Introduction to Depth Sensing:
Technologies, Trade-Offs and Applications

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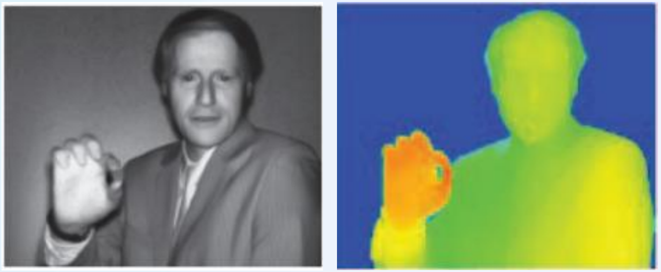
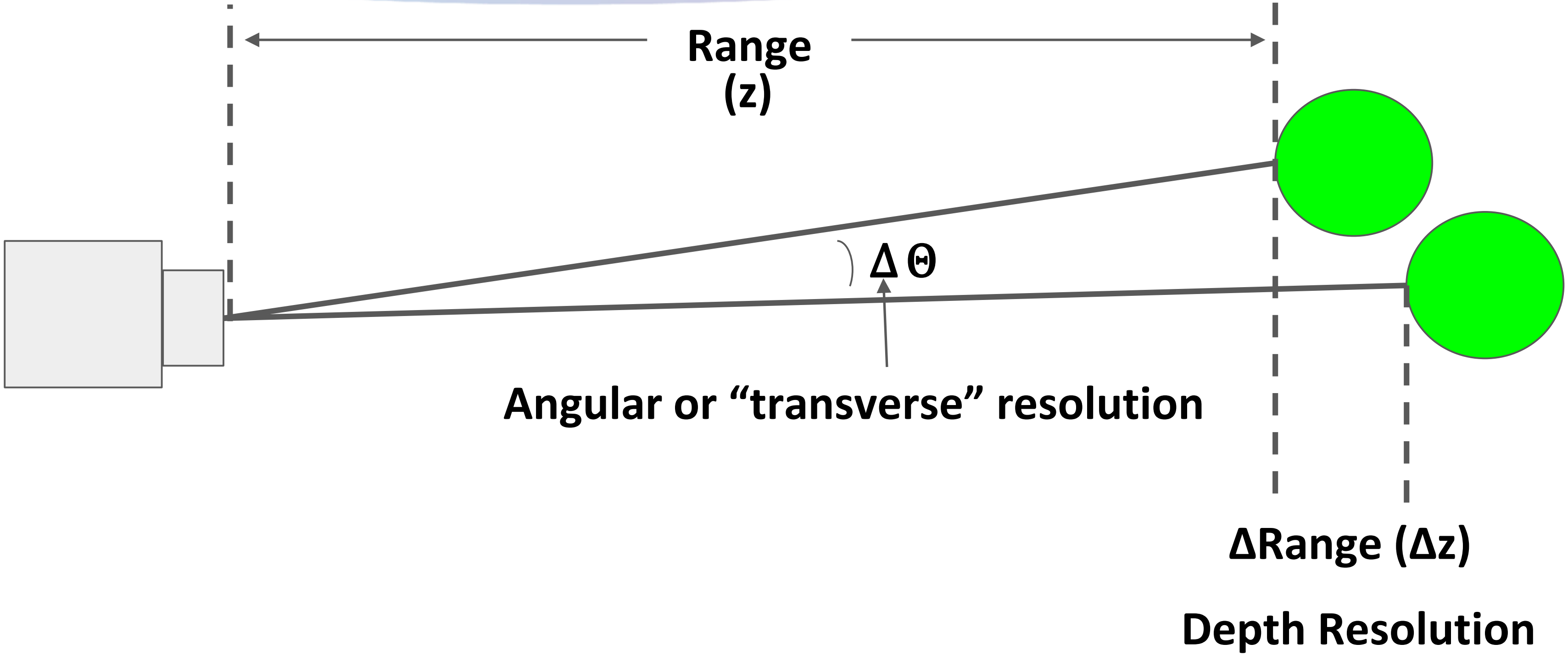


Plank et al, i-ToF, Design, Automation & Test in Europe Conference & Exhibition, 2016

Agenda

- Understanding Application Needs
- Structured Light (Very Brief Overview)
- Stereo Vision
- Time of Flight (Indirect & Direct)
- LiDAR
- Comparison Matrix
- Conclusions
- Resources

