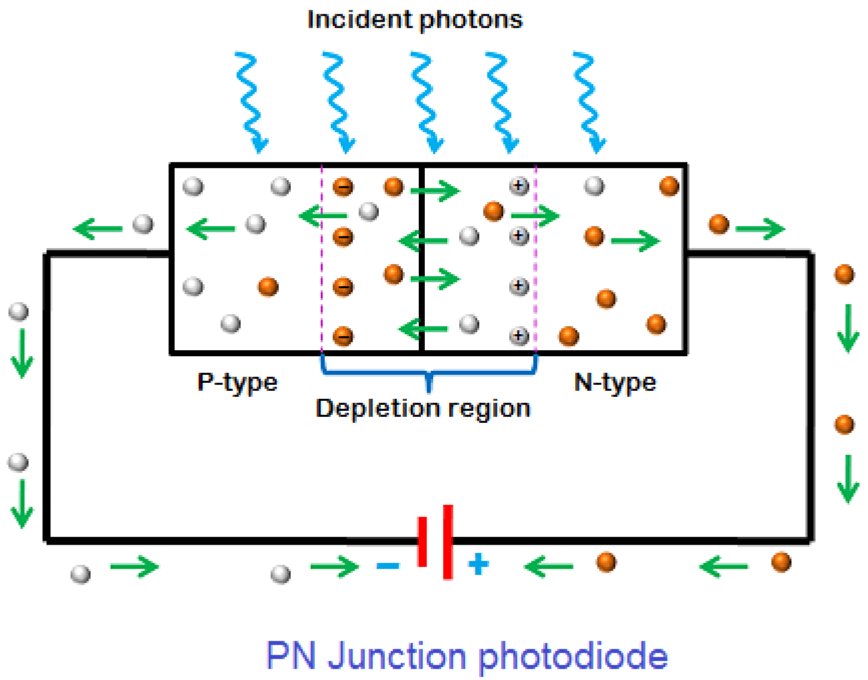
- **Photodetector**
  - Photodiodes or photomultiplier tubes
  - High sensitivity and >100kHz bandwidth required APD (Avalanche Photodiodes)
  - … SPAD avalanche photodiode, (high sensitivity, good spectral response but noisy)

- **Control electronics (synchronisation detector and laser pulses)**

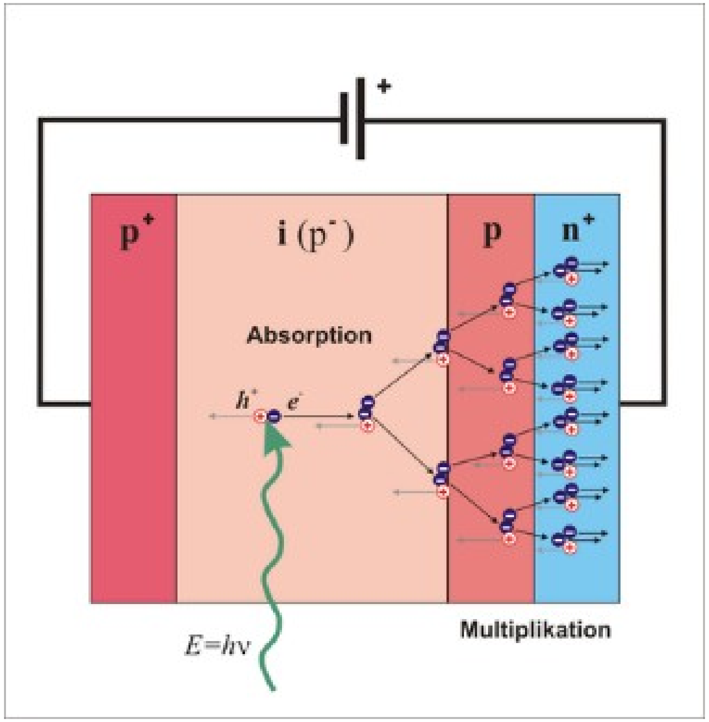
- **A/D convertor (High dynamic range and sample rate)**
  - Multi pulse per sample and multi sample per pulse can both be used.

SEMICONDUCTOR PHOTODIODES

- ► **PIN and APD (Avalanche)**
- ► **See earlier lecture on "optical interfaces" for more details**.



www.physics-and-radio-electronics.com



PHOTOMULTIPLIER TUBE

- Similar principle to avalanche photodiodes
- Very high amplification – capable of detecting single photons
- Used mainly in very long range (atmospheric) Lidars

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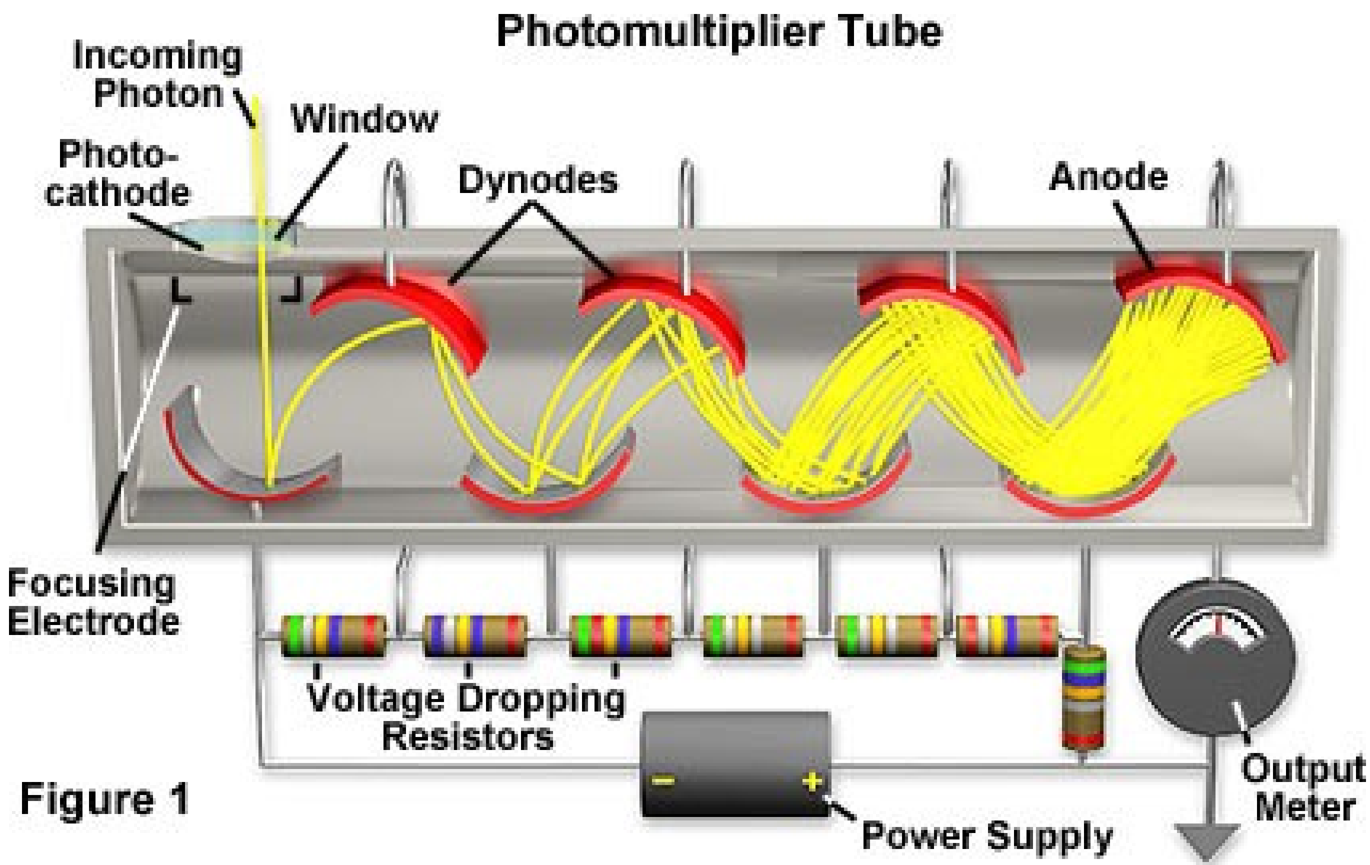

Figure 1

DATA PROCESSING

- **From the measured range and mirror angle data, a Lidar calculates a 3D dataset of points (XYZ) called a “pointcloud”**
- **For surveying (airborne) Lidar, this data is combined/registered with GPS data**
  - Highly accurate GPS (and inertial guidance) data required (resolution <1m)
- **LAS is standard Lidar data format – compressed to LAZ (huge data sets)**
- **Specialised software processes, analyses and displays this data.**

