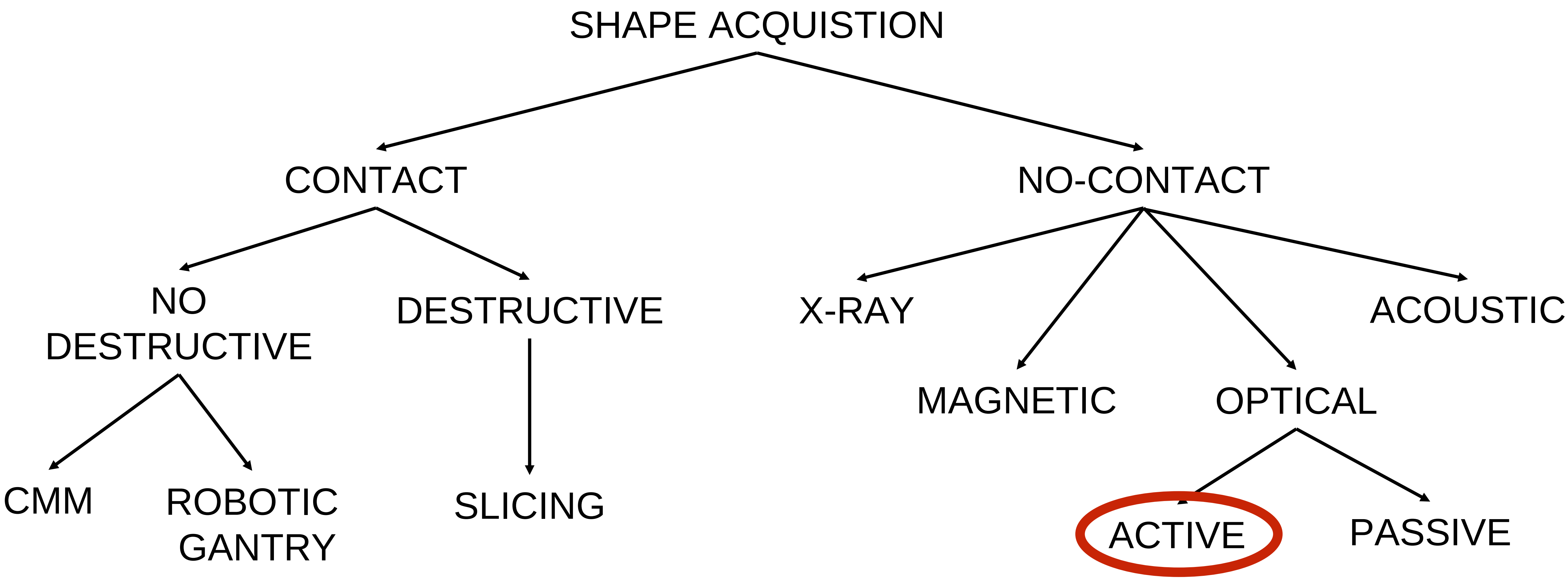
Optical Active 3D Scanning

Gianpaolo Palma

3D Scanning Taxonomy



Recap
Computational Tomography and Magnetic Resonance

- **Advantages**
  - A complete model is returned in a single shot, registration and merging not required
  - Output: volume data, much more than just an exterior surface
- **Disadvantages**
  - Limitation in the size of the scanned object
  - Cost of the device
  - Output: no data on surface attributes (e.g. color)

Recap
Multi-View Stereo Reconstruction

- **Advantages**
  - Cheap (no scanning device needed), fast tech evolution
  - Good flexibility (both small and huge model can be acquired)
  - Cameras are more easy to use than a scanner (lighter, no tripod, no power, multiple lenses …)
  - Non-expert users can create 3D models

- **Disadvantages**
  - Accuracy (not so accurate, problems with regions with insufficient detail)
  - Slower than active techniques (many images to process and merge)
  - Not all the objects can be acquired

Active Optical Tecnology

- **Advantages**
  - Using active lighting is much faster
  - Safe - Scanning of soft or fragile objects which would be threatened by probing
  - Set of different technologies that scale with the object size and the required accuracy
- **Disadvantages**
  - Can only acquire visible portions of the surface
  - Sensitivity to surface properties (transparency, shininess, darkness, subsurface scatter)
  - Confused by interreflections

Active Optical Tecnology

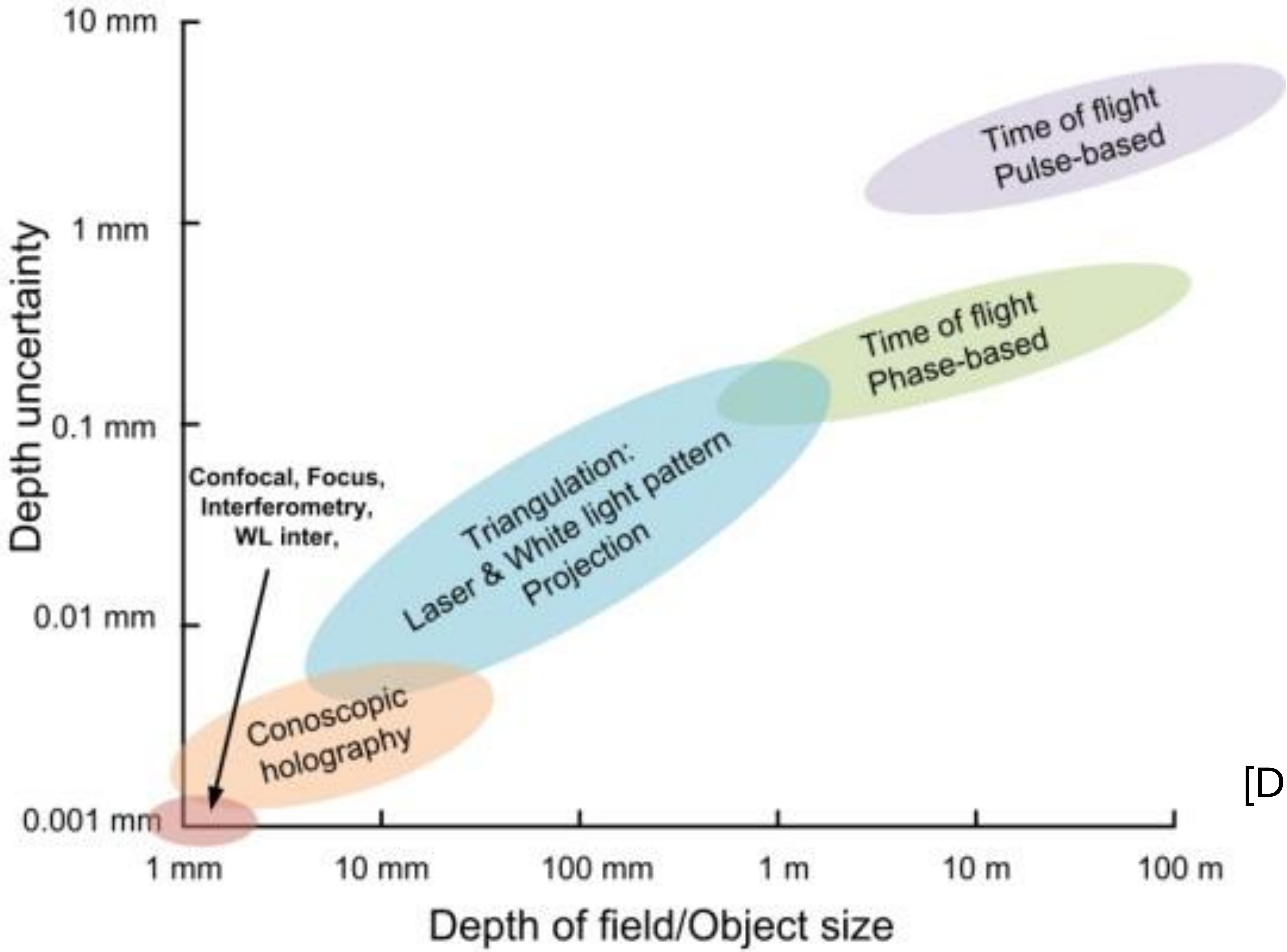
- Active optical vs CT scanner
  - Cheaper, faster, scale well with object size
  - But no volume information and more processing

- Active optical vs Multi-view stereo
  - Faster and more accurate
  - But more expensive and more user expertise

Active Optical Tecnology

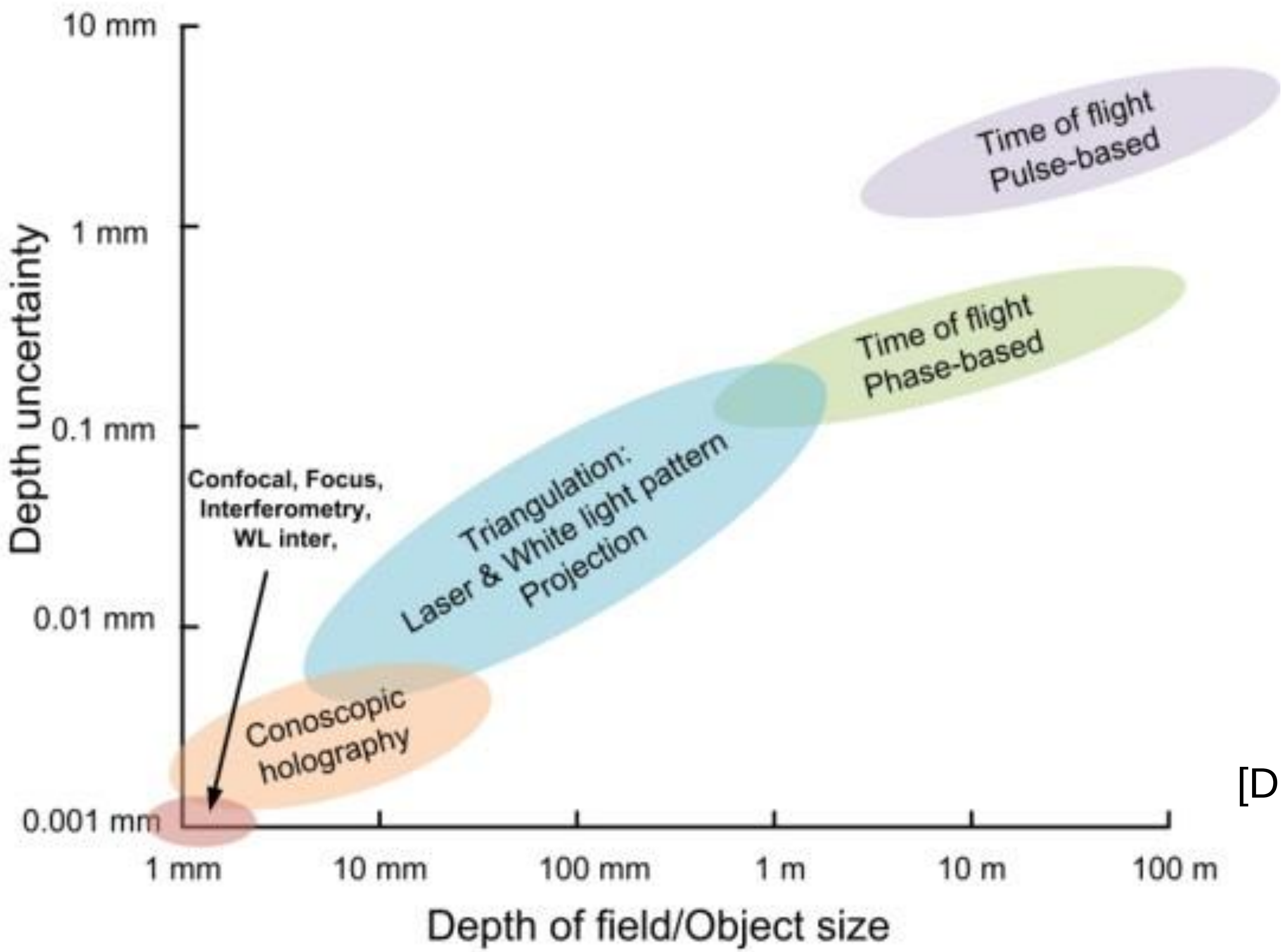
- Depth from Focus
  - Confocal microscopy
- Interferometry
- Triangulation
  - Laser triangulation and structured light
- Time-of-Flight
  - Pulse-based and Phase-based

Why different active optical tecnology?