Application Needs



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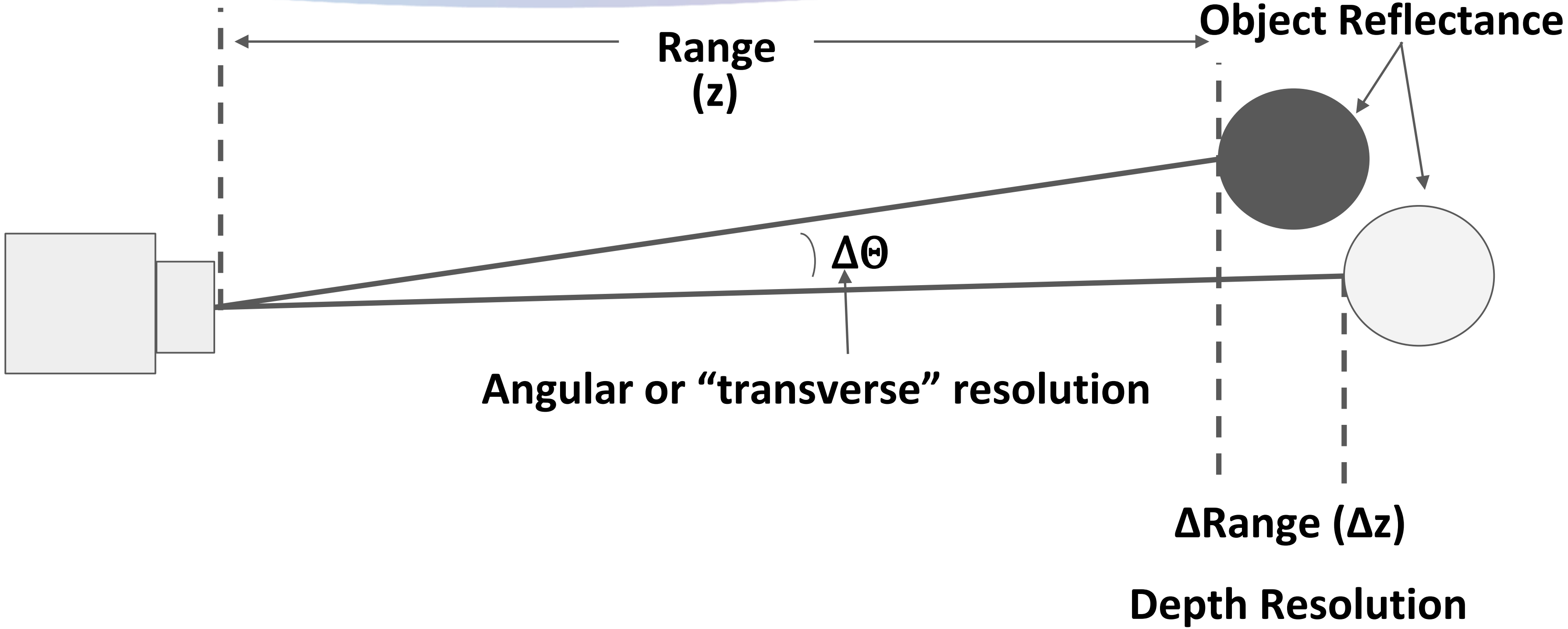
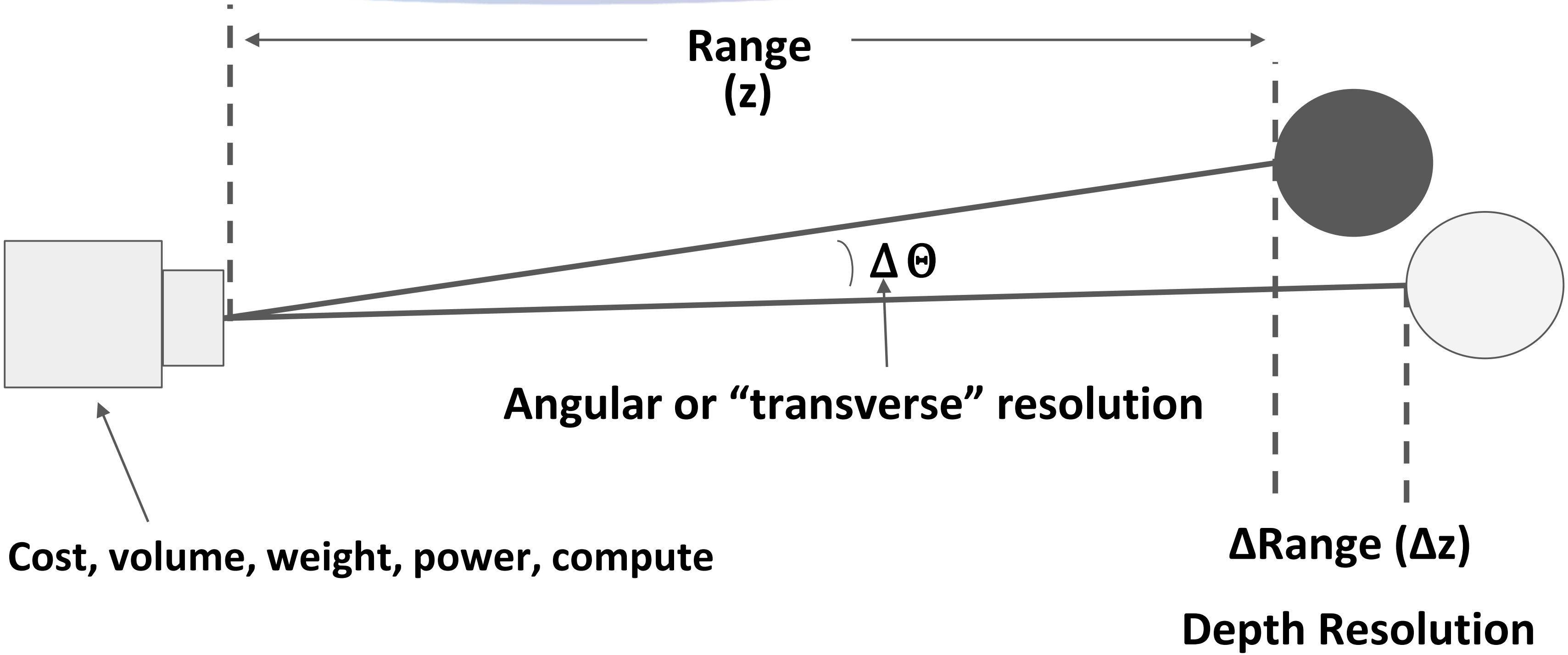
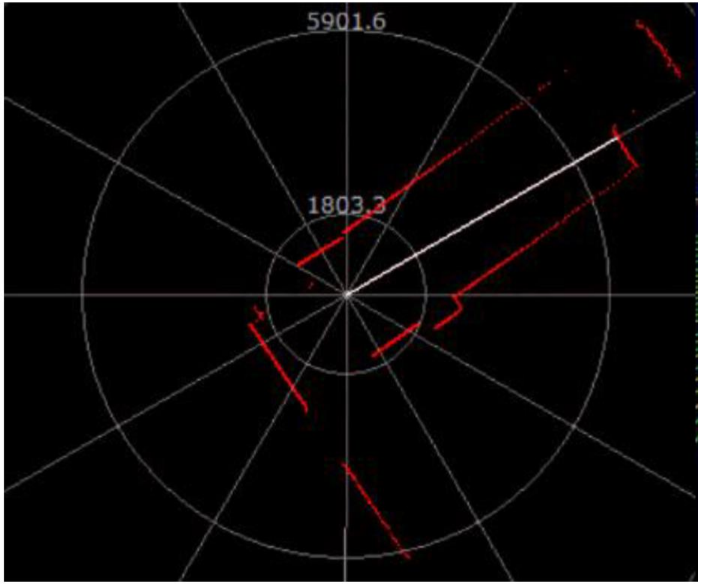
Application Needs



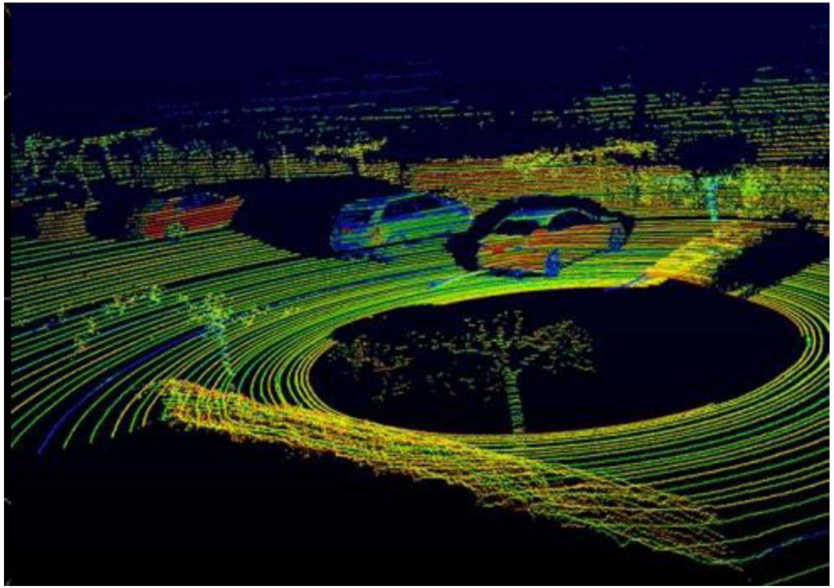
Application Needs



Application Needs: 2d or 3d



https://www.mdpi.com/2076-3417/11/9/3938



2d: Measure angle and range to surfaces in a single 2d plane

3d: Measure horizontal angle, vertical angle, and range in 3d

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Application Needs: Other Considerations

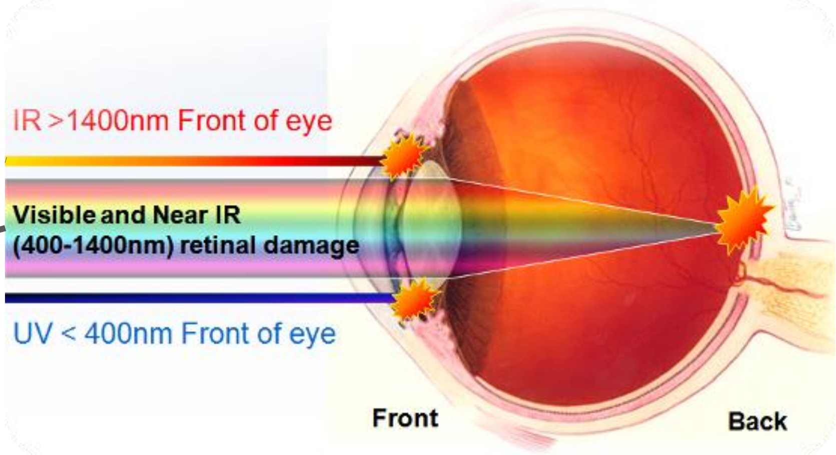
Frame rate: 2d or 3d frames per second – how fast does it need to update?