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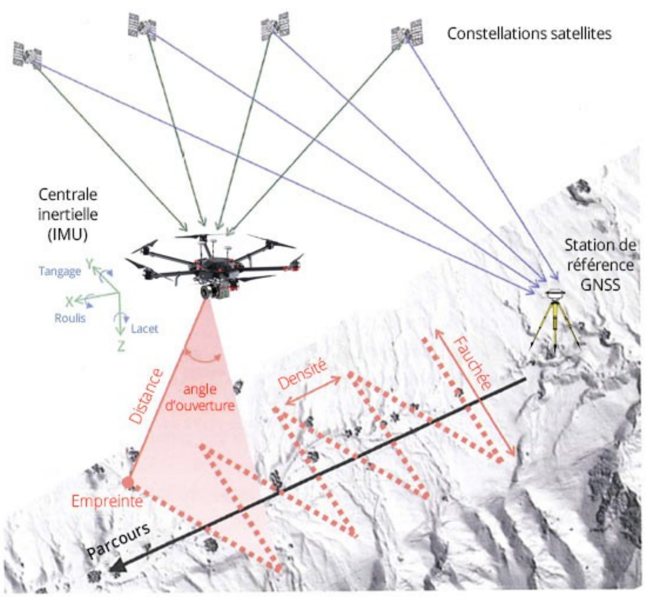

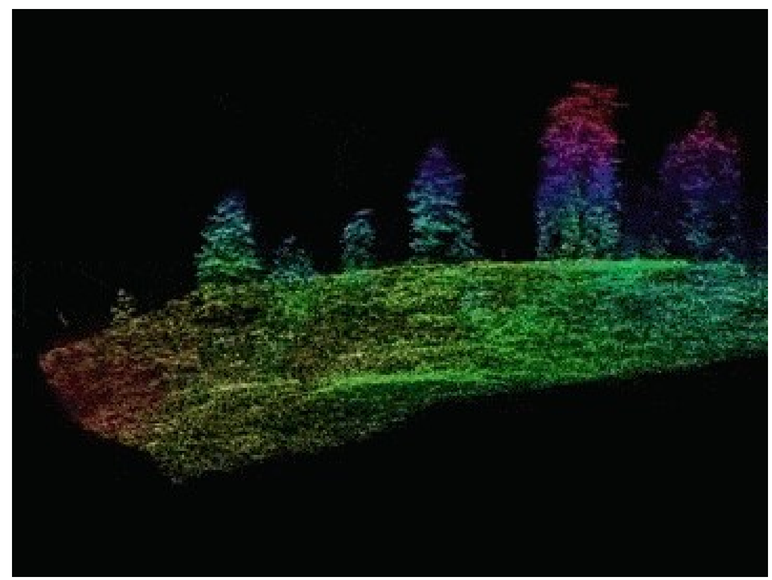

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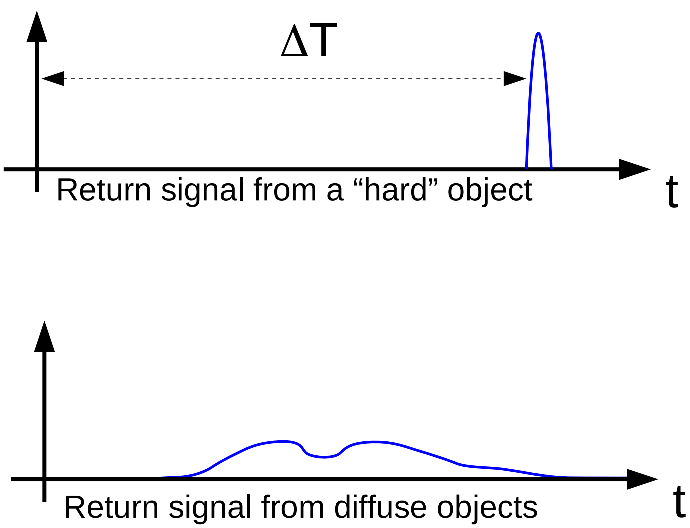
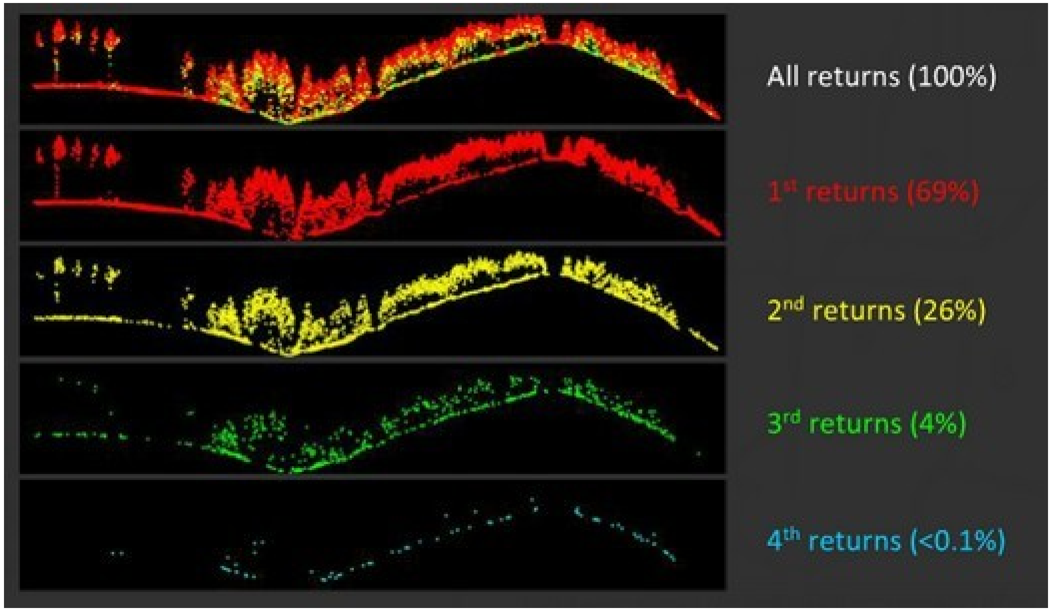
Distance calculation – multiple returns

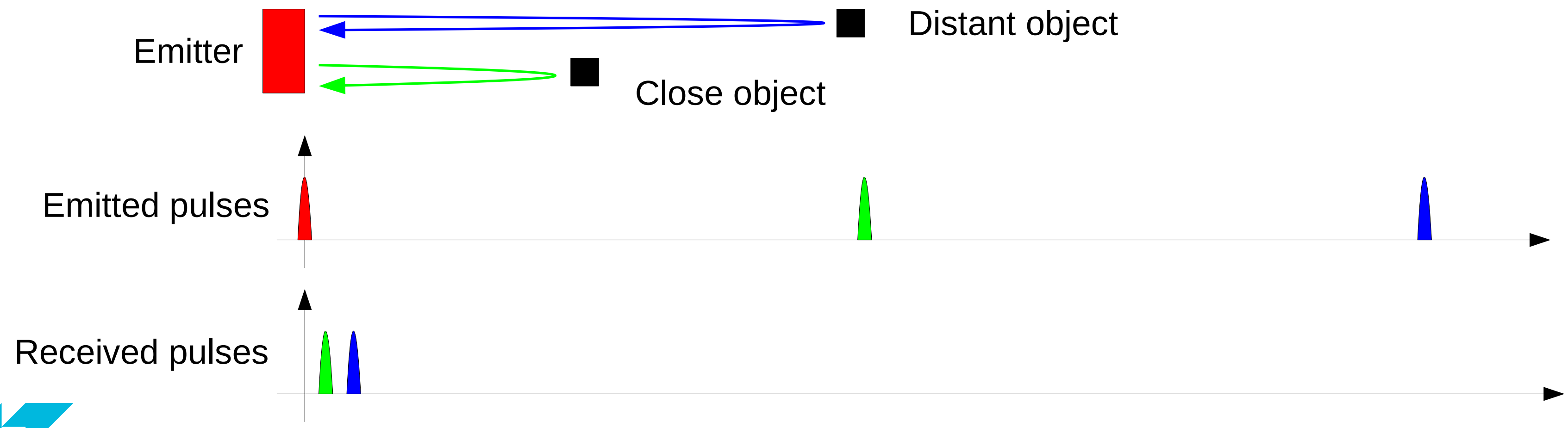
- Simplest case: a unique, clear reflected pulse signal from the target
  - Distance to target, d, given by $d = \Delta T / 2c$
  - Where ΔT is the time delay between pulse emission and return reception and c is the speed of light in the propagation medium (air)
- In more complex cases with "soft" targets, there can be several partial reflections
  - For example from the top of the canopy and the ground in a forest.
- Atmospheric Lidar : ~ continuous return "pulse" from multiple heights