[Drouin et al., 2012]

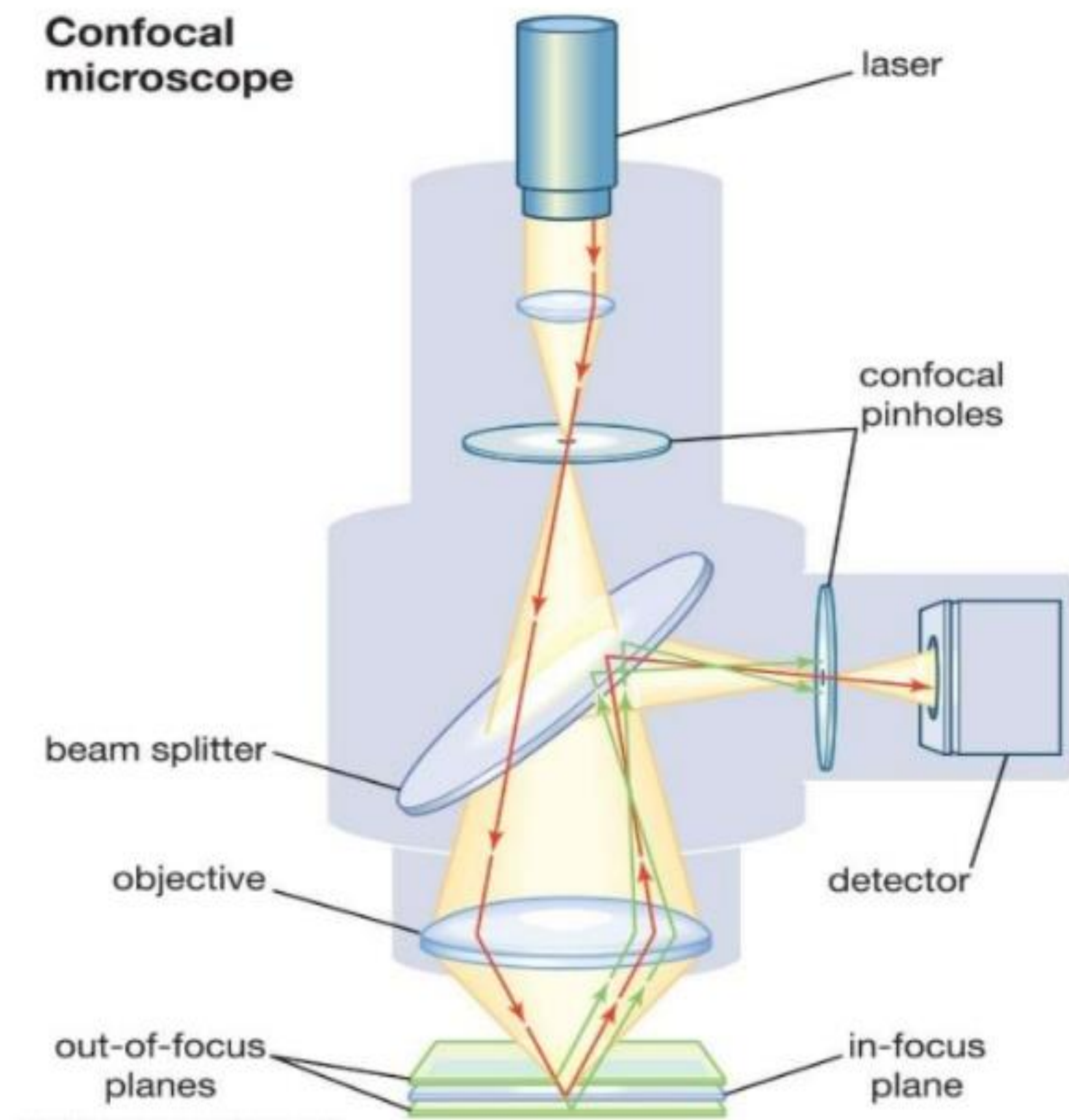
Confocal Microscopy



[Drouin et al., 2012]

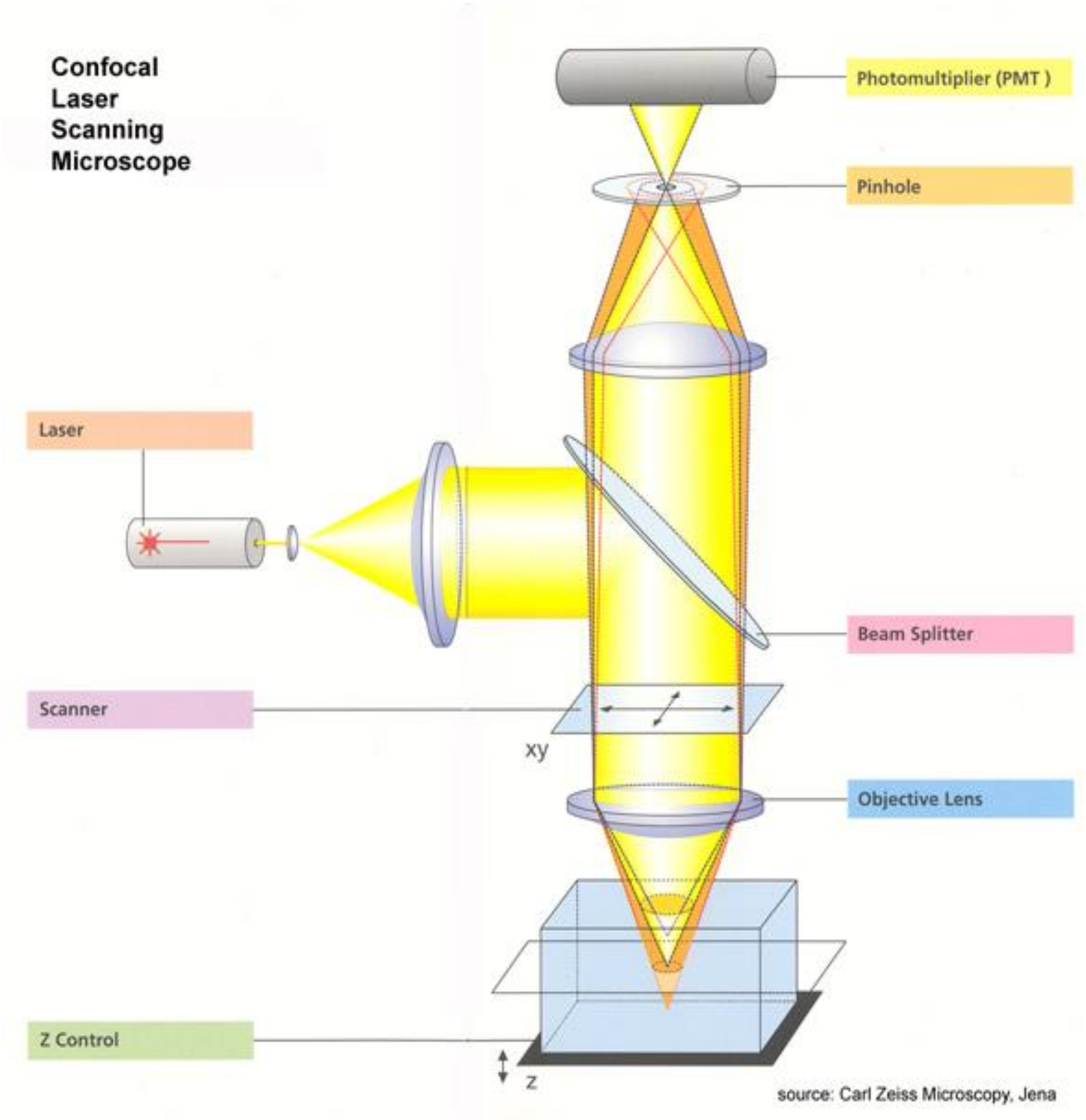
Confocal Microscopy

- Increase the optical resolution and contrast of microscope by placing a pinhole at the confocal plane of the lens to eliminate out-of-focus light
- Controlled and highly limited depth of focus.
- 3D reconstruction with images captured at different focal plane

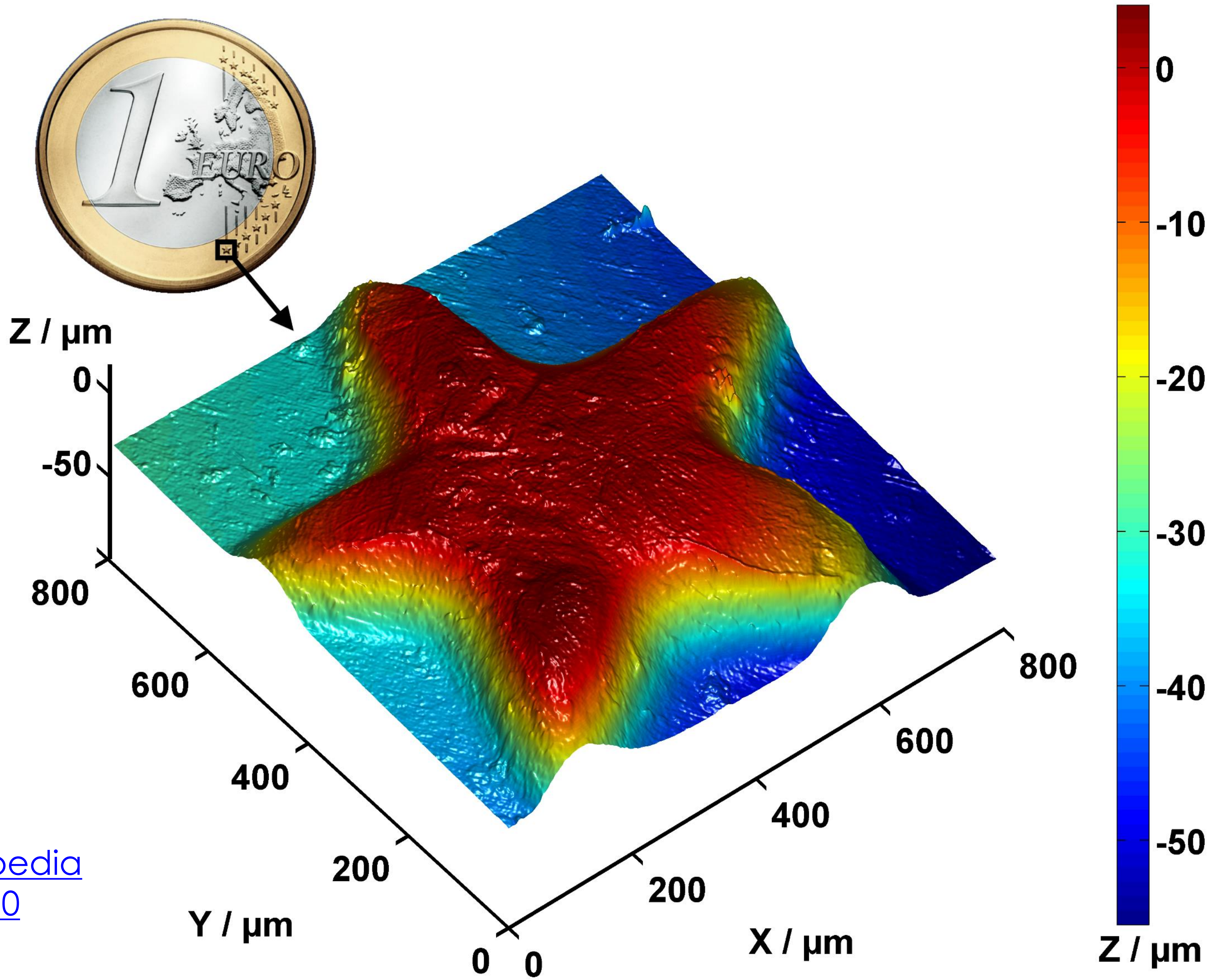


Confocal Microscopy

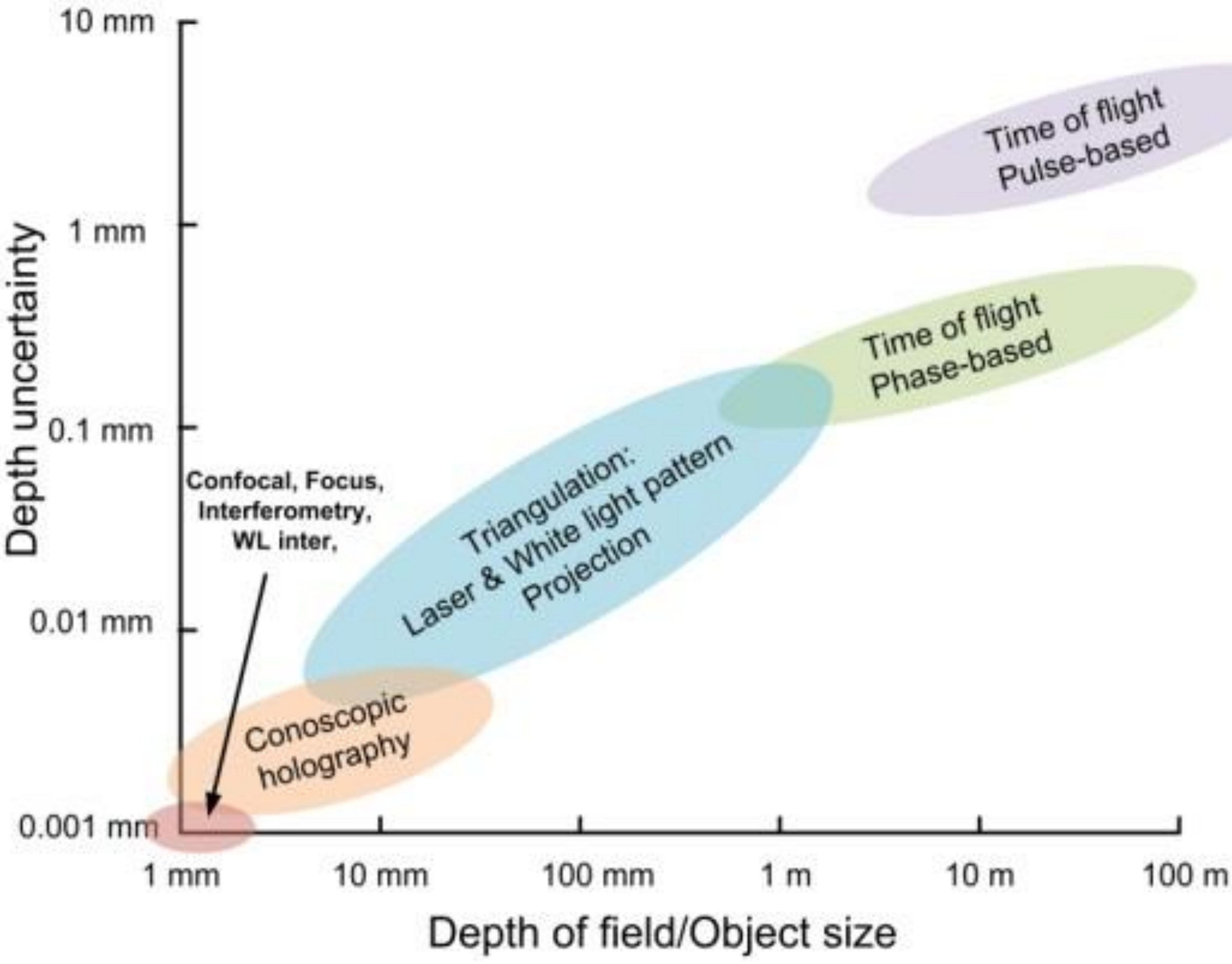
- Scanning mirrors that can move the laser beam very precisely and quickly (one mirrors tilts the beam in the X direction, the other in the Y direction)
- Z-control focus on any focal plane within your sample allowing movement in the axial direction with high precision (>10 nm).