Eye safety for active illumination systems

- What if a person puts their eye right up to illuminator?
- If scanning a light beam, what if the scanner fails?
- Can limit max. allowed optical power and SNR

Laser wavelengths > 1400 nm "eye safe" require expensive detectors (InGaAsP)

905 & 950 nm systems use Si detectors: invisible, require safety measures

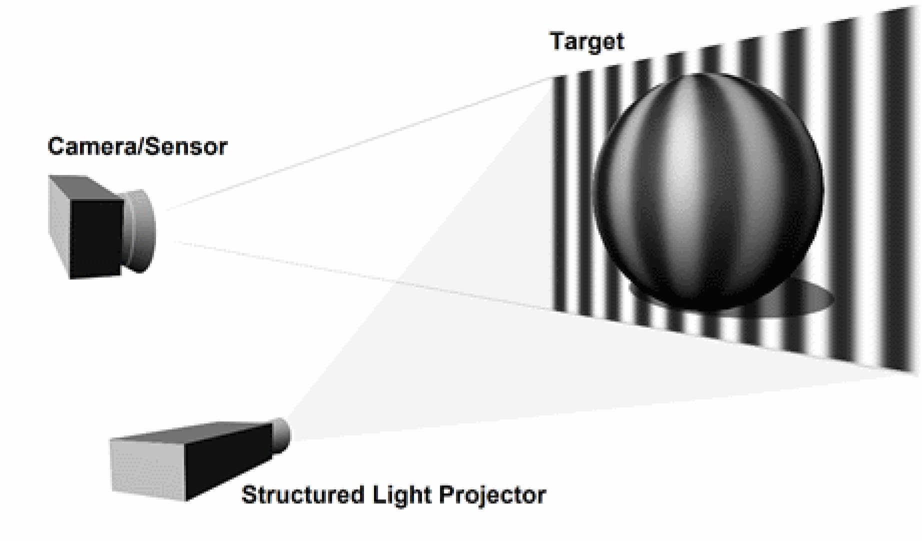


https://www.lasersafe.co.uk/laseradvice3.php

Application Needs: Summary

- Range (maximum and minimum)
- Depth resolution
- Transverse resolution (angle)
- Reflectivity range of objects at operating wavelength
- 2d vs 3d
- Frame rate
- Eye safety (affects SNR, daylight tolerance)

Structured Light (Brief Overview)

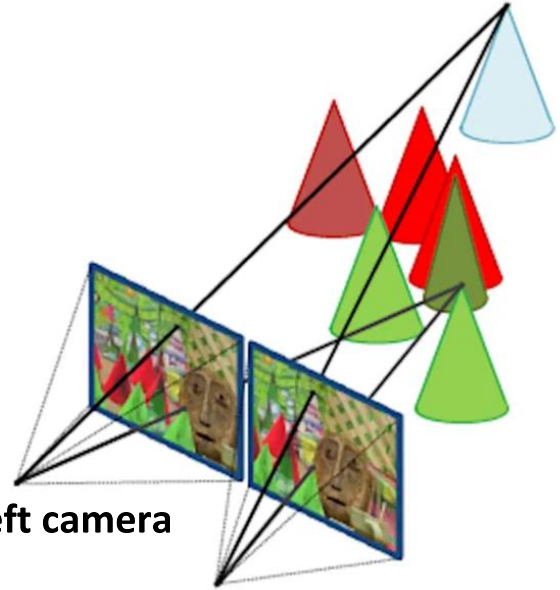


- Project light pattern with known orientation & spread relative to camera (static or changing pattern)
- Trade offs: limited range, daylight can overwhelm signal
- Examples: game inputs, AR & VR, 3d scanning of close-up objects, older versions of phone face unlock & camera autofocus

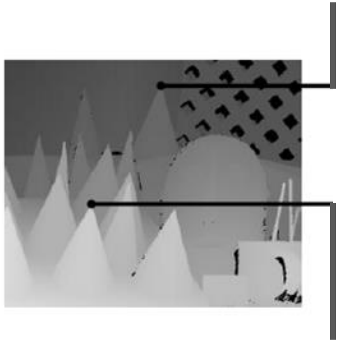
https://www.roboticstomorrow.com/article/2018/04/what-is-structured-light-imaging/11821

Stereo Vision

Two or more cameras, co-register objects, similar to human depth perception

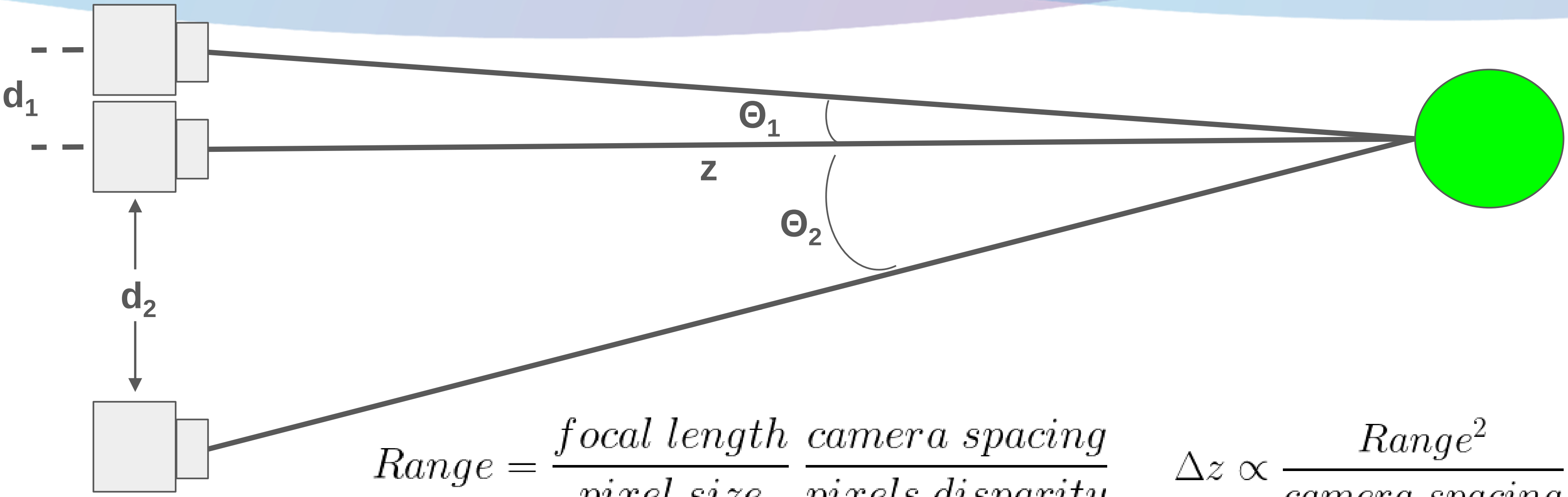


Depth map output "frame"