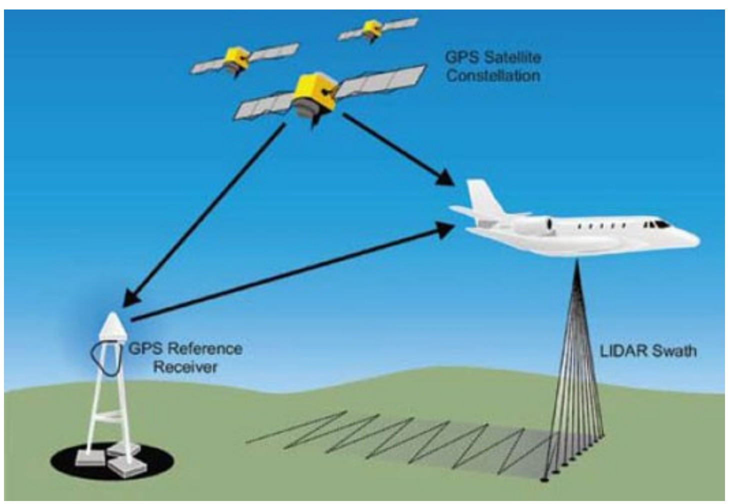
Repetition rate and range ambiguity

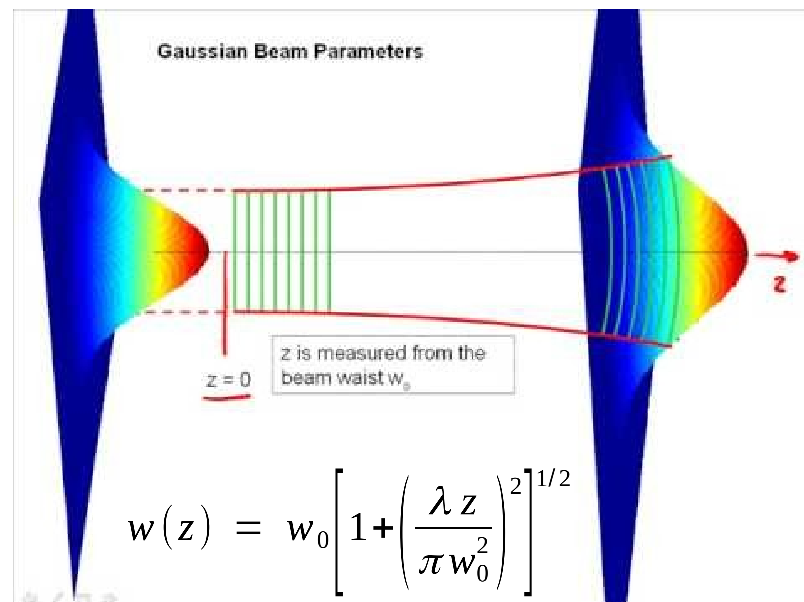
- Lidar pulse repetition rate determines the "**ambiguity distance**"
- To maximise data point acquisition rate, high repetition rates are preferred
- However, this can produce ambiguity in the interpretation of return pulses:
  - Is the pulse returned by a nearby object ? **OR**
  - Is it a pulse returned by a distant object, for a previously emitted pulse ???
- Angular scanning and (usually) weaker return pulses from distant objects help reduce ambiguity
- Pulse repetition rate can determine maximum ambiguity free range : $R=c/2F_p$
  - R is the maximum range and F_p is the pulse repetition frequency, c speed of light



Angular/ spatial resolution

- For a scanning Lidar, the sample point density across the measured field depends on the scan rate (degrees/s) and the repetition rate (pulses/s)
- For a fixed angular scan rate, spatial sampling density will be non-uniform
- For a moving Lidar (e.g. drone) sampling density will also depend on vehicle speed.
- However, to reach a spatial (or angular) resolution corresponding to these sample densities:
  - The laser spot size on the target must be sufficiently small (Gaussian beam divergence) – see lecture on physical properties of propagation media
  - The optical resolution of receiver optics must be sufficient (especially flash Lidar)





Lidar optical power budget

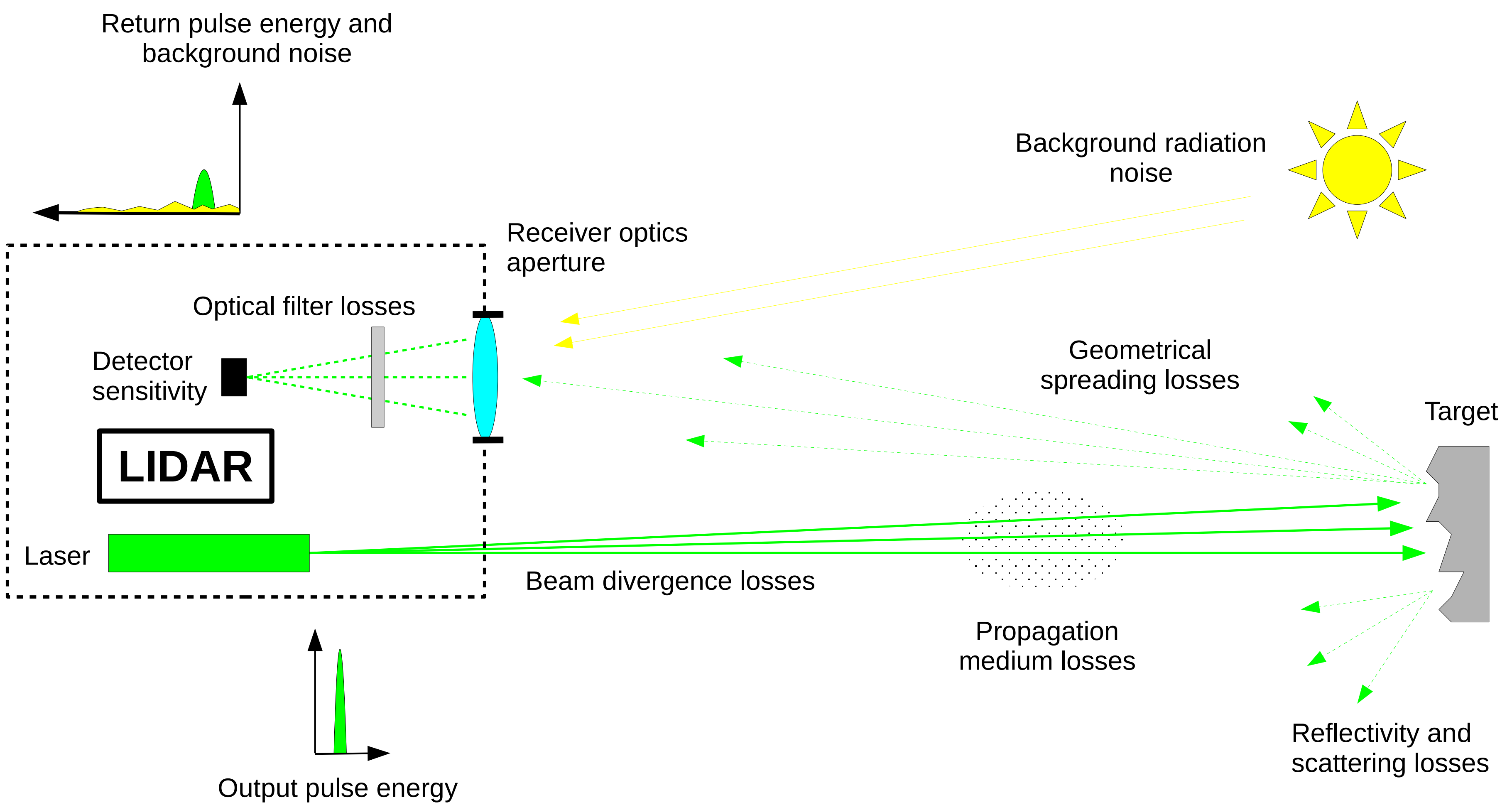
- Lidar range and data acquisition rate also depend on the system power budget
- The power budget depends on numerous factors:
  - Energy per emitted laser pulse
  - Beam spreading losses (Gaussian beam divergence)
  - Attenuation of beam by the propagation medium (mist, dust, fog ...)
  - Target reflectivity/scattering
  - Geometrical spreading of return signal
  - Receiver collecting optics aperture size
  - Receiver optical filter efficiency
  - Photodetector efficiency
  - Background illumination and noise level
- The total received energy per pulse (No. photons) must be sufficiently higher than the background radiation level (varies with wavelength, night/day …)
- LIDAR equation - Received power at range R:

$$P(R) = P_0 \rho \frac{A_0}{\pi R^2} \eta_0 \exp(-2\gamma R)$$

Assuming normal incidence, Lambertian reflection, negligible beam divergence and spot size < the target size