Confocal Microscopy



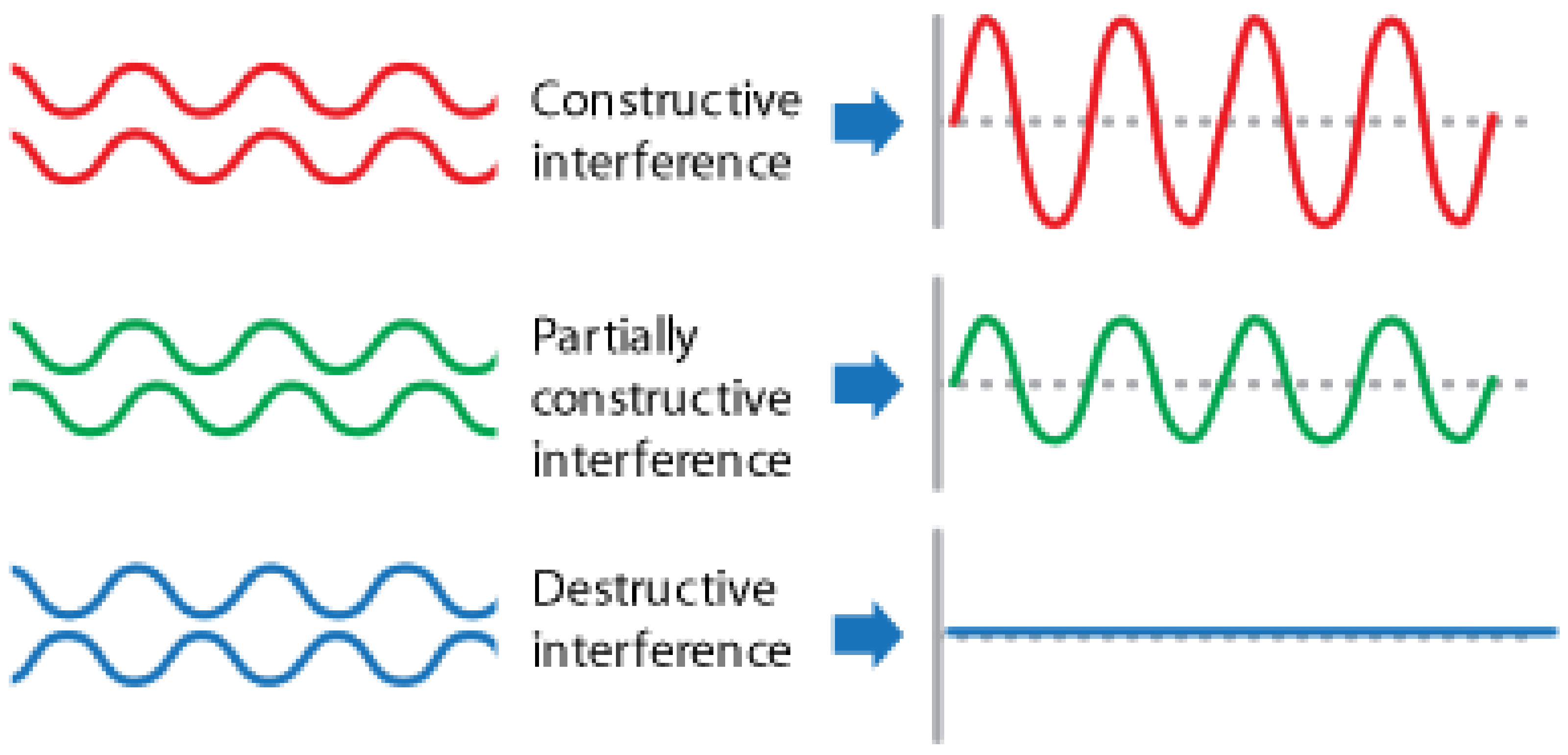
Interferometry



[Drouin et al., 2012]

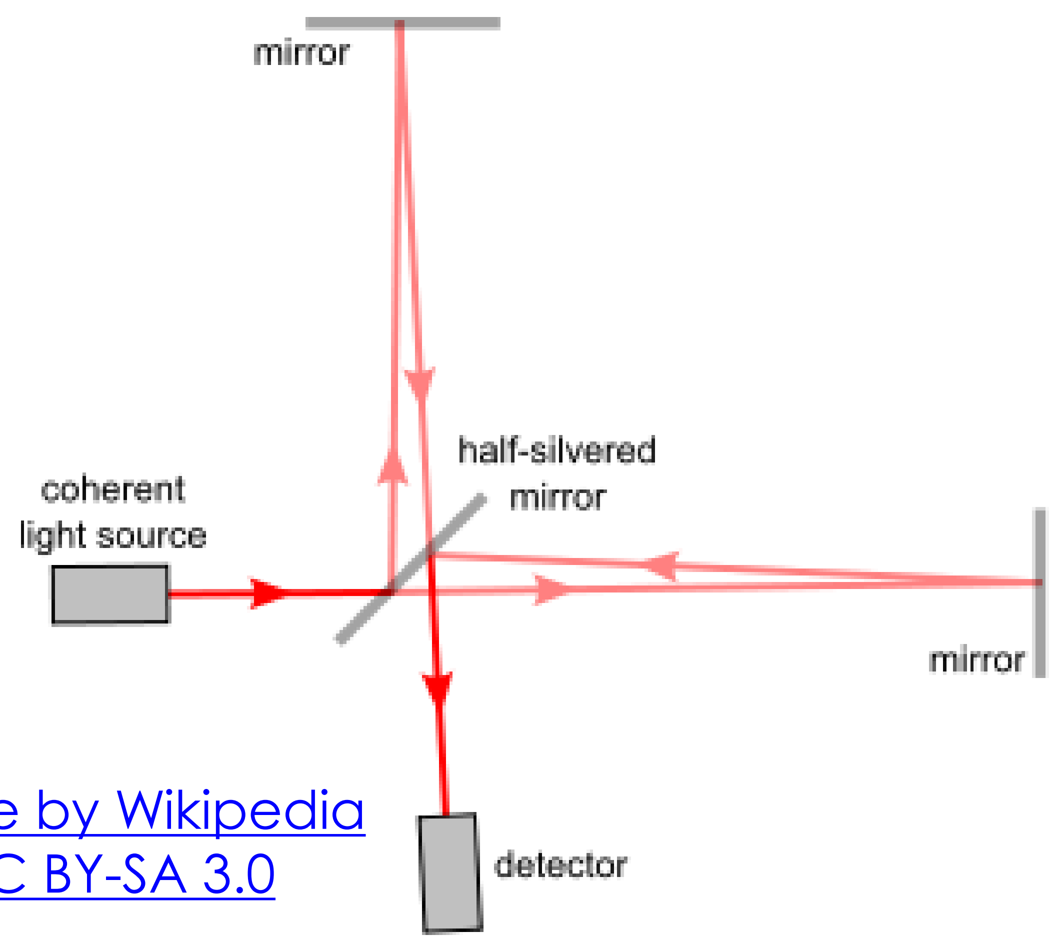
Inteferometry

- **General Idea** - Superimposing waves causing the phenomenon of interference. To extract information from the resulting waves.



Michelson Interferometer

- Single source split into two beams that travel different path, then combined again to produce interference
- Information about the difference in the path by analyzing the interference fringes



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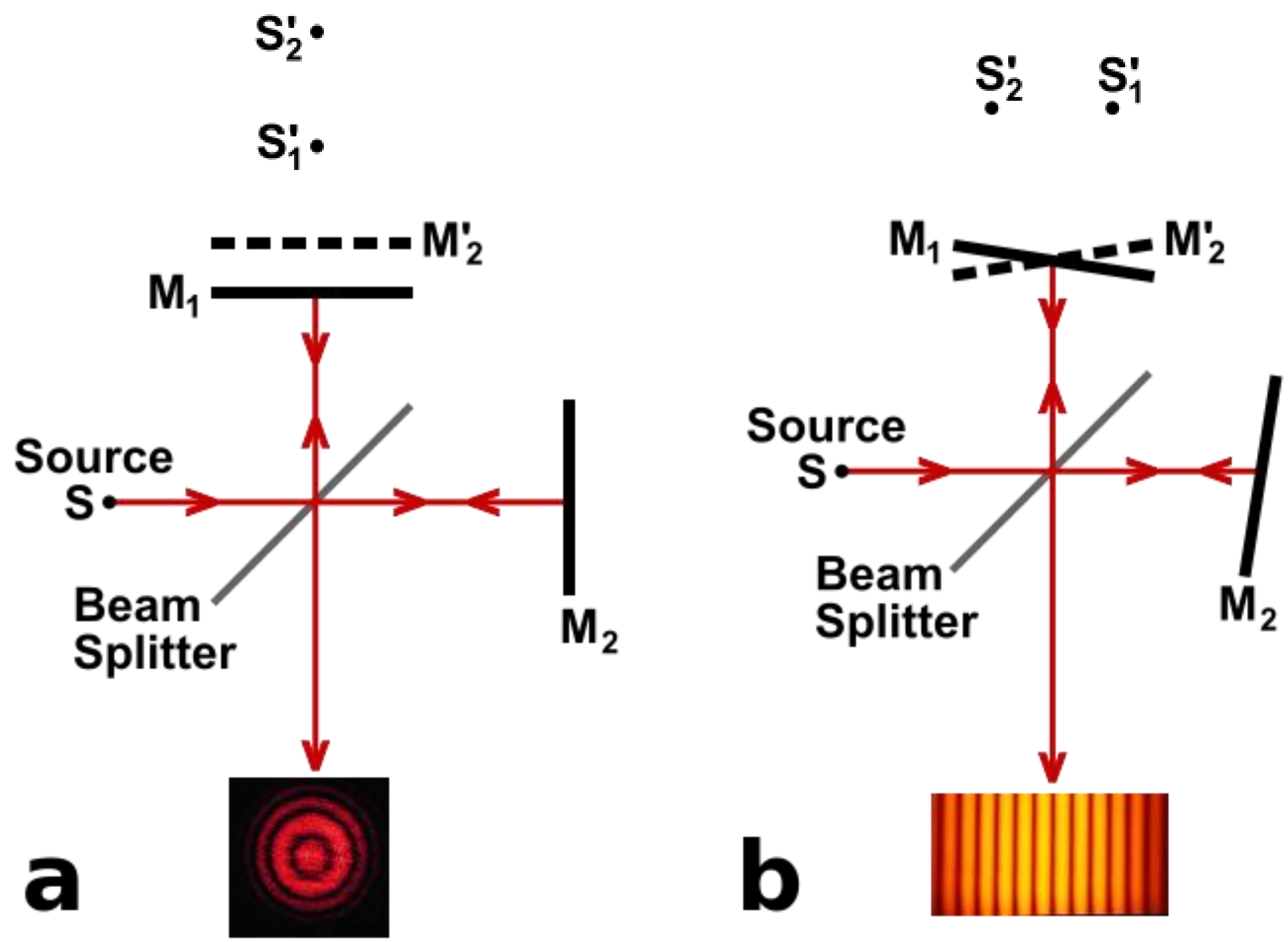