Adapted from IDS Imaging:
https://en.ids-imaging.com/technical-articles-details/items/whitepaper-depth-information-3d-images.html

Stereo Vision Trade Off: Range vs Camera Spacing



$$Range = \frac{focal\ length}{pixel\ size}\frac{camera\ spacing}{pixels\ disparity} \qquad \Delta z \propto \frac{Range^2}{camera\ spacing}$$

Depth resolution worsens with range; cannot resolve range beyond where disparity falls below 1 pixel

Range and depth resolution increased by increasing sensor resolution or camera spacing (d) at the cost of system size

Stereo Vision: Final Thoughts

Can yield very high transverse resolution using off the shelf high resolution cameras

High compute cost and complexity relative to other solutions

Can add structured light for objects without clear registration features (walls, ground)

Examples: Robotic navigation, automotive collision avoidance

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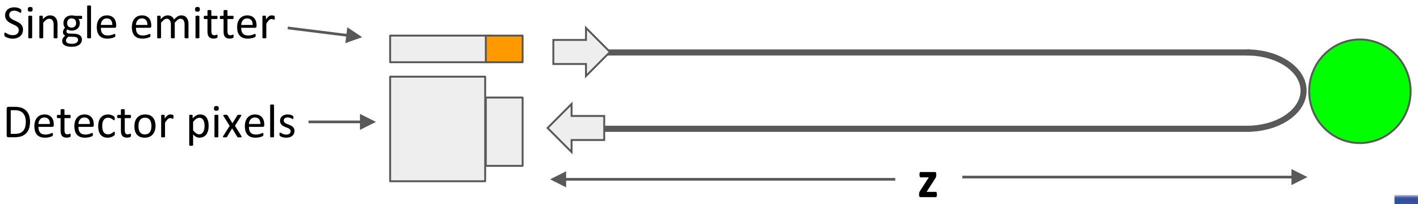
Time of Flight (ToF)



$\Delta z = c \, \Delta t / 2$

Speed of light c ≅ 1 foot (0.305 m) per nanosecond

Out-and-back time of one nanosecond means Δz ≅ 0.5 ft

"Direct" time of flight directly measures light transit time with fast detectors

"Indirect" time of flight amplitude modulates emitted light and uses slow detectors

Like stereo imaging, both produce 2d "frames" of pixels with x, y, and distance (z)

Plank et al, i-ToF, DATE, 2016

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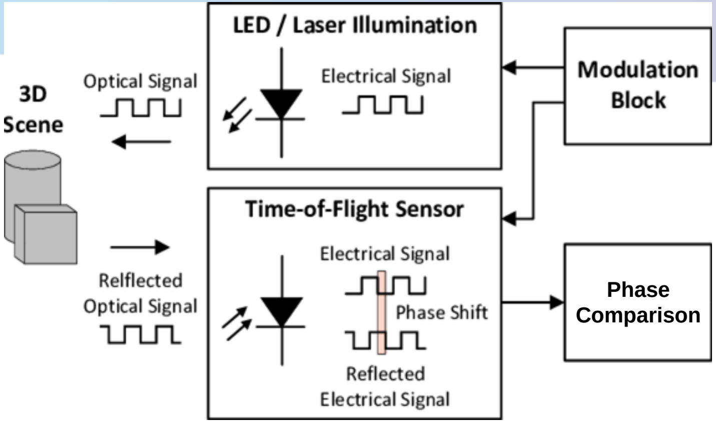
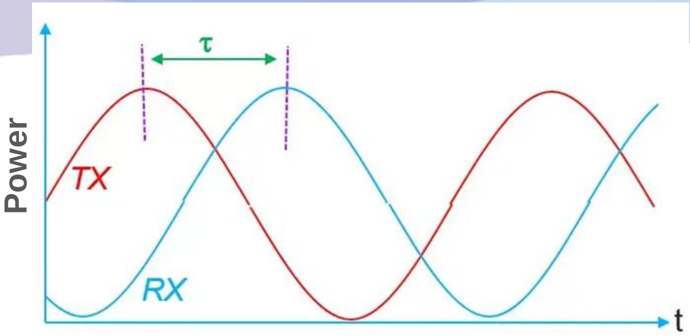
Time of Flight: Indirect



Plank et al, DATE, 2016



OSRAM white paper “LIDAR, optical distance & time of flight sensors”

Electronically compare phase of emitted and reflected light to determine distance traveled

Δz impacted by modulation frequency (1-200 MHz), but can resolve much smaller Δt than period τ

“Multi-path” light from different parts of scene hitting same pixel causes ambiguity

Variations in range & reflectivity require multiple exposures, decreasing frame rate

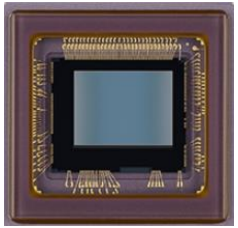
Can get high frame rates ~100 fps with low variation, e.g. an assembly line

Time of Flight : Indirect

Compute cost much lower than stereo imaging

Daylight can overwhelm illumination signal at longer ranges

Example Product Specs:



Sony IMX570

640x480, 5 mm Δz up to 3.5 m range, 56 fps

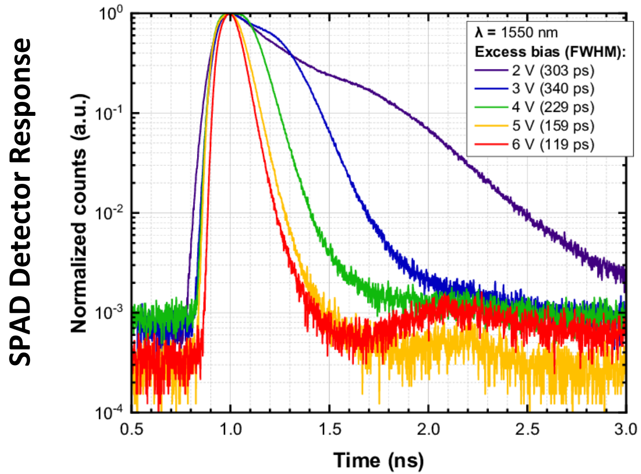
Teledyne Hydra3d

832x600, Range 0.5 - 10 m, Δz : the greater of 1% range or 2 cm

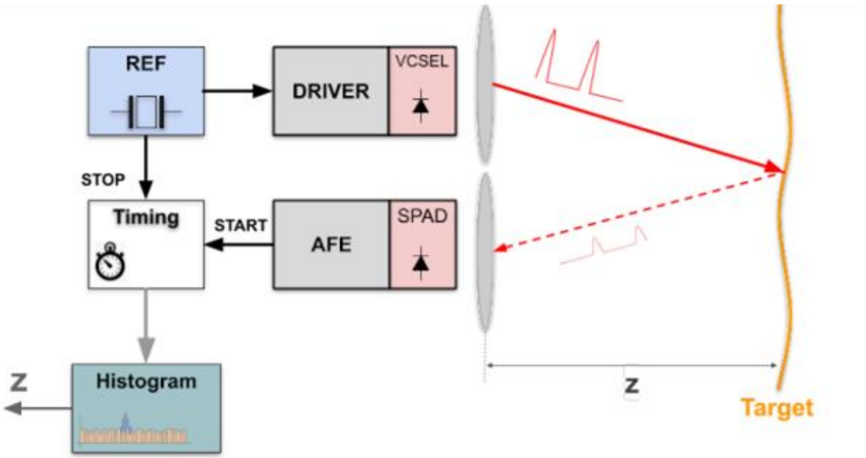
HDR mode: 10 m range, 15-85% reflectivity, 25 fps