Where P_0 is the peak emitted power, ρ the target reflectivity, A_0 the receiver aperture area, η_0 the receiver optical transmission, γ the atmospheric attenuation coefficient

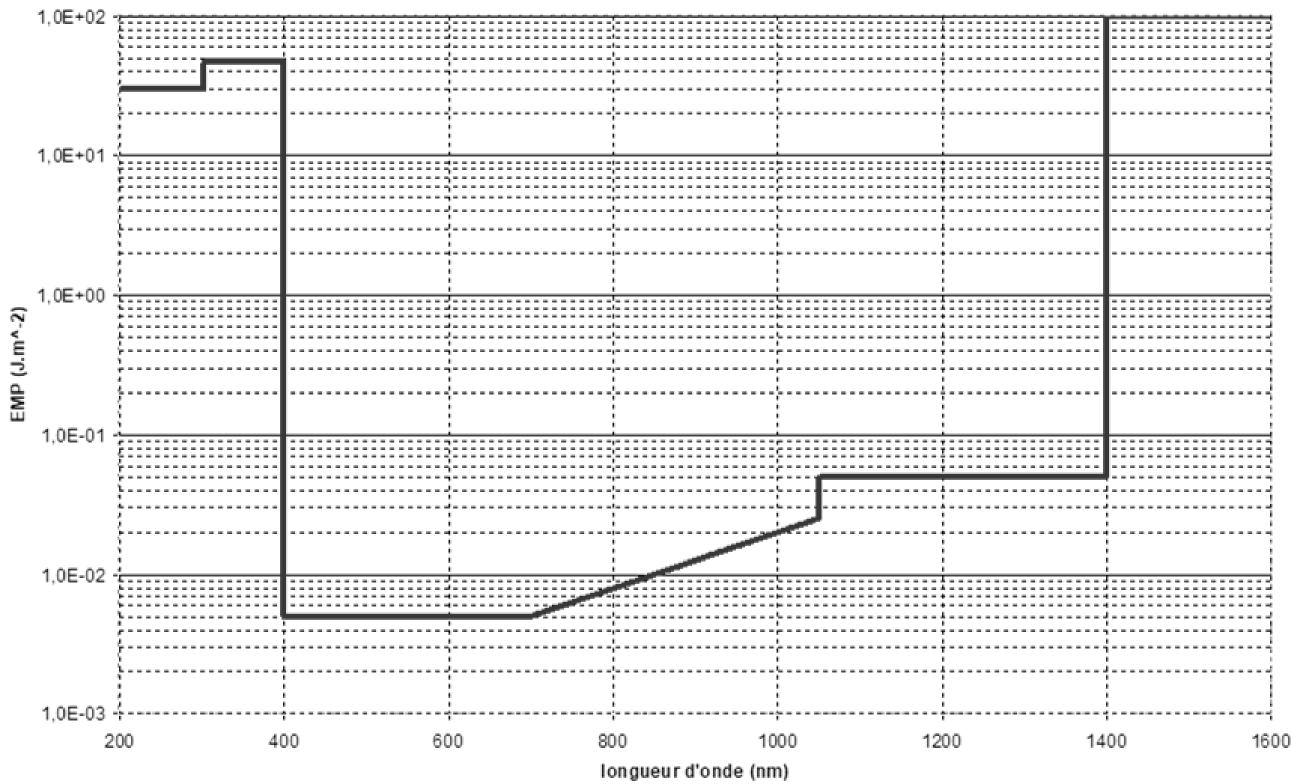
Lidar optical power budget



$$P(R) = P_0 \rho \frac{A_0}{\pi R^2} \eta_0 \exp(-2\gamma R)$$

Eye safety power limits

- The simplest solution for improving the power budget is to use more output power
- However, eye safety rules limit output power (PME – permitted emitted levels)
- Exact rules are relatively complex – depend on wavelength, divergence, pulse duration ...
  - Permitted power varies greatly with wavelength (higher in UV and IR)
  - Short pulses are advantageous as they give a lower average power



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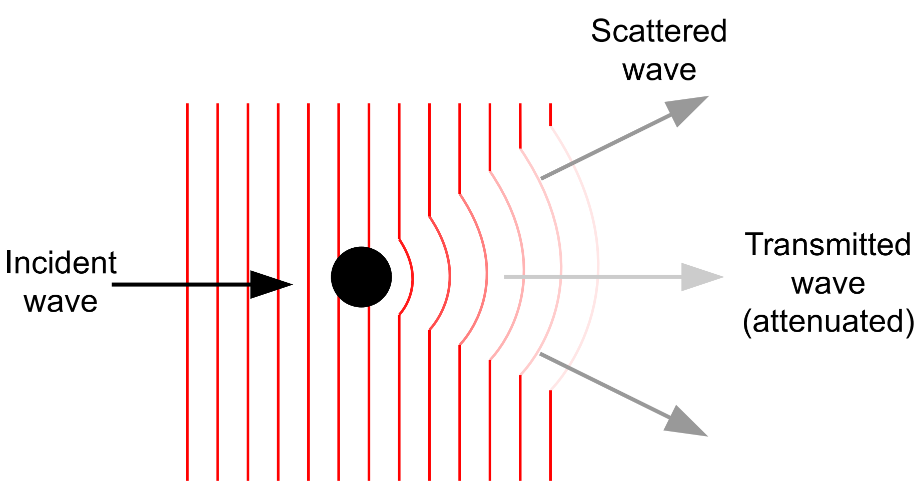
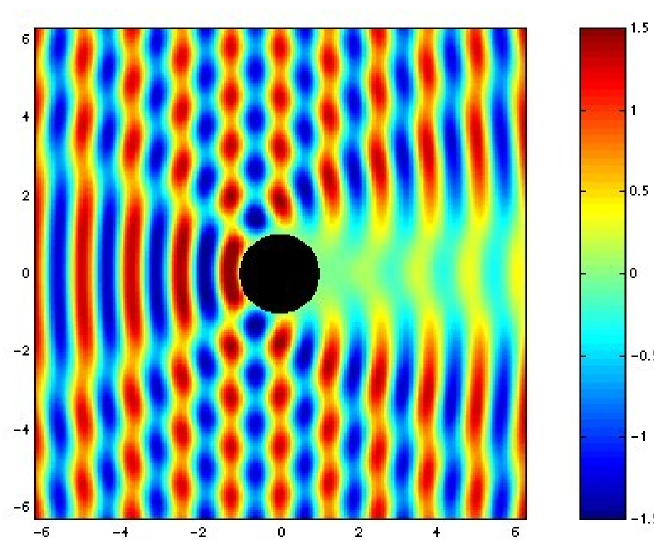
Scattering, diffusion, diffraction ...

- The way the light beam interacts with a target has a major influence on the returned signal strength (hence Lidar range) and on the information that can be deduced.
- Light can be absorbed, reflected (“specular” = mirror-like) or more generally **“scattered”**. Scattering, diffusion and diffraction are similar inter-related phenomena causing the **deviation** of a propagating wave (or particle) due to interactions between the wave and an obstacle





Scattering, diffusion, diffraction ...

There are **three** main scattering models based on the relative size of the scattering particle (d) and the wavelength (λ). **Rayleigh, Mie, Geometrical**.