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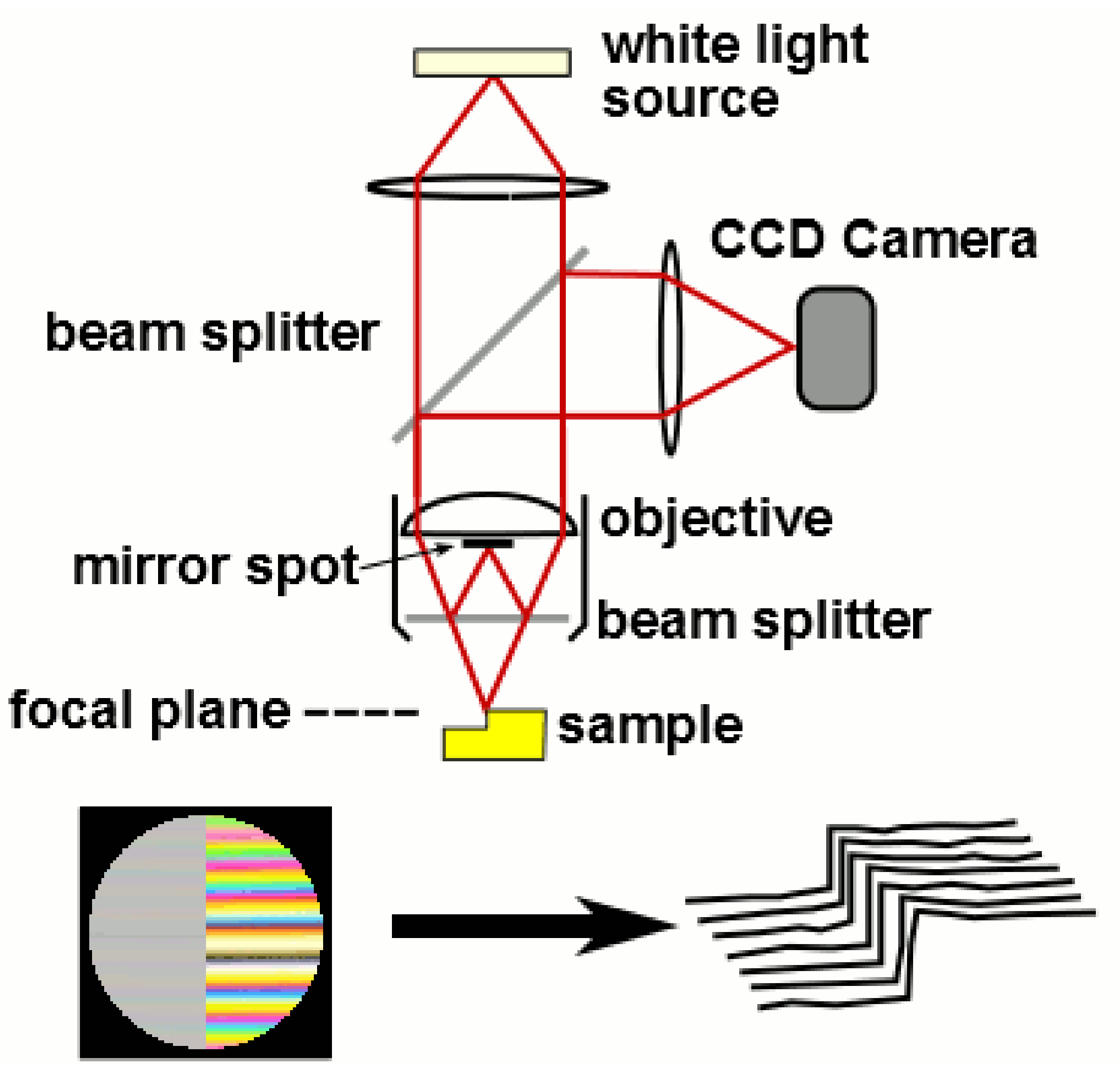
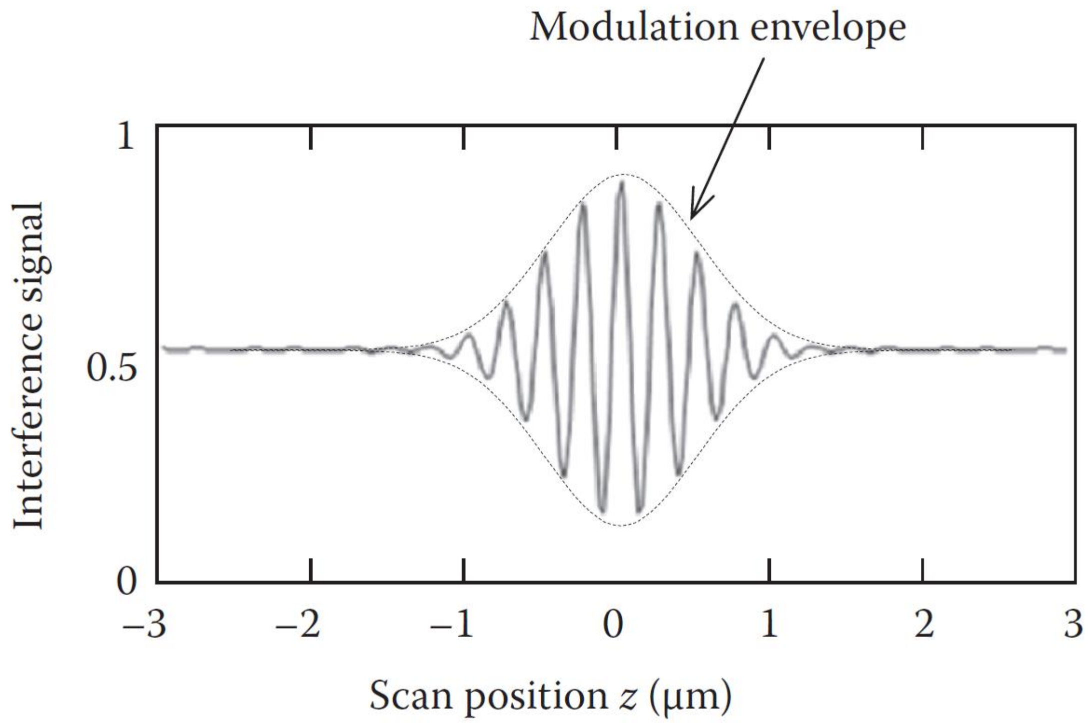
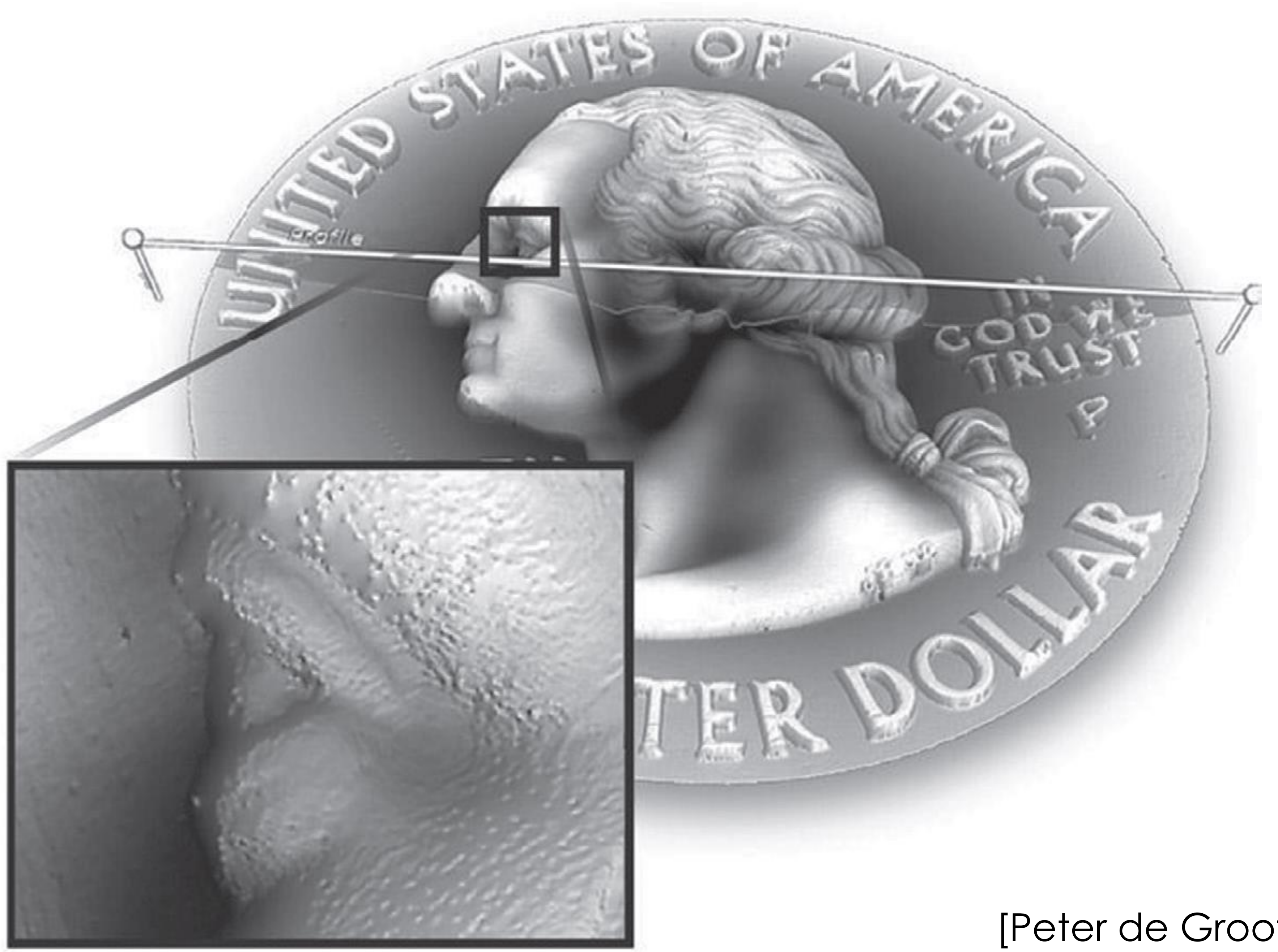
White Light Interferometry

- Accurate movement of objective in the z axial direction to change length of beam path
- Find the maximum modulation of the interference signal for each pixel



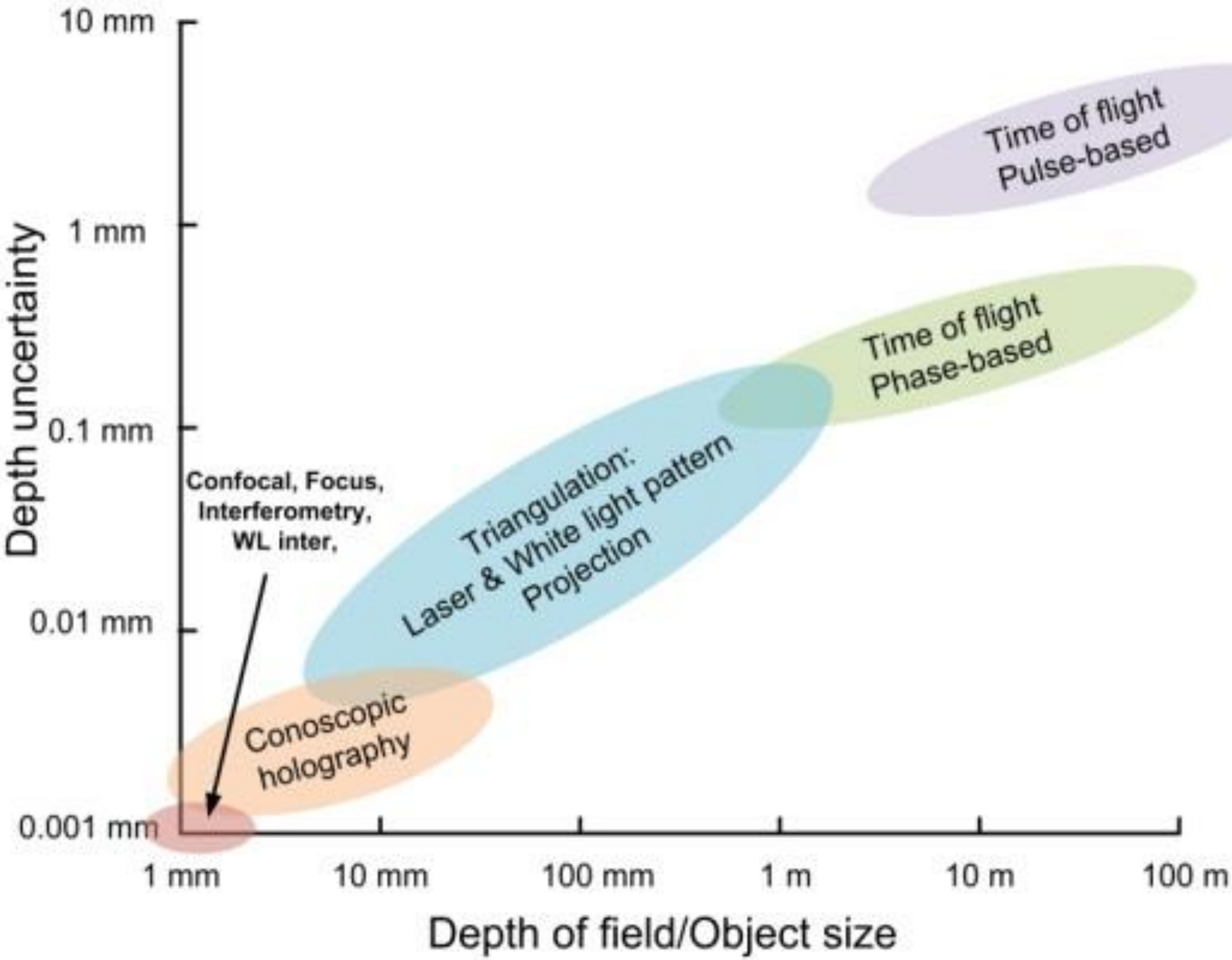


White Light Interferometry



[Peter de Groot, 2015]

Conoscopic Holography

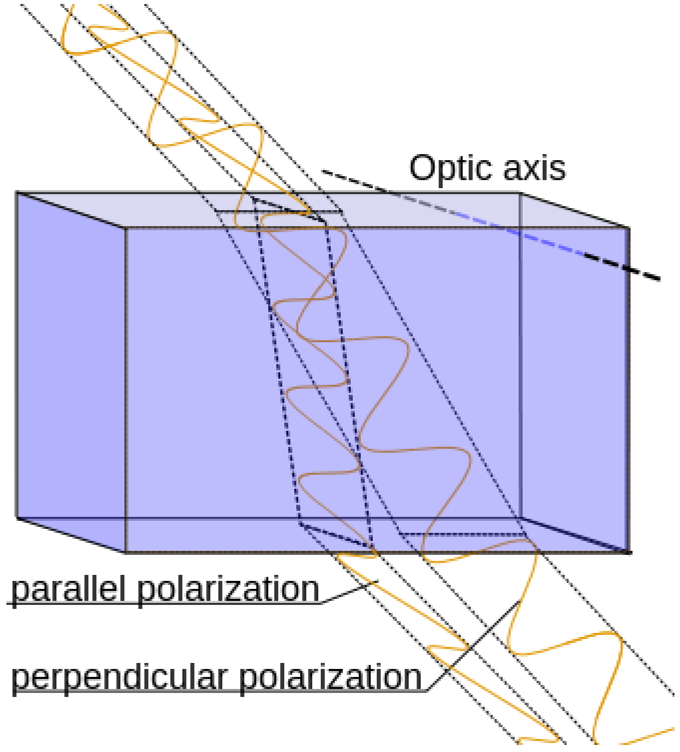


[Drouin et al., 2012]