Example Applications: Factory, warehouse, security, traffic & parking sensors

Time of Flight: Direct, or "Flash LiDAR"



Signorelli et al, IEEE JSTQE 8/2021



H. Venkataraman, Embedded Vision 2024

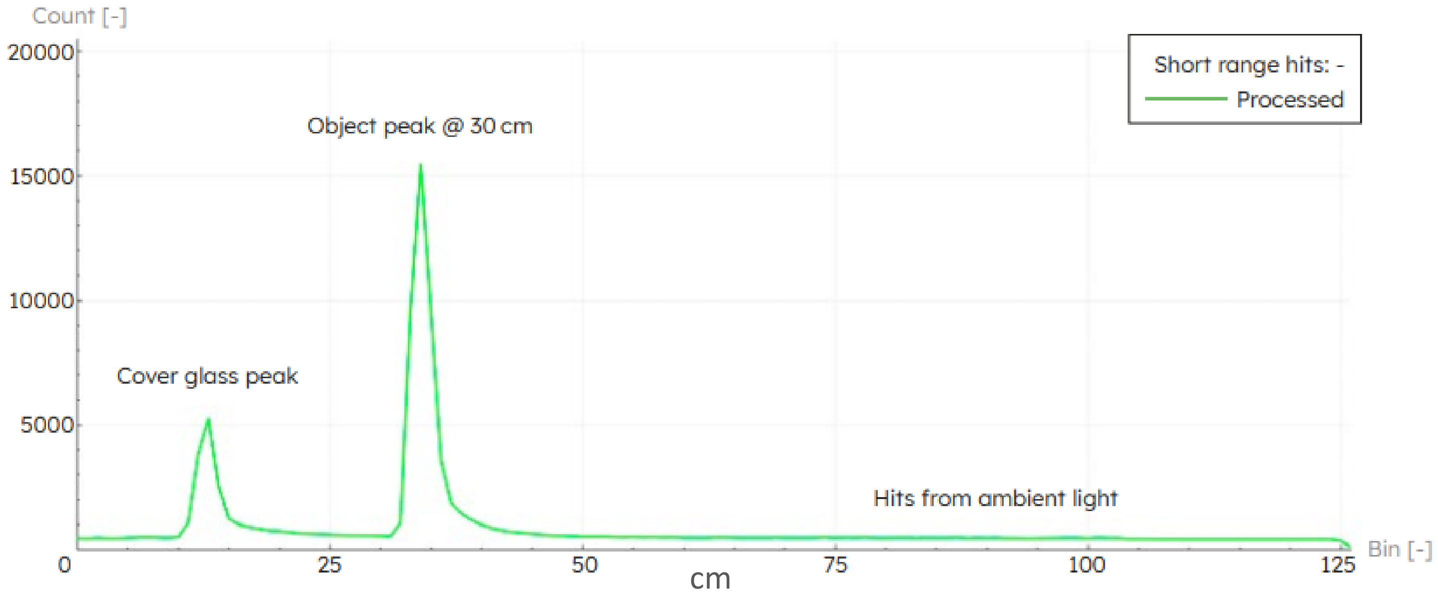
Directly measures arrival time of rising edge of light pulse with fast emitters (1 ns pulse)

Fast detectors: single photon avalanche photodiodes (SPAD)

SPADs have ~30% chance of detecting a single photon

Many wide-angle pulses & detections build each pixel's arrival time histogram (~20 MHz pulse rep. rate)

Time of Flight: Direct, or "Flash LiDAR"



source: OSRAM White Paper "Understanding Time of Flight Sensing

Each pixel's arrival time histogram separates multiple light "bounces" from different distances

Data from Osram TMF882X: 8x8 resolution, 0.01 - 5 m range, Δz: 2% or 5 mm, frame rate: 30 fps

Direct ToF, or “Flash LiDAR”: Transverse Resolution

Detector array **Laser (VCSEL) array** **Diffractive optic** **Illumination array**

SPAD arrays are becoming denser (Sony IMX459: ~600x200, 10 um pixels), but resolution also limited by need to distribute short pulse laser light across whole scene in single “flash”

Consumer devices often use array of VCSELs, then diffractive optics to make copies of this array

Yields a limited array of “light dots” (iPhone Pro 12/13 has ~48x12 dots interpolated to 256x192)

Larger, more power-hungry systems can use a flat top laser beam, etc., to achieve higher resolution

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Direct ToF, or "Flash LiDAR" Trade Offs & Applications

Low compute time & low-cost silicon sensors available

Choosing a silicon sensor limits laser power/SNR due to eye safety

Frame rate vs. histogram collection time (particularly for low reflectance objects)

"Flash LiDAR" = direct ToF with more powerful laser and better optics, higher range

Applications: Presence detection, gesture detection, security, newer face unlock and camera low light autofocus, low-mid resolution room & object scanning

iPhone measure app can be used for search & rescue footprint tracking

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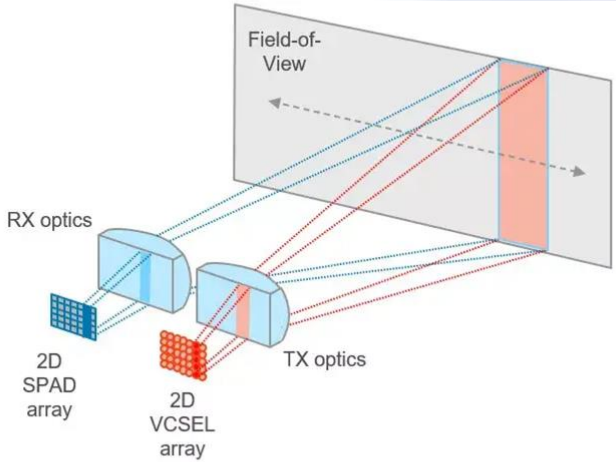
Scanning LiDAR (not "Flash")