1. Rayleigh scattering: d << λ

- Scattering strength is proportional to f^4 (so $1/\lambda^4$)
- Optical signals ($\lambda \sim 1\mu m$) → significant Rayleigh scattering by air molecules (blue sky)

2. Mie (resonant) scattering : d ~ λ

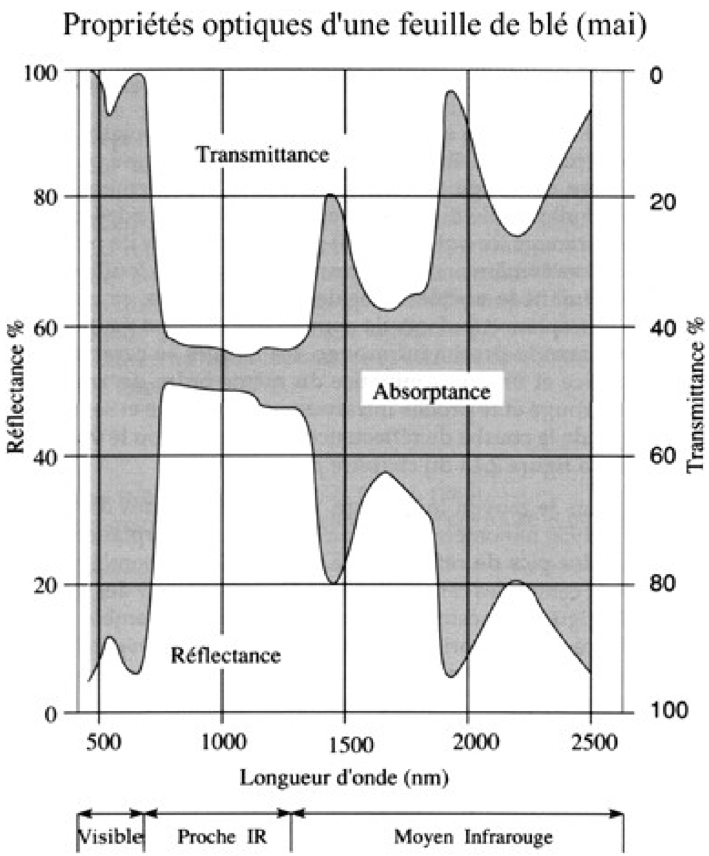
- Optical signals ($\lambda \sim 1\mu m$) significantly scattered by airborne particles, dust, water vapour …
- Little wavelength dependence so scattered visible light appears white (e.g. clouds)
- For IR wavelengths (automotive Lidar), water droplets (fog, rain) can strongly reduce range.

3. Geometrical regime: d >> λ

- Wave effects can be neglected and geometrical (ray) propagation models used : reflection
- This is the case when interfaces are "smooth" at the wavelength scale.
- Usually relatively strong reflections from such objects … but sometimes little back-scatter.

Target optical property variations

- The optical properties of a target can vary greatly with material and wavelength
  - Large detector (emitter) dynamic range required
- Wavelength choice is important for each application to extract the desired information
- Multiple wavelength Lidars can be used to extract different types of information
  - e.g. 532nm (underwater) and 1550nm (land) for an airborne coastal topographic radar

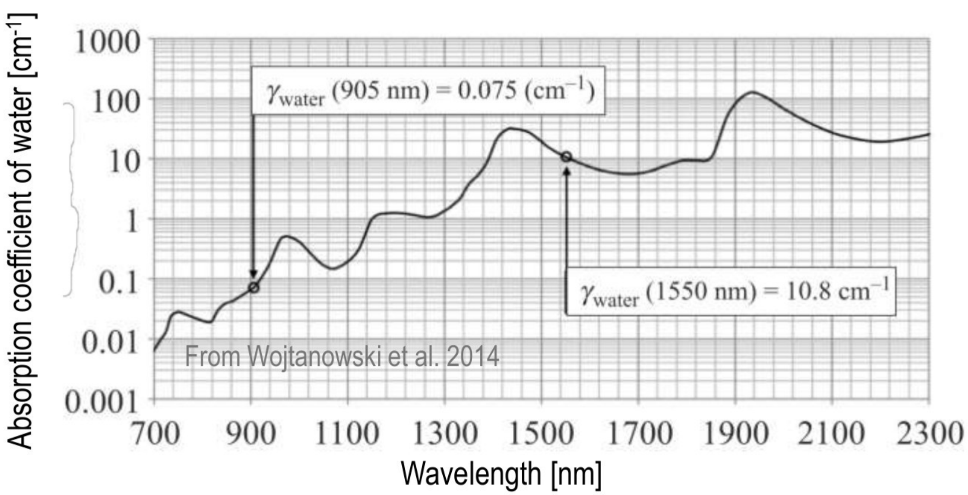


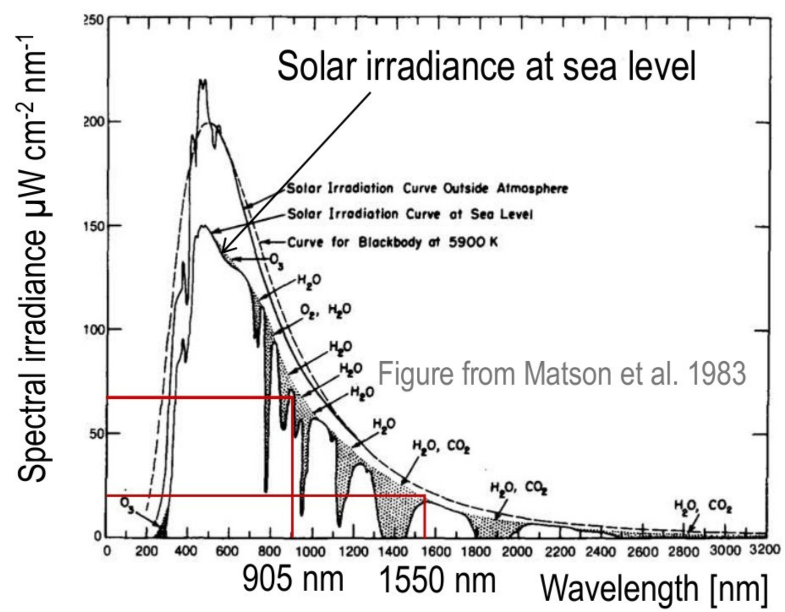
MATERIAL	REFLECTIVITY @ λ = 900 nm
Dimension lumber (pine, clean, dry)	94%
Snow	80-90%
White masonry	85%
Limestone, clay	up to 75%
Deciduous trees	typ. 60%
Coniferous trees	typ. 30%
Carbonate sand (dry)	57%
Carbonate sand (wet)	41%
Beach sands, bare areas in desert	typ. 50%
Rough wood pallet (clean)	25%
Concrete, smooth	24%
Asphalt with pebbles	17%
Lava	8%
Black rubber tire wall	2%

Source: www.riegl.co.at

Wavelength choice example

- Optimal Lidar wavelength for an application is always an engineering compromise
- Multiple criteria including, laser power, pulse duration, divergence, target reflectivity, wavelength availability, laser cost, stability, operating temperature range ...
- Example – automotive Lidar - suitable lasers available at 905nm and 1550nm
- 1550nm
  - Better for eye safety (higher power limit)
  - Lower background noise
  - Requires more expensive (non-silicon) photodetectors
  - High absorption by water molecules (rain, fog, wet roads and vehicles)
- 905nm
  - Better transmission through atmosphere
  - Cheaper silicon based photodiodes
  - Higher background radiation