Conoscopic Holography

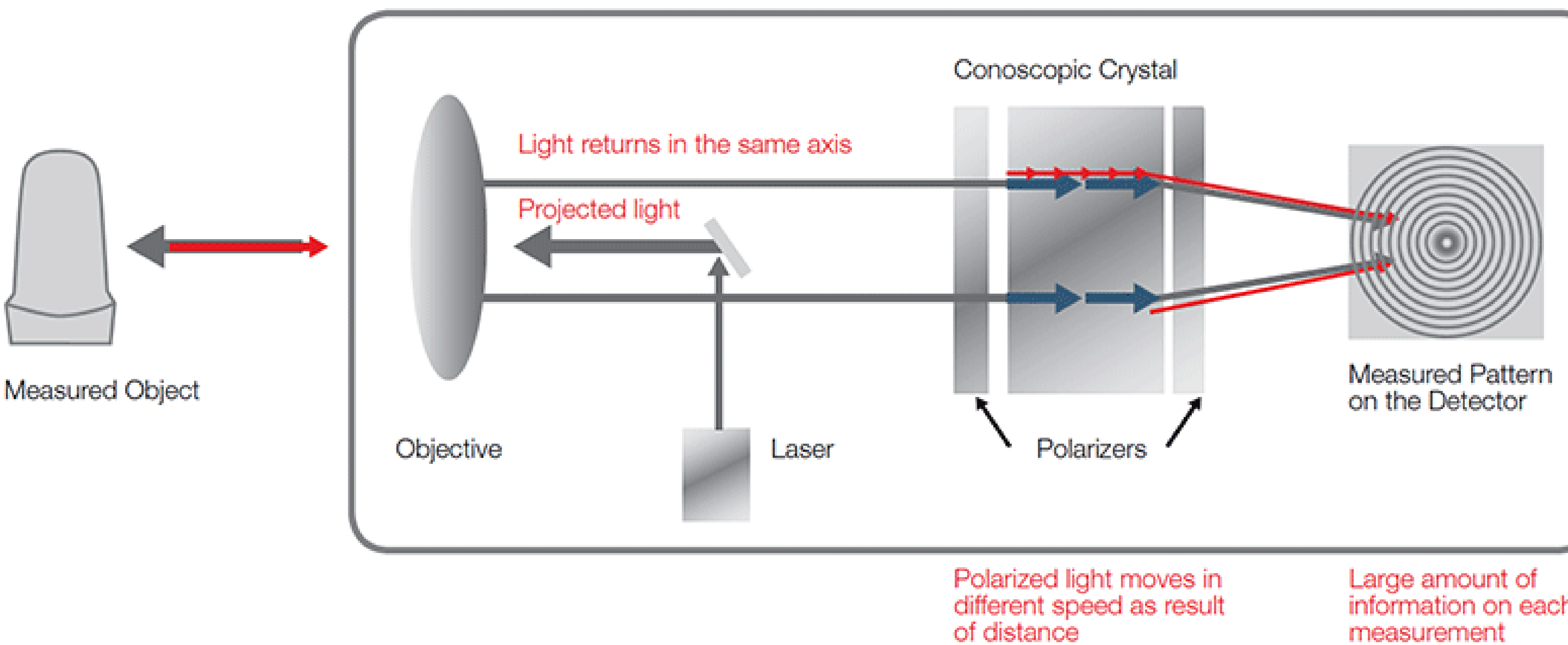
Birefringent crystal

- The refractive index depends on the polarization and propagation direction of light. The refractive index in one crystal axis (optical axis) is different from the other.
- Splitting of the incident ray in two ray with different path according polarization
  - Ordinary ray
    (a constant refractive index)
  - Extraordinary ray
    (the refractive index depends on the ray direction)

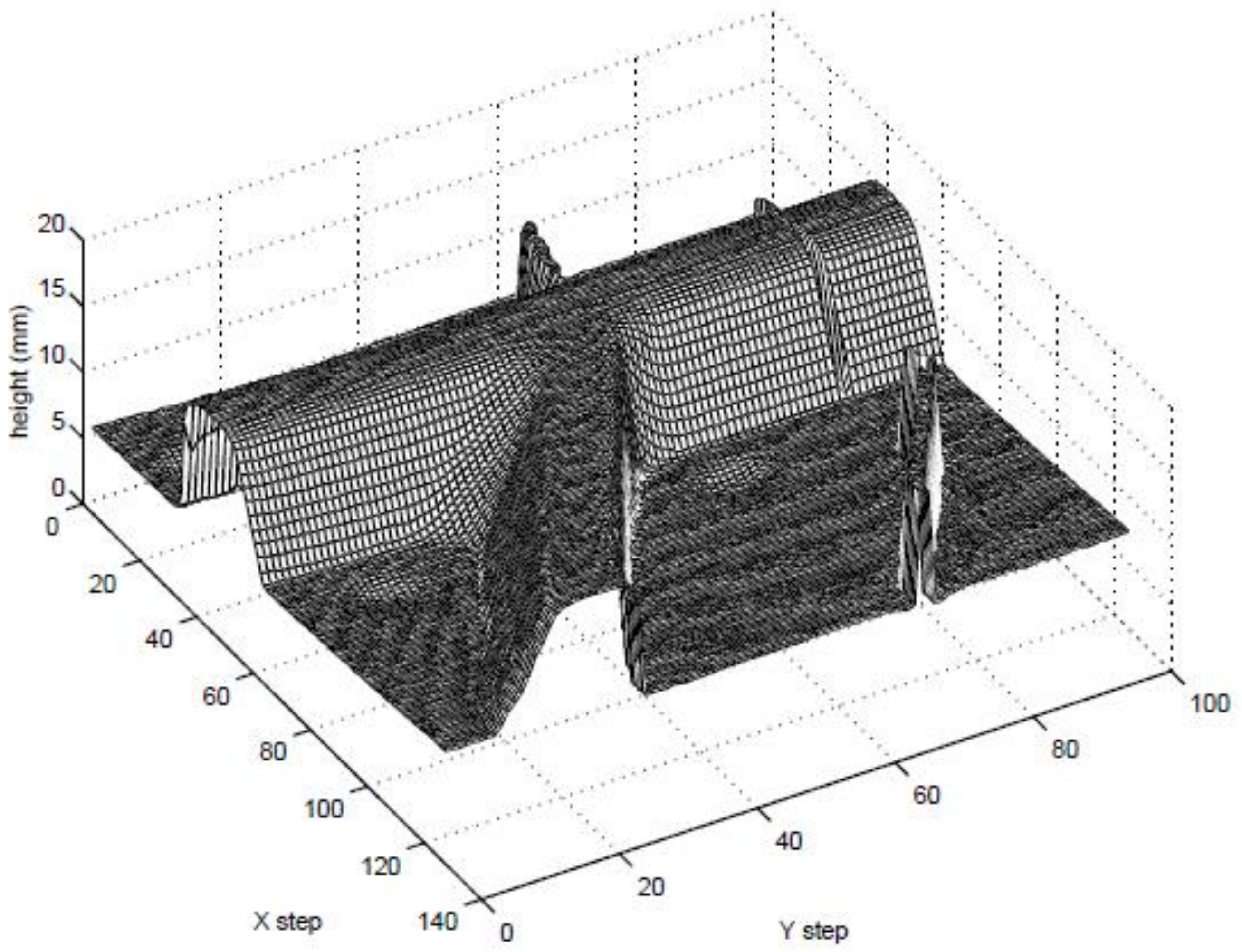


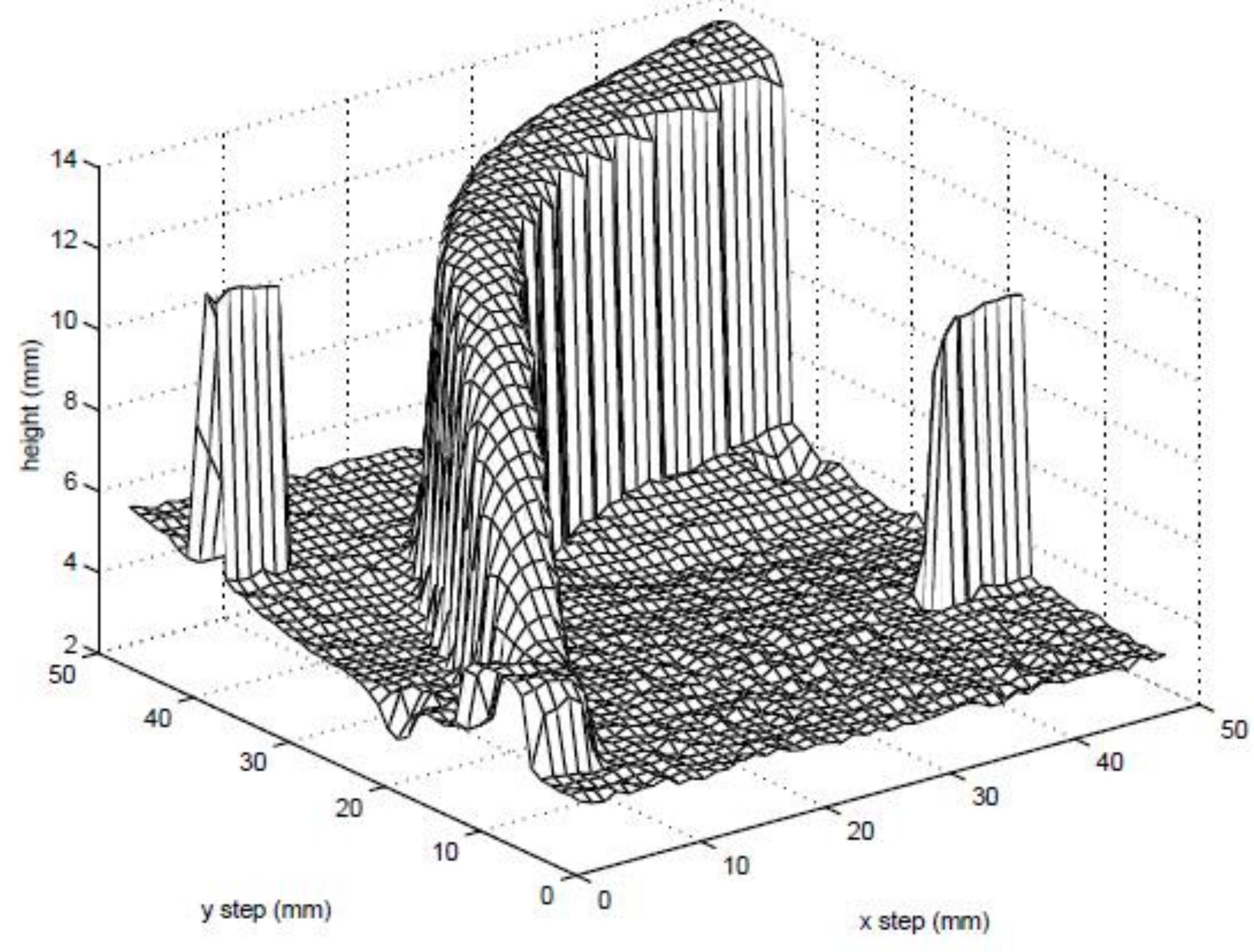
Conoscopic Holography

- Analyzing the interference pattern of ordinary and extraordinary waves of the beam reflect by the measured same