Scanning illumination can deliver more power and increase transverse resolution

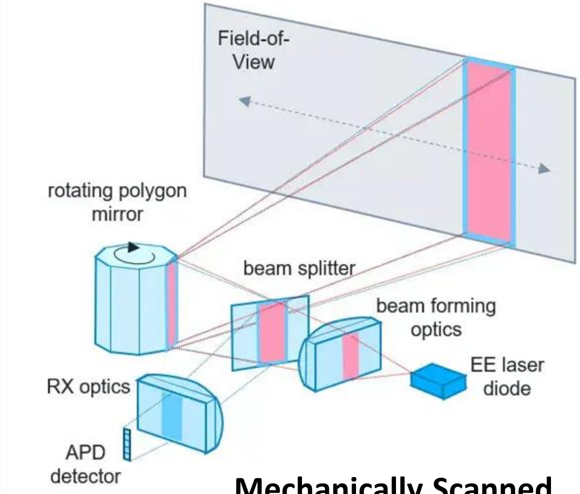


Sequentially Switched Illumination

Fast, no moving parts

Eye-safe at higher power on target than "flash"

Reusing same detector array for different parts of FOV increases transverse resolution



Mechanically Scanned

Slower, moving parts

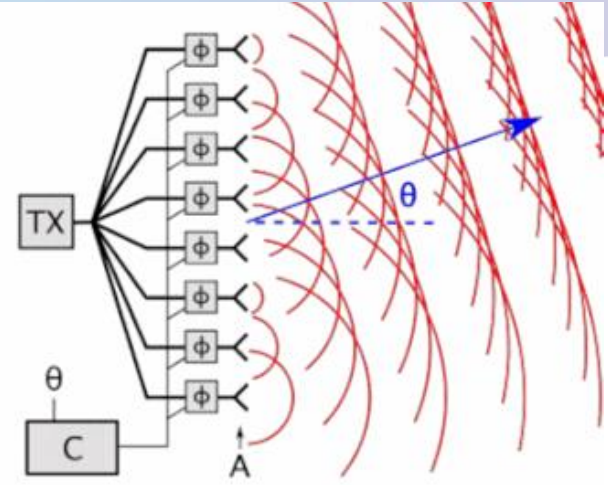
Long range with high power edge-emitting laser

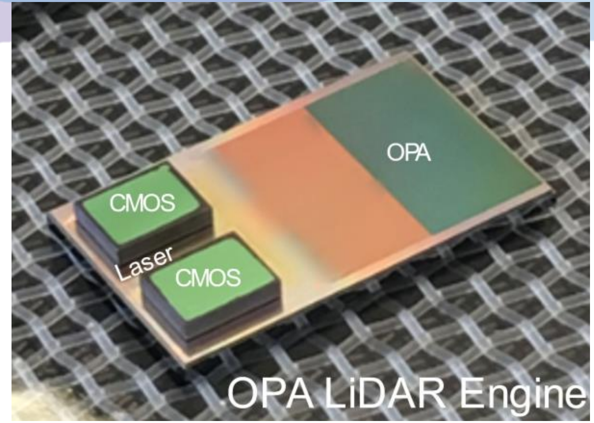
Can use cheaper linear detector with transverse resolution set by mechanical scan

Figures: OSRAM white paper "LIDAR, optical distance & time of flight sensors"

Solid-State Scanning: Optical Phased Array (OPA)

Source: Analog Photonics





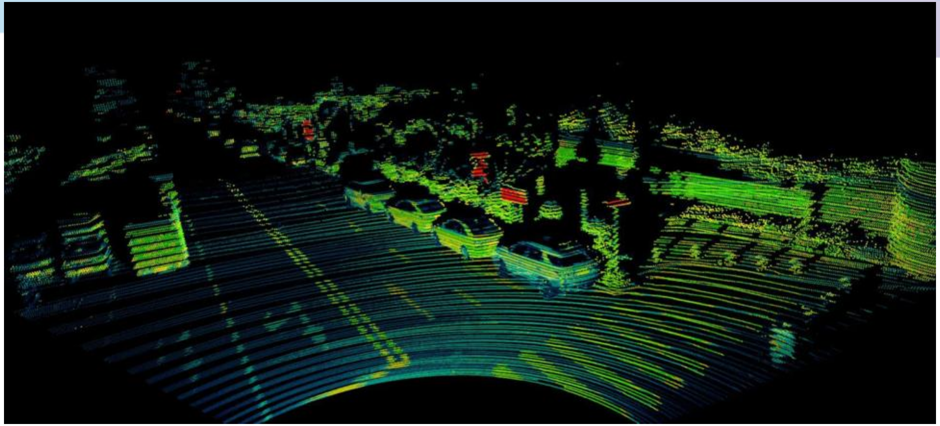
Analog Photonics Inc. achieved 1 micron pitch array

No moving parts, fast (depends on phase modulator, in order of slow to fast: liquid crystal < thermo-optic < electro-optic) and relatively low cost using integrated optics

Number of phase modulators determines number of resolvable angles, packing density of modulators determines overall sweep angle or field of view (FOV)

Resolution, FOV are improving: Analog Photonics claims ~8192 pixels (~37 x 217), 17 x 100 deg FOV, using fast electro-optic modulation and chirped pulse approach

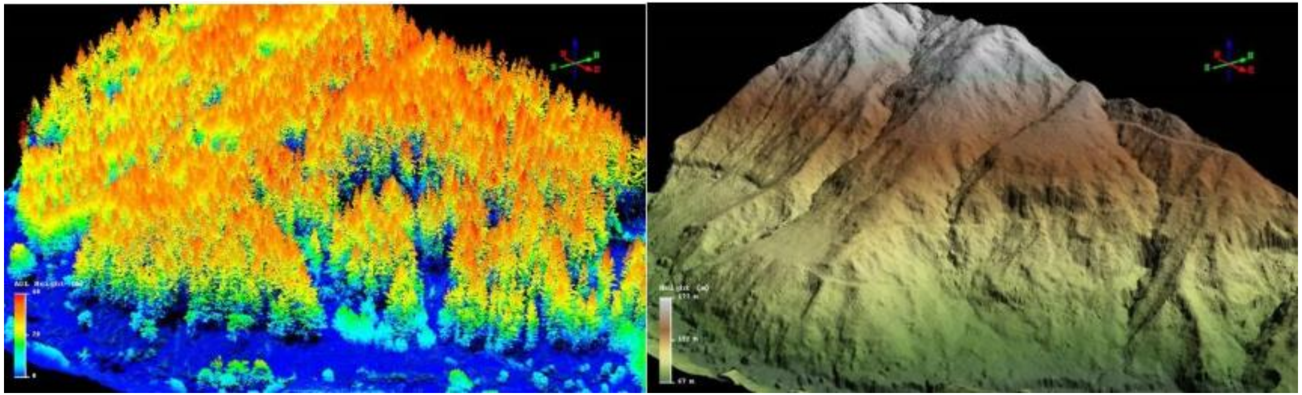
Scanning LiDAR Applications



Leishen LiDAR

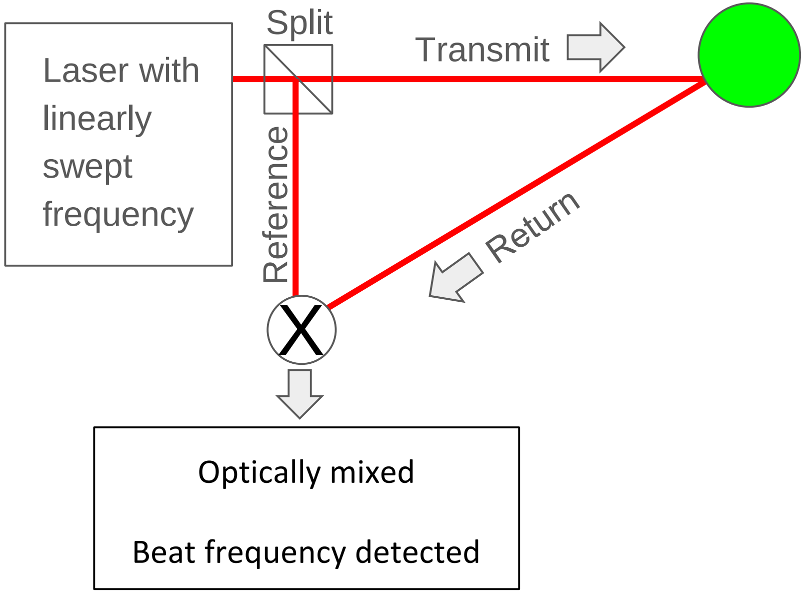
Automotive & aircraft collision avoidance