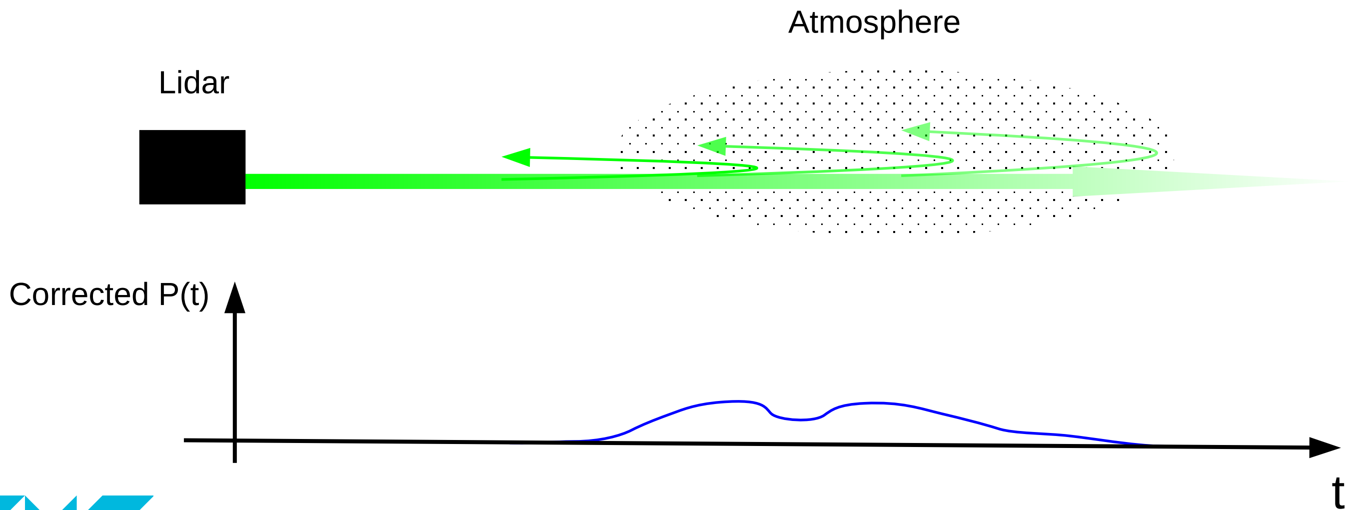


LECTURE PLAN

- Introduction. What is Lidar ? Basic Principle
- Different Lidar types and applications
- Anatomy of a Lidar – main components
- Basic Lidar equations
- Lidar and light-matter interactions
- **Atmospheric** Lidar and its applications
- **Topographic** Lidar and its applications
- **Automotive** (robot, drone …) Lidar
- Conclusion

Atmospheric Lidar – basic principle

- Atmospheric Lidars send powerful laser pulses into the atmosphere
- Molecules, aerosols, dust … at various points along the beam path will retro-diffuse the signal beam back to the detector
- Losses due to system parameters and due to distance (divergence, geometric spreading, molecular diffusion …) are known and can be compensated out – at least approximately
- Returned signal strength vs delay gives an approximate map of diffusion vs height.
- This allows cloud height, cloud density, dust density … to be estimated or measured
- Regular and frequent calibration required to factor out “usual” molecular diffusion
- Extensively used in meteorology and pollution measurement



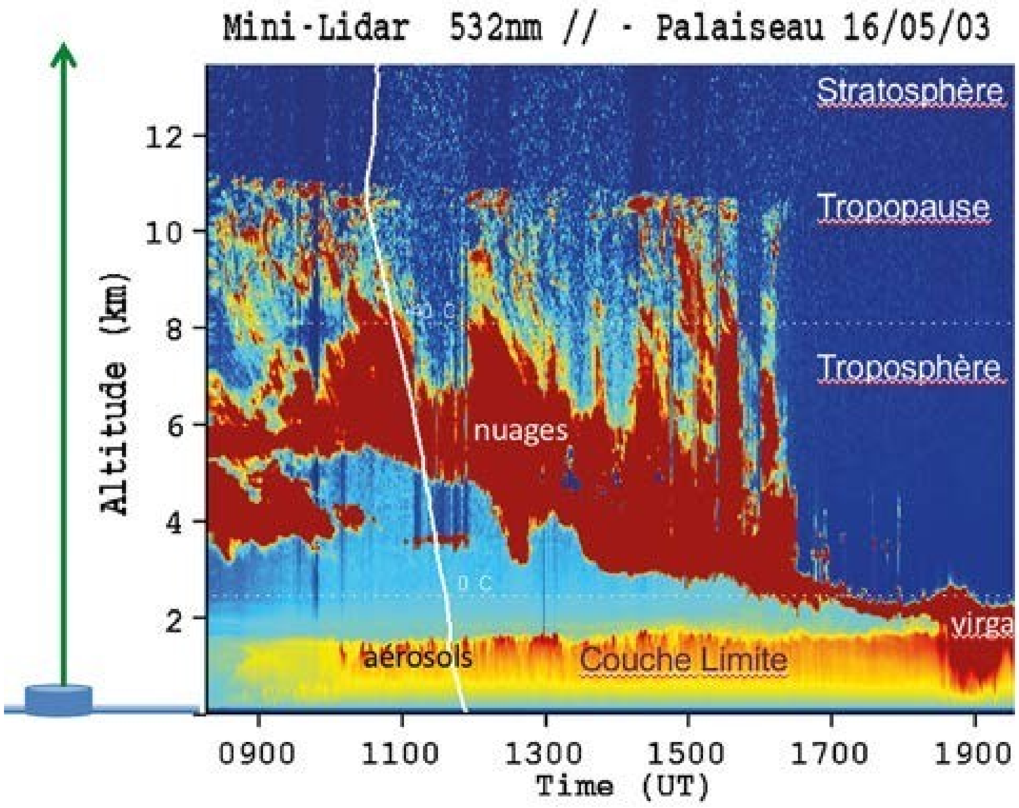
Modified Lidar equation - “soft” targets

LIDAR equation (atmospheric diffusion):

$$E(t)_R = \frac{CE_0}{z^2}(\beta_R + \beta_a) exp\left[-2\int_0^Z (c_R(z') + c_a(z'))dz'\right]$$

E_R = Energy received by the LIDAR
E_0 = Energy emitted by the LIDAR
C = LIDAR constant (optical efficiency ...)
β_R = Rayleigh retro-diffusion factor (z)
β_a = Aerosol retro-diffusion factor (z)
c_R = Rayleigh extinction coefficient (molecular)
c_a = Aerosol extinction coefficient (the unknown)
z = distance

Atmospheric Lidar output examples



Suivi temporel de mesures LIDAR (moyenne de 200 tirs en 10 s) sur le aérosols des basses couches et un front nuageux qui s'épaissit avec le temps. Jusqu'à 16h, la couche nuageuse est suffisamment poreuse (présence de trous) pour que quelques-uns des tirs LIDAR (sur les 200) atteignent la tropopause (Ref. 18)

- Simultaneous investigation with several wavelengths allows a more detailed/precise analysis
- Using specific wavelengths, corresponding to characteristic molecular absorptions allows specific molecules to be targetted
- More sophisticated light-matter interactions can yield additional information

Atmospheric Lidar – commercial example

1. ND:YLF Laser (523.5nm) semiconductor laser,
   Output Energy 10 μJ
   Pulse Repetition Frequency 2.5 kHz

2. **Transceiver: diameter** 20 cm
   Beam Divergence 50 μrad
   Field-of-View 100 μrad

3. Detector: Si:APD

4. Data acquisition: photon-counter

5. Detection objective: aerosol, cloud and PBL

6. Working mode: 24-hr/7
   No operator

Specialist Atmospheric Lidar Techniques

Differential Absorption Lidar (DIAL)

- Two pulses at different specific wavelengths at absorption lines of a given molecule
- Ozone, water vapour, greenhouse effect gases, gas pollution, (SO_2, NO_2, …)

Doppler LIDAR (Wind)

- Monostatic, heterodyne, coherent detection, Mie diffusion Lidar
- Mapping of wind speed fields close to airports – surveillance of turbulance vortices at the end of runways

Fluorescence LIDAR

- Na, Fe, Ca
- Living organism detection (plankton, biodiversity and coral reef health mapping)
- Remote detection of biological attack and at-sea degassing pollution

Raman LIDAR

- Uses inelestic scattering (wavelength change) to measure the concentration of specific trace gases (water vapour, greenhouse effect gases ….)