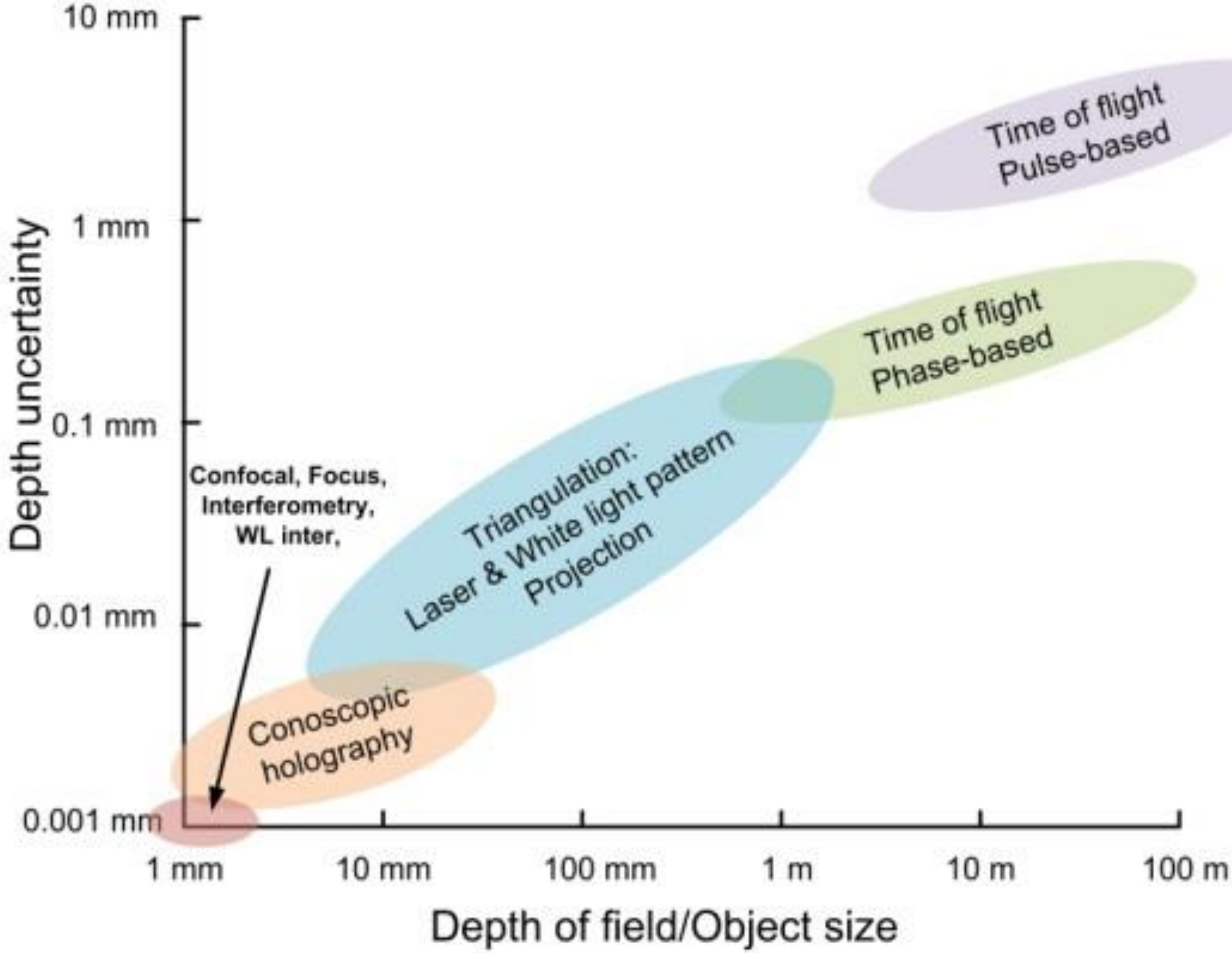


Conoscopic Holography





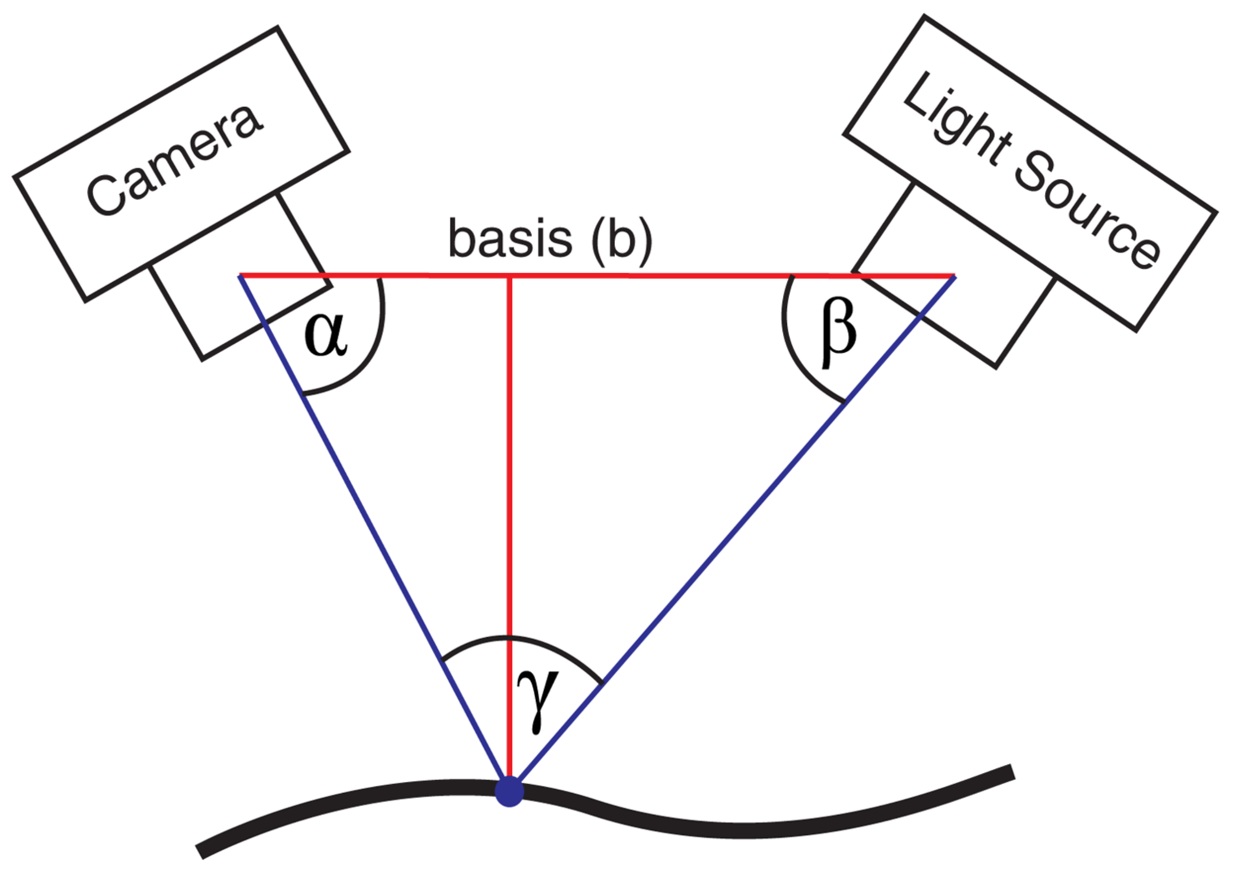
Laser Triangulation



[Drouin et al., 2012]

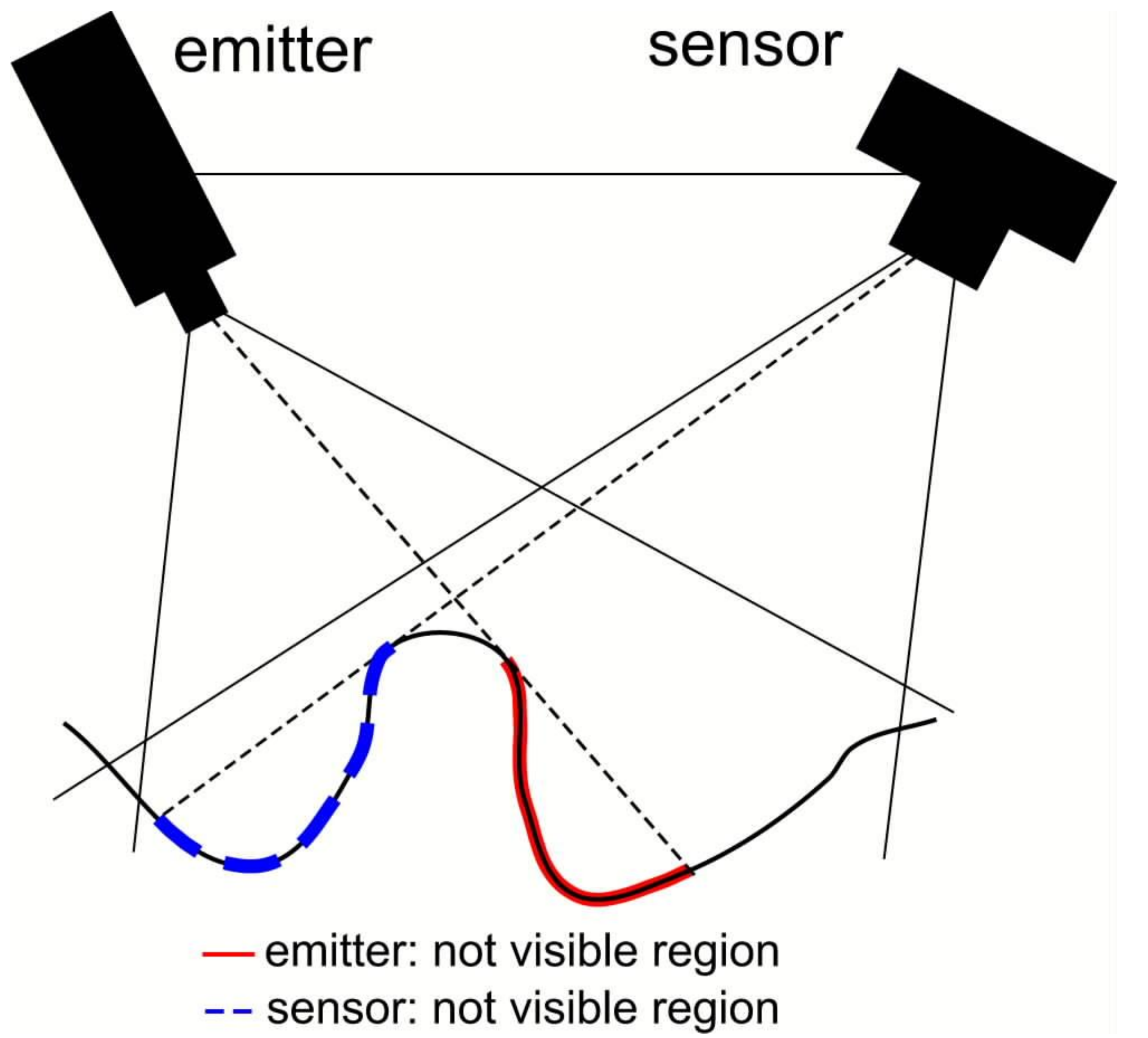
Triangulation based system

- Location of a point by triangulation knowing the distance between the sensors (camera and light emitter) and the angles between the rays and the base distance

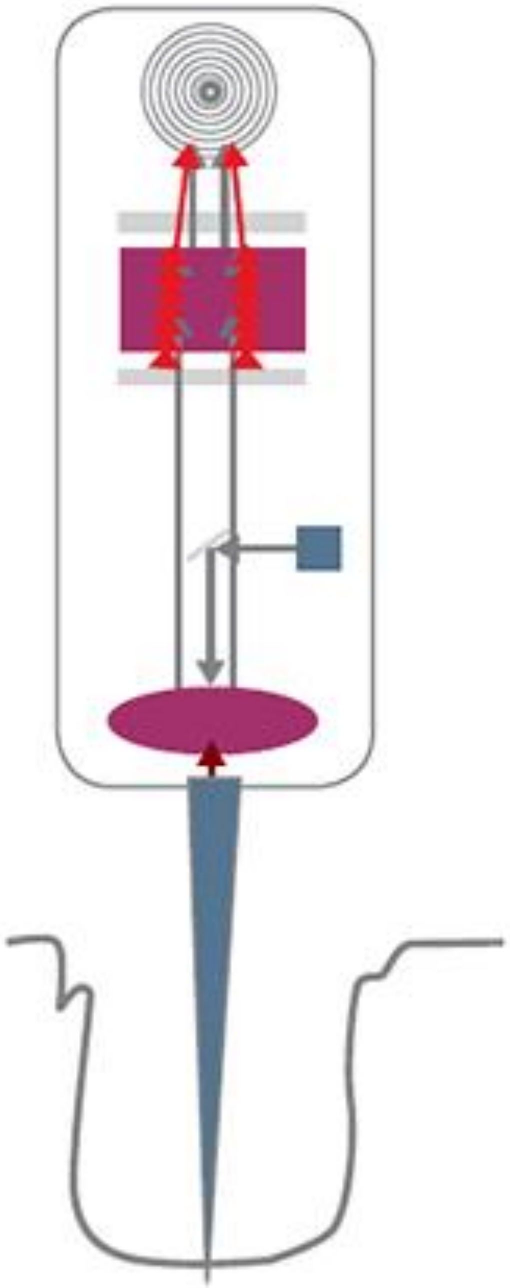


Triangulation based system

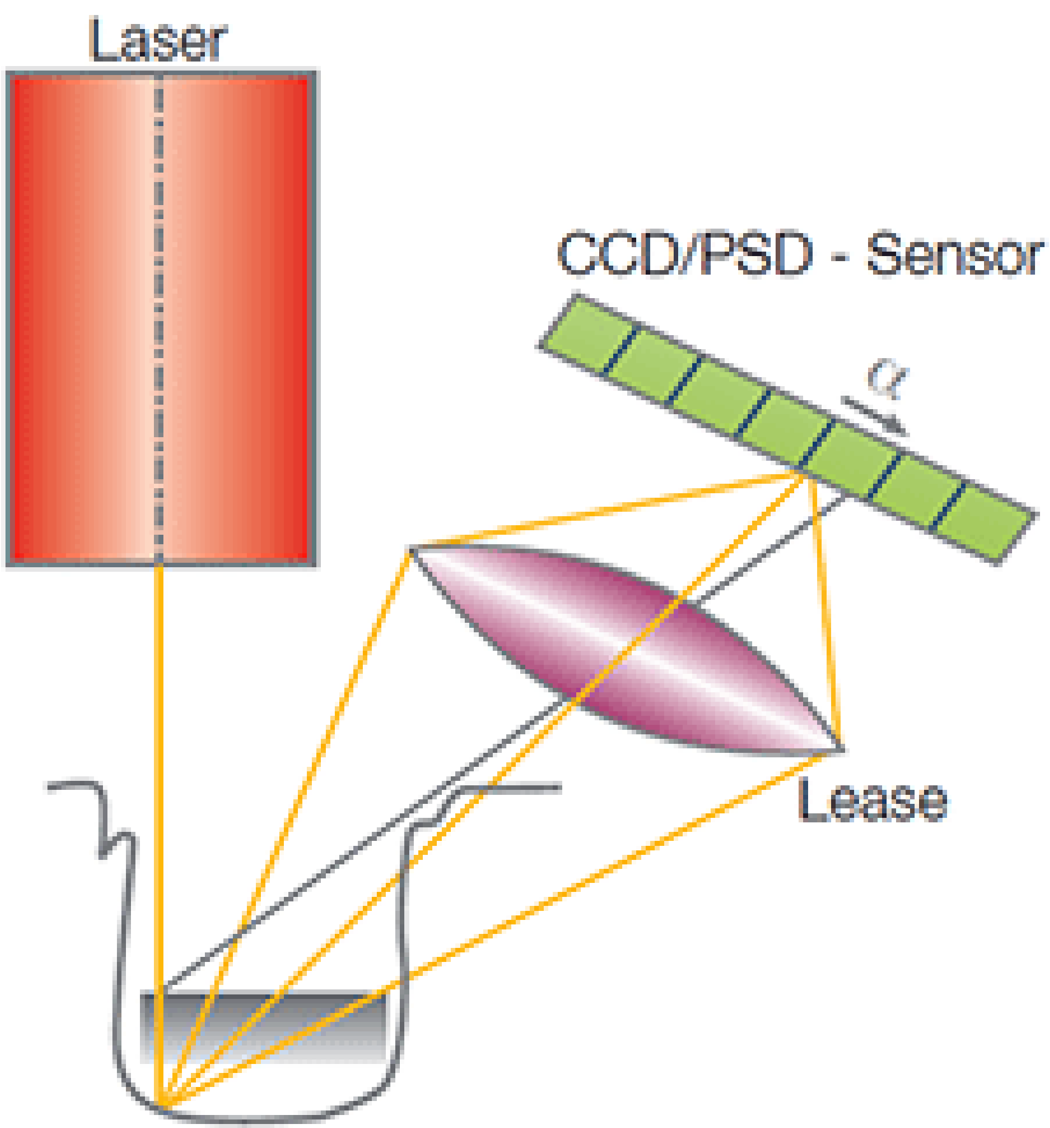
- An inherent limitation of the triangulation approach: non-visible regions
- Some surface regions can be visible to the emitter and not-visible to the receiver, and vice-versa
- In all these regions we miss sampled points
- Need integration of multiple scans