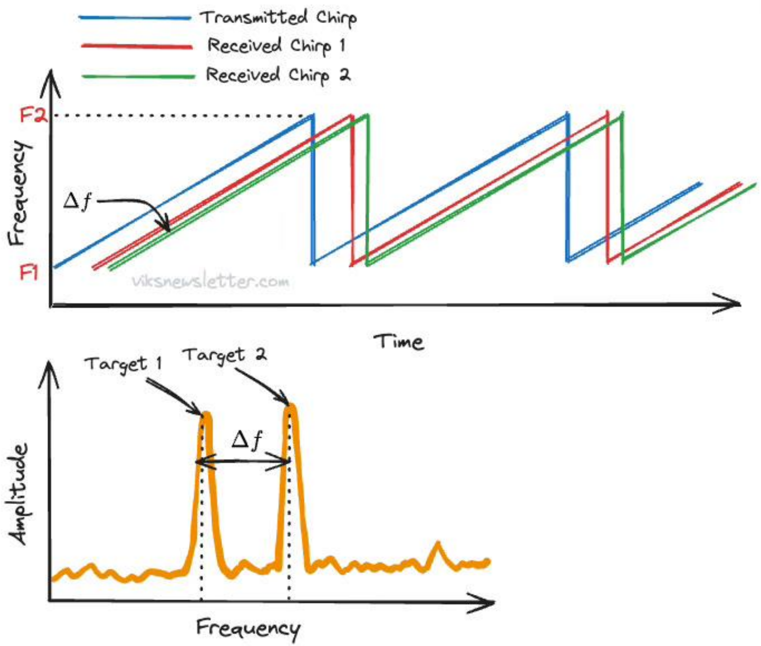
Terrain mapping from aircraft



https://interpine.nz/forest-yields-from-lidar-metrics-handling-big-data-for-plot-yield-imputation/

Chirped Pulse or "Continuous Wave Frequency Modulation"

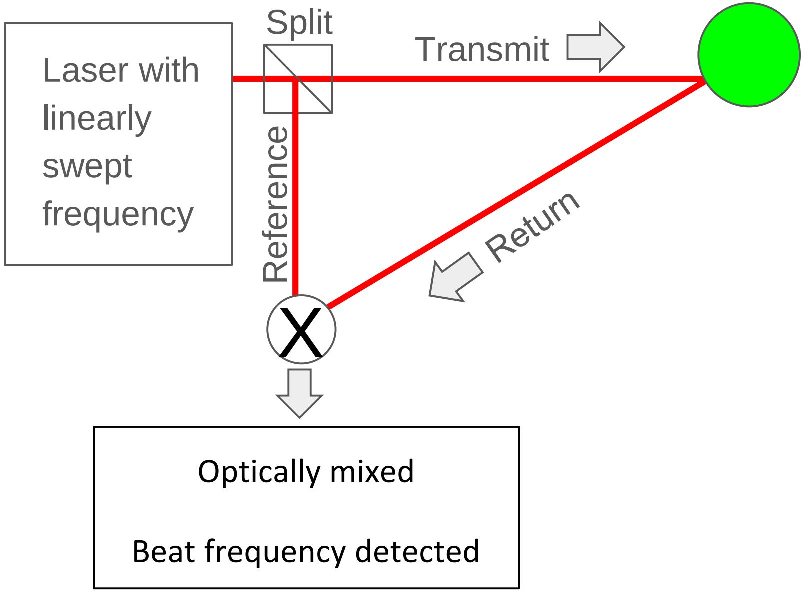


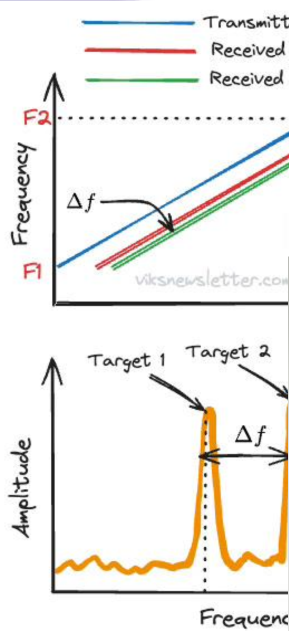


https://www.viksnewsletter.com/p/how-automotive-radar-uses-chirp-signals

- Uses scanned configuration with single laser, more complex optics (but integrated optics help)
- Robust to ambient light because only the signal is frequency modulated
- Get velocity measurement "for free" using multiple pulses to isolate Doppler shift

Chirped Pulse or "Continuous Wave Frequency Modulation"





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- Get velocity measurement "for free" using multiple pulses to isolate