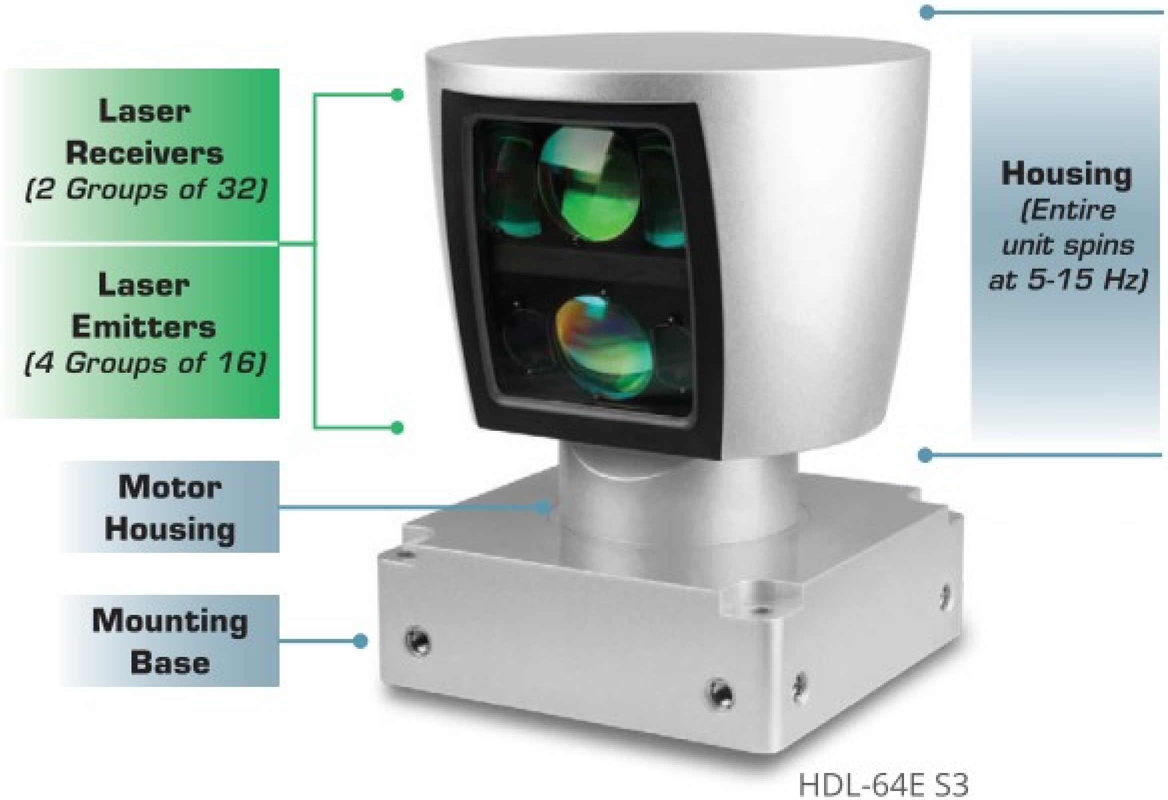
LECTURE PLAN

Automotive Lidar – main constraints

- **Small volume and weight**
  - Direct effect on vehicle size and fuel consumption / range
- **Low power consumption** (< tens of W)
  - Direct effect on vehicle fuel consumption / range
- **LOW COST**
  - < a few 100€ for premium car adoption
  - ~ 100€ for mainstream adoption … even less if multiple Lidars / vehicle.
- Must respect **general public eye safety** regulations
  - Atmospheric or military Lidar constraints are less restrictive

Example automotive Lidar - Velodyne HDL-64E

- Roof mounted mechanically scanned Lidar
- Multiple lasers / receivers to achieve power budget, eye safety and sample rate



Example automotive Lidar - Velodyne HDL-64E

Sensor:	• 64 lasers/detectors • 360 degree field of view (azimuth) • 0.09 degree angular resolution (azimuth) • 26.8 degree vertical field of view (elevation) -+2° up to -24.8° down with 64 equally spaced angular subdivisions (approximately 0.4°) • <5 cm distance accuracy • 5-15 Hz rotation rate update (user selectable) • 50 meter range for pavement (~0.10 reflectivity) • 120 meter range for cars and foliage (~0.80 reflectivity) • >1M points per second • <0.05 milliseconds latency
Laser:	• Class Im - eye safe • 4 x 16 laser block assemblies • 905 nm wavelength • 10 nanosecond pulse • Adaptive power system for minimizing saturation and blinding
Mechanical:	• 12V input (16V max) @ 4 amps • <29 lbs. • 10" tall cylinder of 8" OD radius • 300 RPM - 900 RPM spin rate (user selectable)
Output:	• 100 MBPS UDP Ethernet packets

Lidar integration

- Roof mounted vulnerable and “un-aesthetic” (automotive stylists hate them !)
- Head/rear lamp integration is preferred … but field of view <360°
- Several cheap Lidar necessary

Automotive Lidar, Radar, camera comparison

RADAR / Camera / LIDAR Comparison

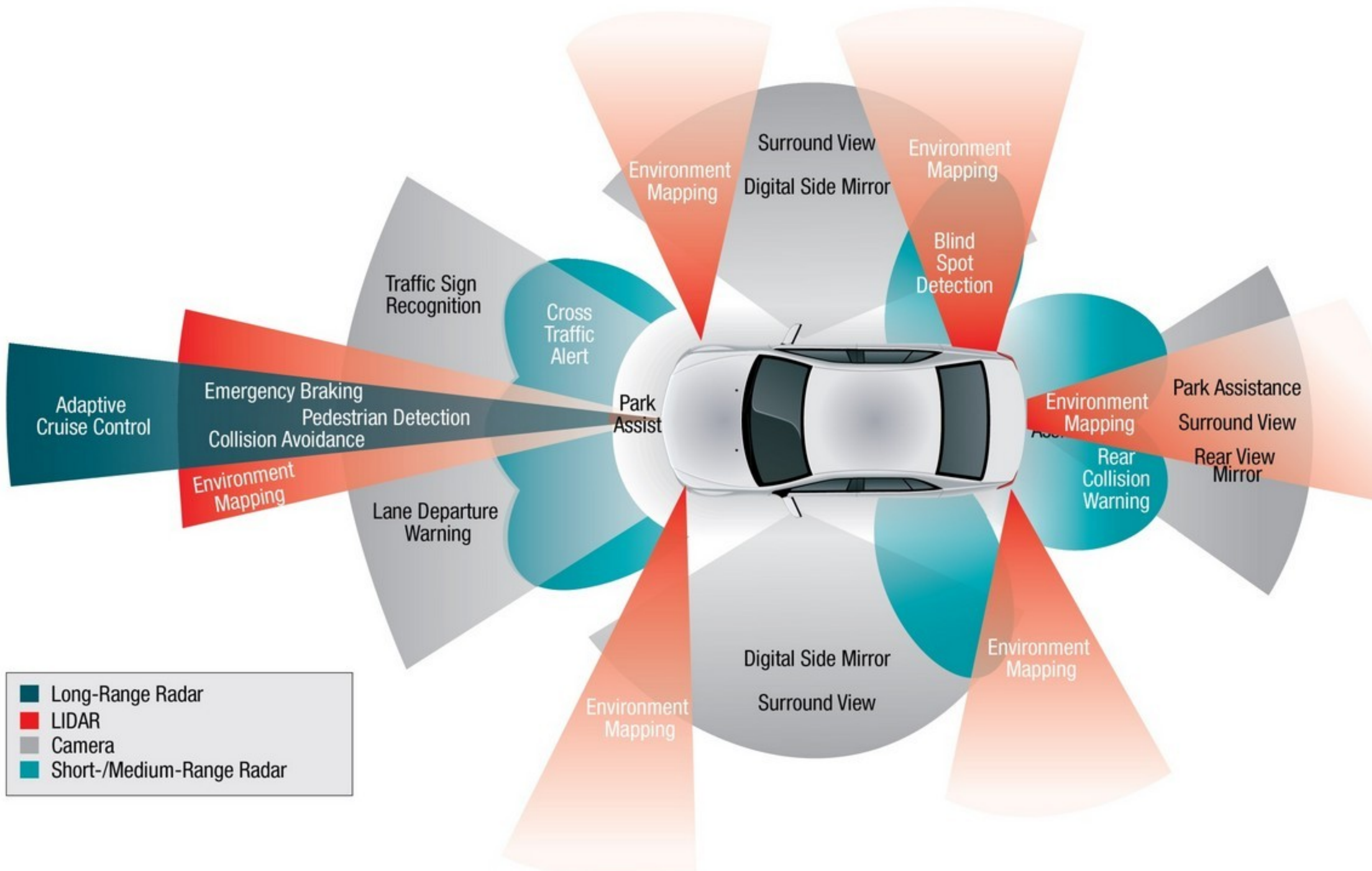
Sensor	Typical Range	Horizontal FOV	Vertical FOV	2020 Price Range	Comments
24 GHz RADAR	60 m [1]	56° [1]	~ ± 20°	< $100	USA Bandwidth 100 -250 MHz [2] Robust for Rain/snow ; People Detection / Angular Resolution
77 GHz RADAR	200 m [1]	18° [1]	~ ± 5°	< $100	USA Bandwidth 600 MHz [2] Robust for Rain/snow ; People Detection / Angular Resolution
Front Mono Camera	50 m [1]	36° [1]	~ ± 14 °	< $100	Versatile Sensor (Applications) Limited depth perception ; affected by rain / fog Needs illumination (Visible/IR)
LIDAR (Flash)	75 m	140°	~ ± 5°	< $100	Concerns for Rain/Snow; Good reflection off people w/ angular resolution Range & S/N limited by eye safety
LIDAR (Scanning)	200 m	360°	~ ± 14°	< $500	Concerns for Rain/Snow; Typically higher price for angular resolution Range & S/N limited by eye safety