Conoscopic Holography vs Triangulation



CONOSCOPIC HOLOGRAPHY

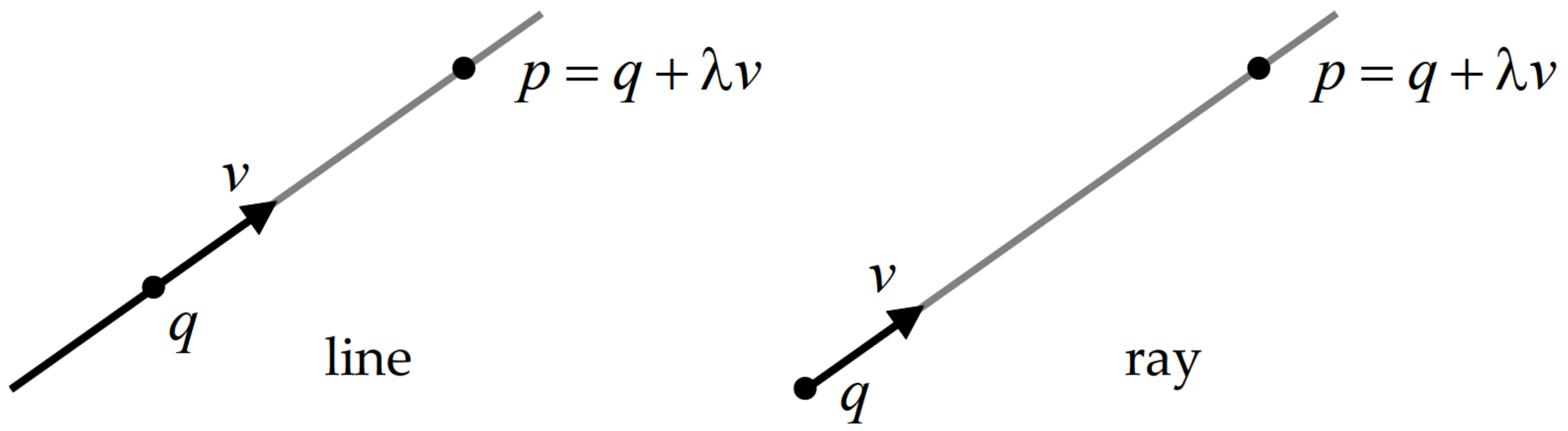


TRIANGULATION

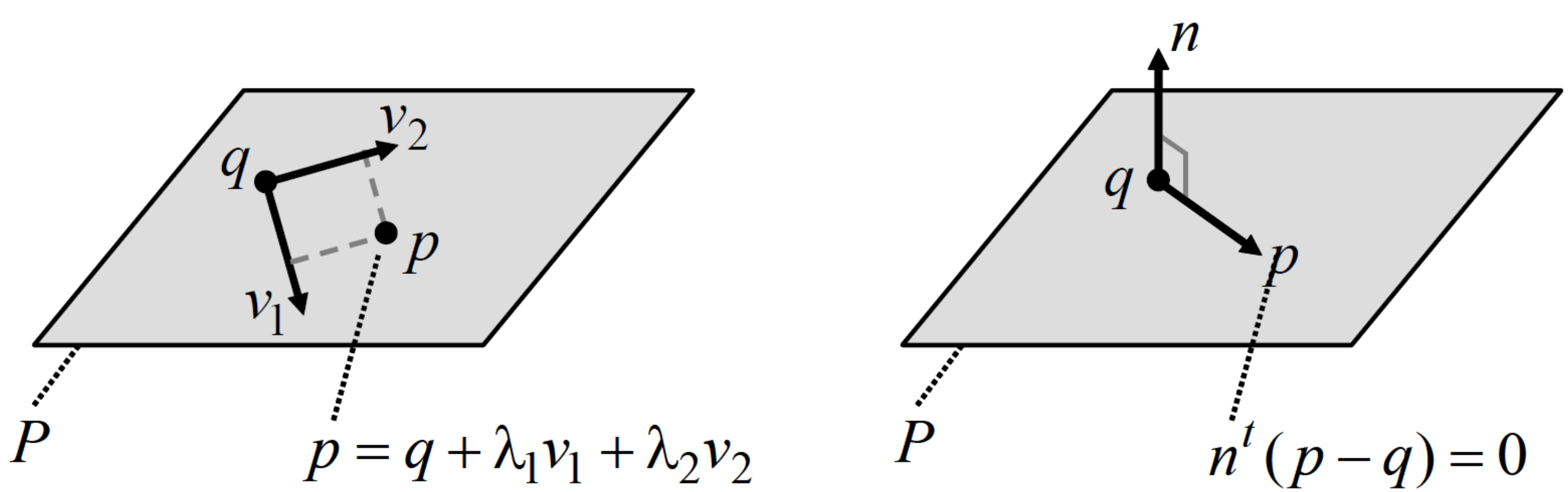
Mathematics of triangulation

[Douglas et al., SIGGRAPH 2009]

Parametric representation of lines and rays



Parametric and implicit representation of a plane



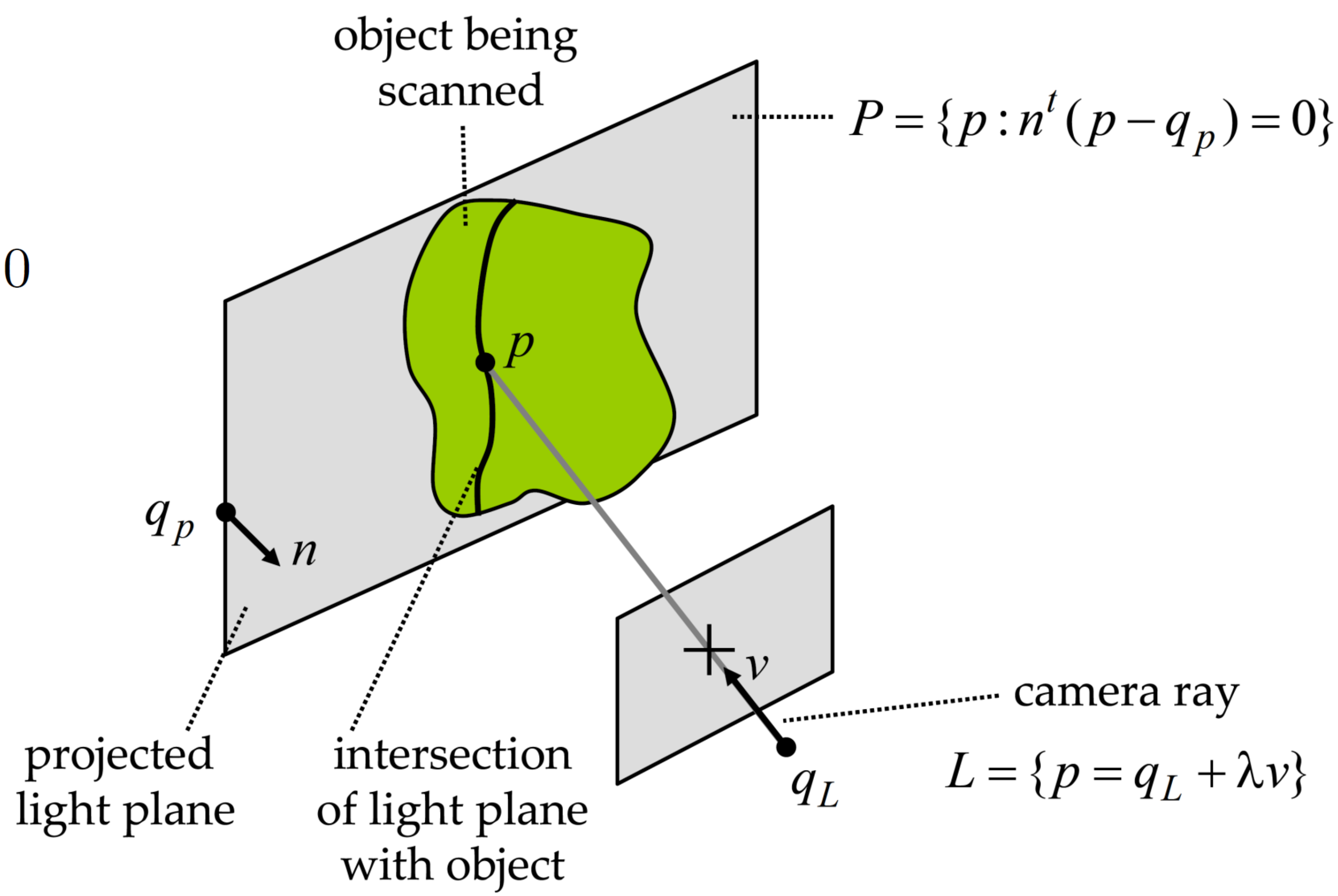
Mathematics of triangulation

[Douglas et al., SIGGRAPH 2009]

Ray-plane intersection

$$n^t(p - q_p) = n^t(\lambda v + q_L - q_p) = 0$$

$$\lambda = \frac{n^t(q_P - q_L)}{n^t v}$$



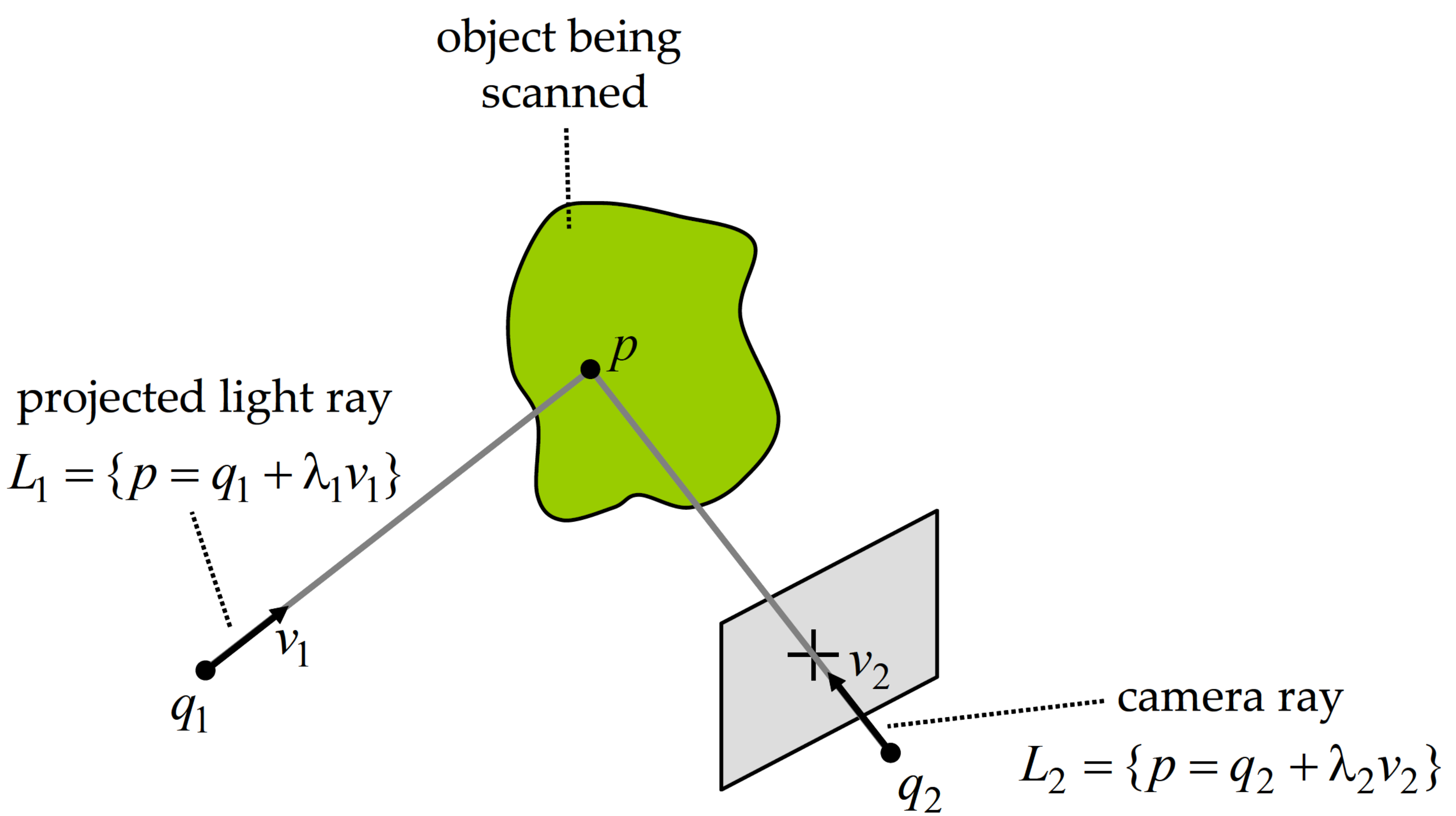
Mathematics of triangulation

[Douglas et al., SIGGRAPH 2009]