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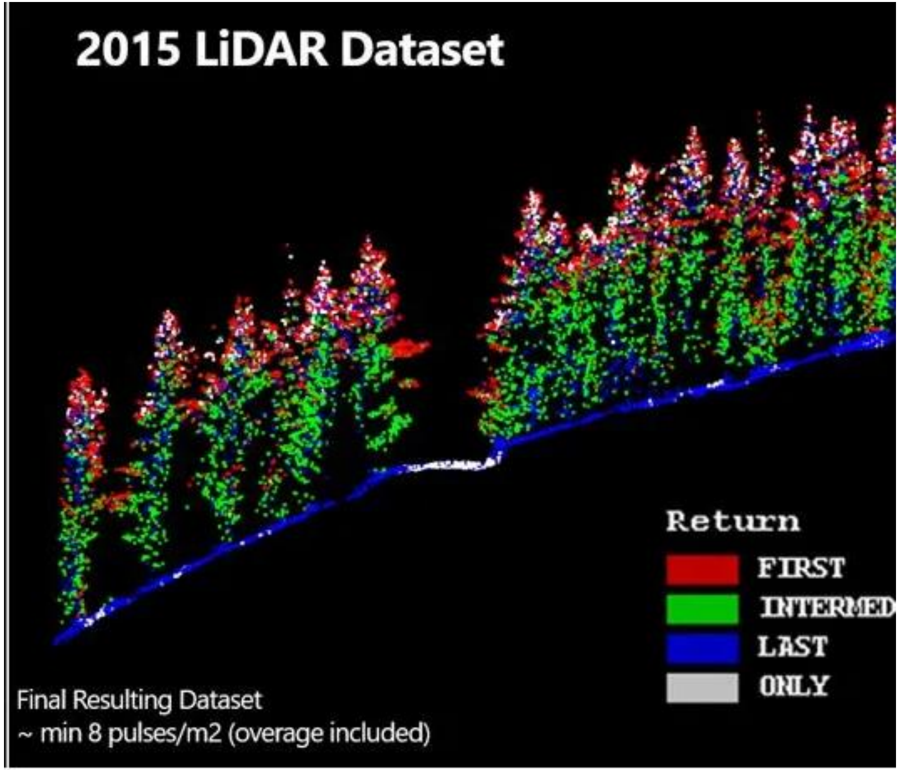
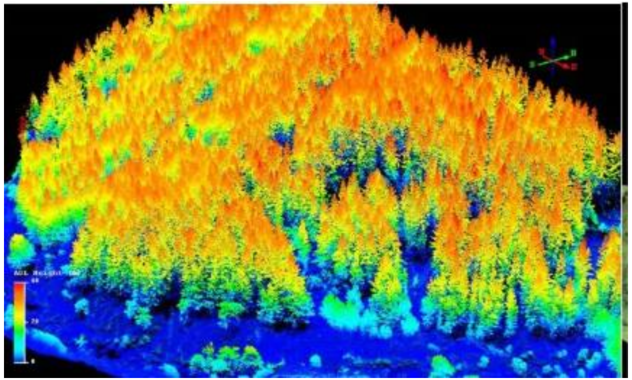
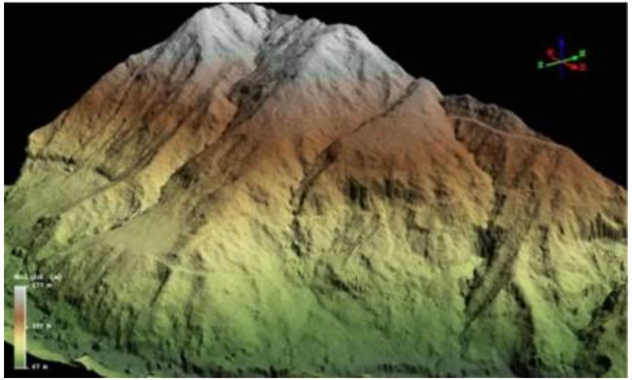
Multiple Return LiDAR Applications

Late Returns See Ground Through Trees

Simultaneous Terrain and Tree Mapping







https://interpine.nz/forest-yields-from-lidar-metrics-handling-big-data-for-plot-yield-imputation/

Multiple Return LiDAR Applications

Late returns: found lost medieval Cambodian city under jungle

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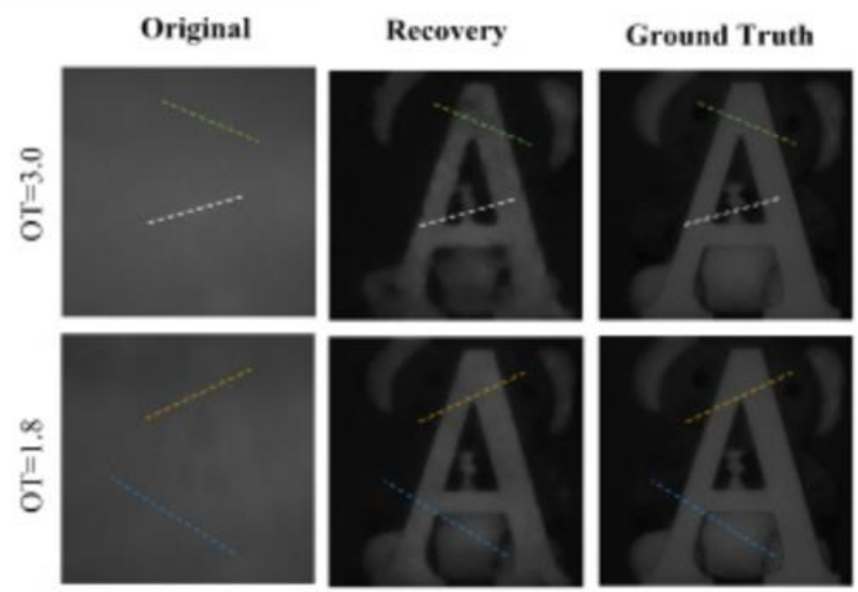
Multiple Return LiDAR Applications

Late returns: found lost medieval Cambodian city under jungle

Early returns: can see through fog



Jin, S, et al. Opt. Exp. v. 32, n. 11, pp. 18812 (2024) https://opg.optica.org/oe/fulltext.cfm?uri=oe-32-11-18812&id=549953

Comparison Matrix

	Stereo	ToF Indirect	ToF Direct	LiDAR Mechanical	LiDAR OPA	LiDAR Chirped
Range	med	low-med	low-med	high	high	very high
Δz res.	med-high	med	med	high	high	very high
Resolution	high	low-med	low-med	high	med	N/A
Vulnerability	low*	ambient multi-path	ambient	vibration	low	Immune to ambient
Compute	high	low-med	low	low	low	low
Power	med	low	range dep.	high	med	med-high
Size	med-large	small	small	large	small	small-med
Cost	high	med-high	low-med	very high	med-high	high

*If using stereo with active illumination, the active part is vulnerable to ambient

Conclusions

- Structured light popular in AR/VR inputs & older consumer products
- Direct & indirect time of flight popular in high-end consumer products with low size, low-medium range, low-medium transverse resolution
- Stereo popular in medium price, high compute, medium size robotic & automotive applications with high transverse resolution, medium range
- Mechanically scanned chirped pulse (CWFM) LiDAR offers highest range and relative depth resolution, popular in high cost, high power, high size systems
- Optical phased array LiDAR continues to improve in lateral resolution and field of view, often uses chirped pulse
  - Has size, power and frame rate advantage over mechanically scanned LiDAR

Resources

Structured Light Intro
https://www.roboticstomorrow.com/article/2018/04/what-is-structured-light-imaging/11821

Stereo Vision Intro
https://en.ids-imaging.com/technical-articles-details/items/whitepaper-depth-information-3d-images.html

https://medium.com/analytics-vidhya/distance-estimation-cf2f2fd709d8

Indirect Time of Flight Details & Limitations
https://past.date-conference.com/proceedings-archive/2016/pdf/0446.pdf

Direct ToF AMS Osram White Paper
https://www.digikey.jp/Site/Global/Layouts/DownloadPdf.ashx?pdfUrl=81B091F0075F402A8A2B0D15524D4314

2025 Embedded Vision Summit

"Introduction to DNN Training" - Fundamentals
Kevin Weekly 5/21 1:30 PM

Direct ToF Consumer Product Deep Dive
https://4sense.medium.com/apple-lidar-demystified-spad-vcsel-and-fusion-aa9c3519d4cb

Overview of LiDAR, Direct & Indirect ToF
https://ams-osram.com/innovation/technology/depth-and-3d-sensing/lidar-optical-distance-and-time-of-flight-sensors

Optical Phased Array LiDAR & Commercial Product
https://www.analogphotonics.com/technology/

Optical Phased Array: More Detail & Limitations
https://opg.optica.org/oe/fulltext.cfm?uri=oe-28-21-31637&id=440892

Time Gated Imaging Through Turbid Media
https://opg.optica.org/ol/abstract.cfm?uri=ol-49-22-6581