- False positives → Nuisance to consumer → Turns feature off (if possible)
- False negatives → did not meet spec / expectations
- Optimum combination of sensors will be a learning process
- Sensor fusion …can be done at best on common subset in field of view

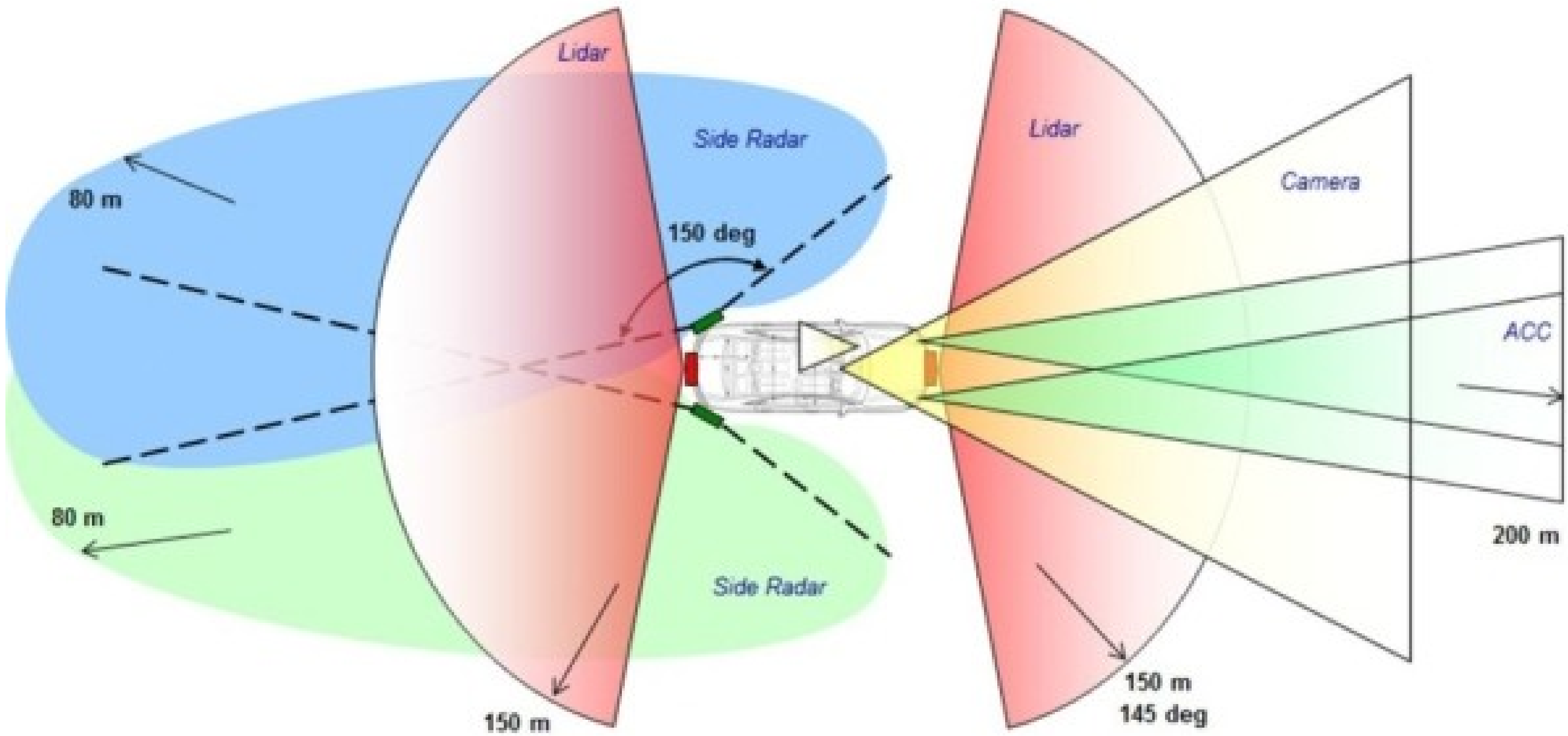
1 : Vehicle-to-Vehicle Communications: readiness of V2V technology for application – DOT HS 812014 ; Table V-7
2 : Millimeter Wave Receiver concepts for 77 GHz automotive radar in silicon Germanium Technology – D.Kissenger (SpringerBrief's 2012)

Automotive Lidar – Radar : complementary

- Lidar and Radar (and standard cameras) are “good” at different things (range, resolution ...)
- Radar, Lidar and cameras will probably all be required
- System redundancy is very important (safety) for self-driving vehicle applications.



Automotive Lidar – Radar : complimentary



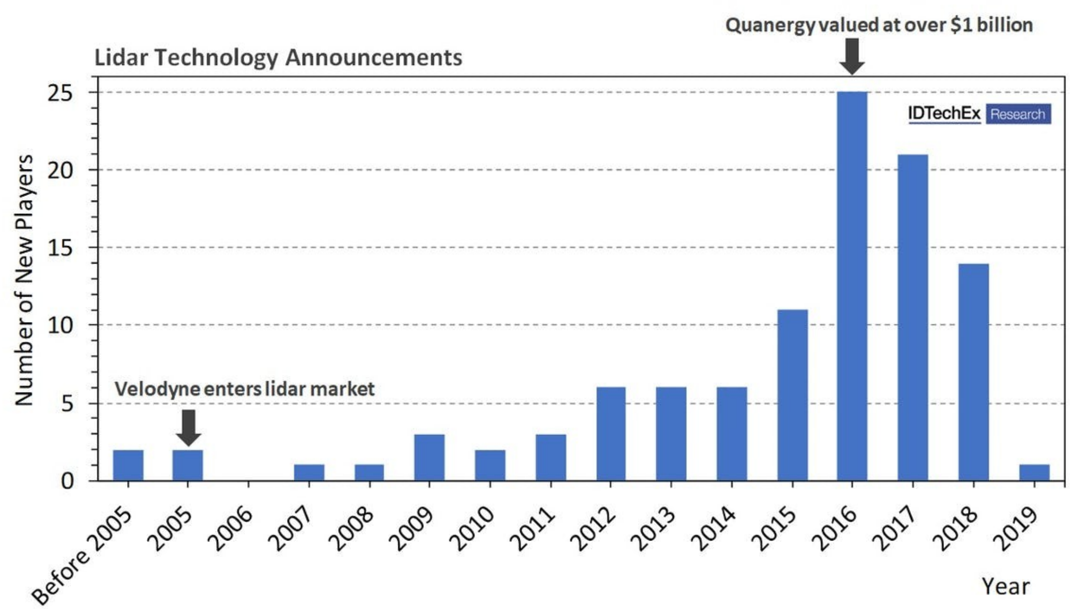
Automotive Lidar – Future ?

- Automotive Lidar is a potentially huge market
- A subject of very extensive research over the last few years
- Numerous different Lidar approaches currently under investigation – multiple startups.

"Automotive Lidar Market: Battlefield of a Hundred Technology Suppliers"
https://www.idtechex.com/en/research-article/automotive-lidar-market-battlefield-of-a-hundred-technology-suppliers/20156

Example automotive Lidar companies

- Velodyne
- LeddarTech
- Luminar
- AEye
- Ouster
- Blackmore
- Baraya
- Quanergy
- Innoviz
- Analog Photonics



LECTURE PLAN

Conclusion – to remember

- **Lidar is an extension of the Radar (or sonar) technique to use with light**
- **Lower wavelength (vs radar/sonar) allows higher resolution**
- **Only became feasible with the invention of the laser (high power directive source)**
- **Initially bulky fixed Lidars used as tools for atmospheric research/analysis**
- **Improvements in laser, scanning and detector technology make portable lidar possible**
- **Extensively used in surveying/archaeology : vehicle, airplane and satellite mounted**
- **Most recently, further improvements/cost reductions → drone and car mounting**
- **Huge automotive Lidar market imminent – emerging autonomous vehicles**
- **Very intense subject of current R&D**
- **Numerous advanced techniques under investigation**
  - Flash lidar, ToF, coherent, MEMs, frequency/amplitude modulation CW …
- **Spin-off into related fields because of reduced costs: drone, Virtual Reality ...**

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