Ray-ray intersection

$$q_1 + \lambda_1 v_1 = q_2 + \lambda_2 v_2$$

Intersection that minimizes the sum of the squared distance to both the rays



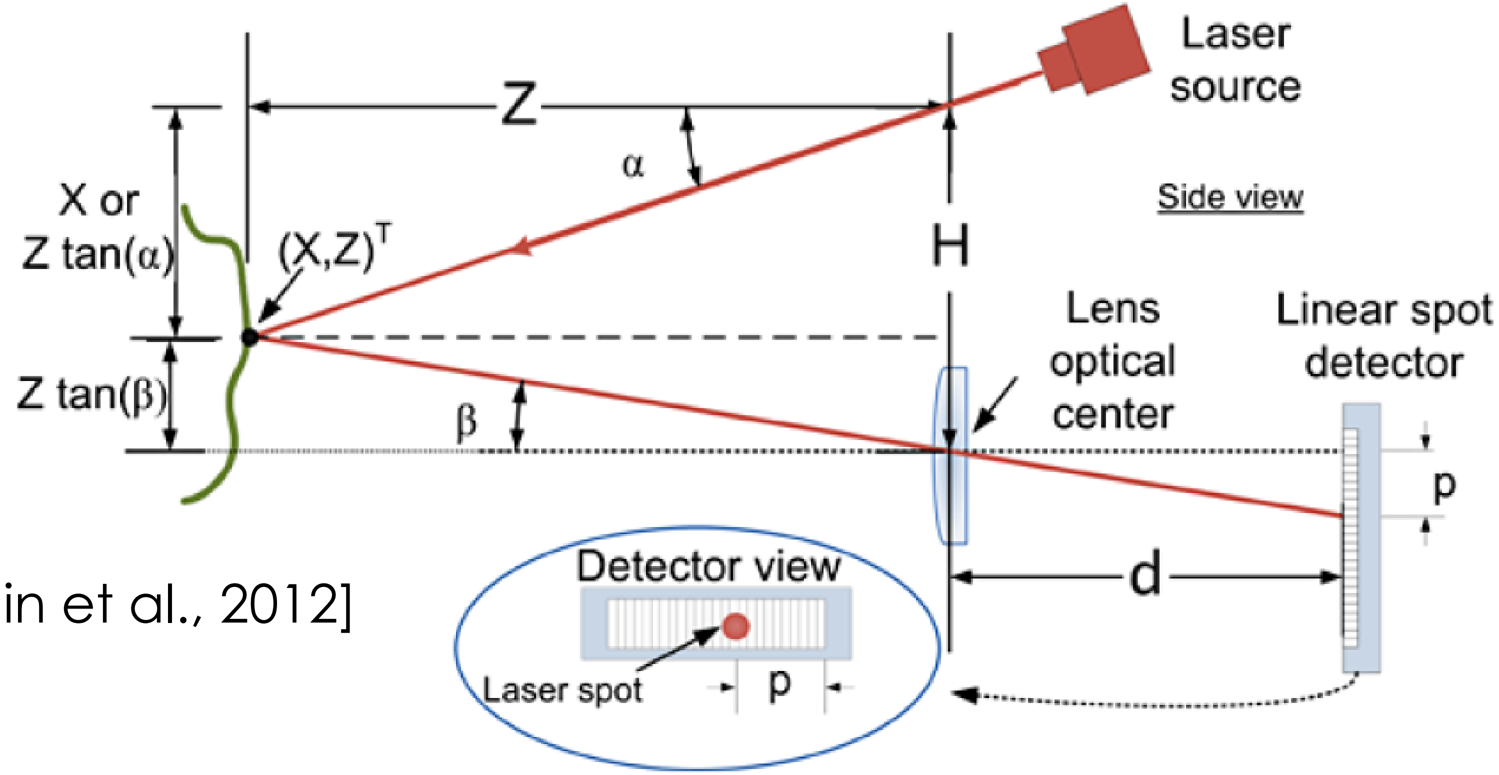
$$\min_{\lambda_1,\lambda_2} \left\|(q_2 + \lambda_2 v_2)^2 - (q_1 + \lambda_1 v_1)^2\right\|^2 \Rightarrow \begin{pmatrix}\lambda_1\\ \lambda_2\end{pmatrix} = \begin{pmatrix}\|v_1\|^2 & -v_1^t v_2\\ -v_2^t v_1 & \|v_2\|^2\end{pmatrix}^{-1} \begin{pmatrix}v_1^t(q_2 - q_1)\\ v_2^t(q_1 - q_2)\end{pmatrix}$$

Spot Laser Triangulation

- Spot position location (find the most intensity pixel and compute the centroid using the neighbors)

$$p = i_M + \frac{\sum_{i=-N}^{N} I(i_M + i)i}{\sum_{i=-N}^{N} I(i_M + i)}.$$

- Triangulation using trigonometry



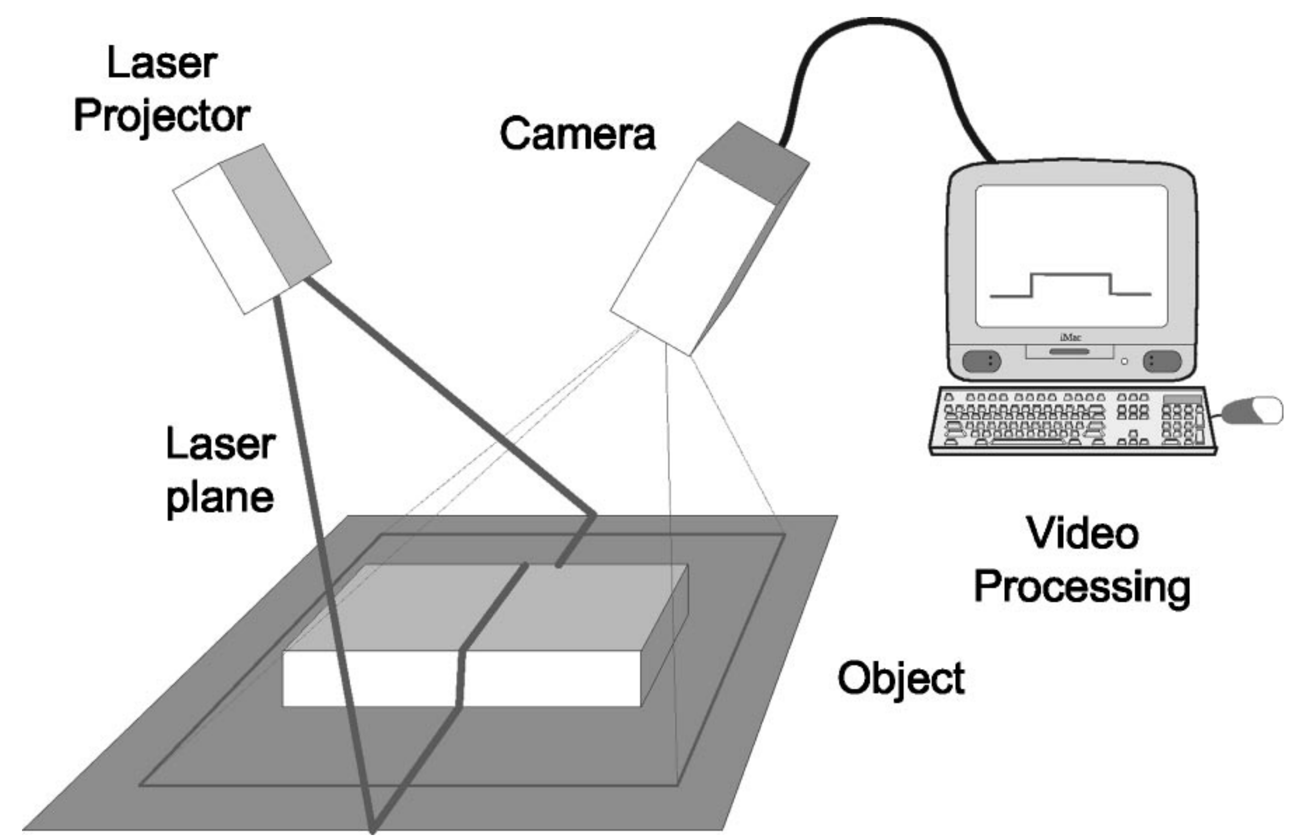
[Drouin et al., 2012]

$$Z = \frac{H}{\tan\alpha + \tan\beta}$$

$$X = Z\tan\alpha$$

Laser Line Triangulation

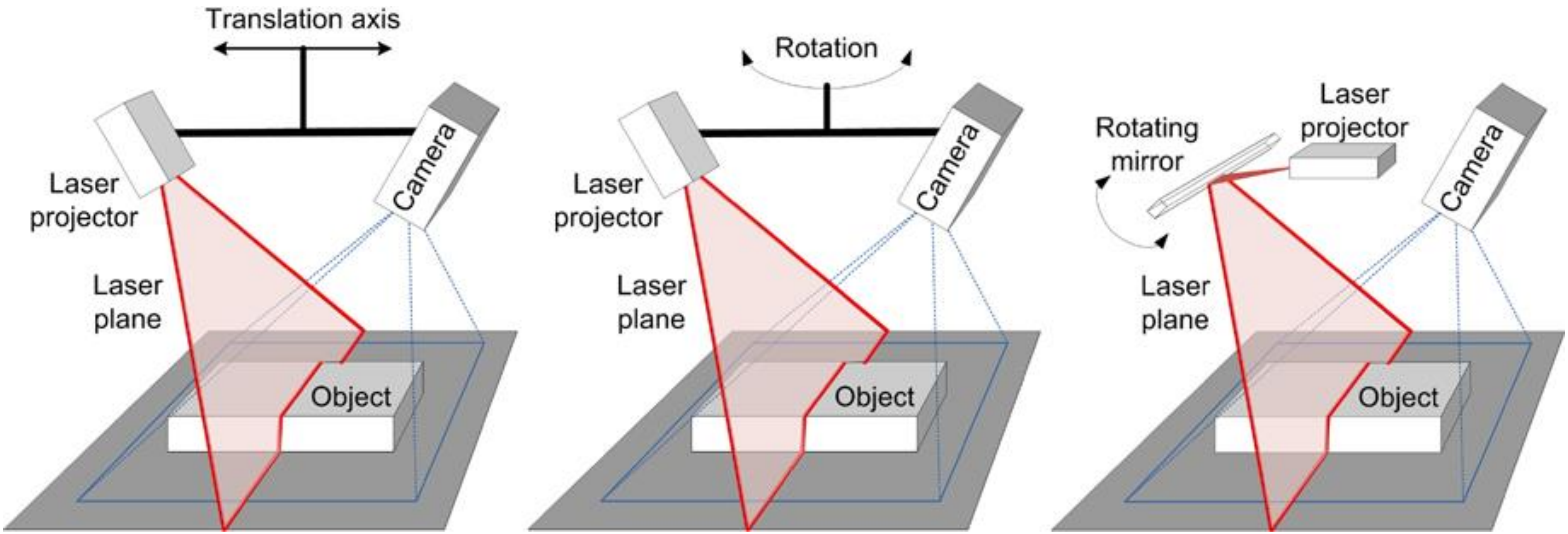
- Laser projector and camera modelled as a pinhole camera
- Detection of the pixel in the laser line with computer vision algorithm (peak detection)
- Ray-plane triangulation



[Blais, 2004]

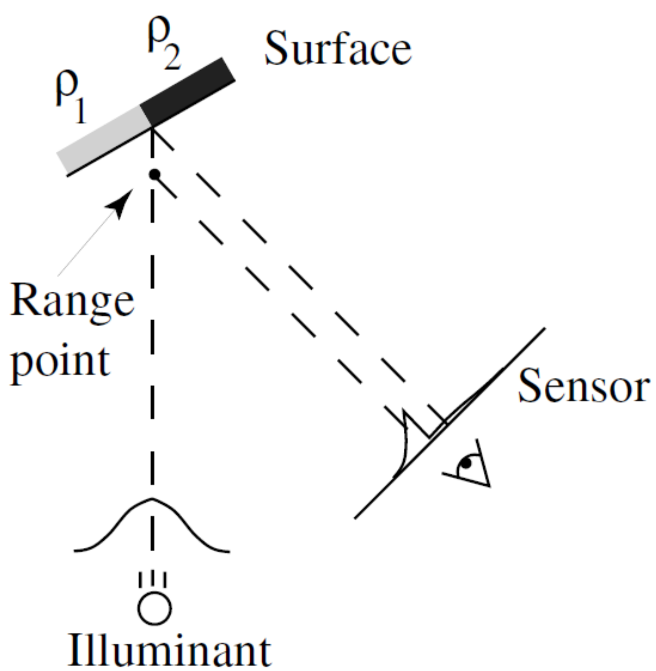
Laser Line Triangulation

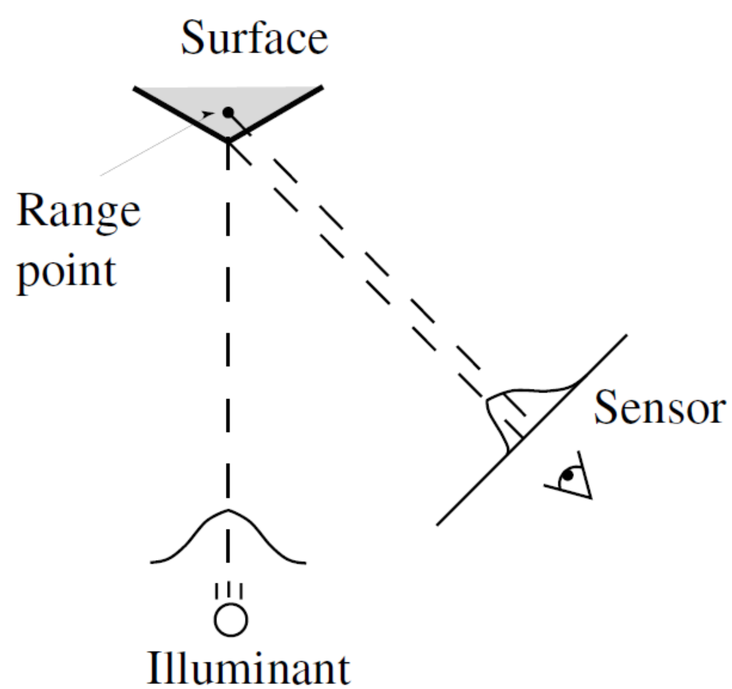
- Rotate or translate the scanner or rotate the object using a turntable



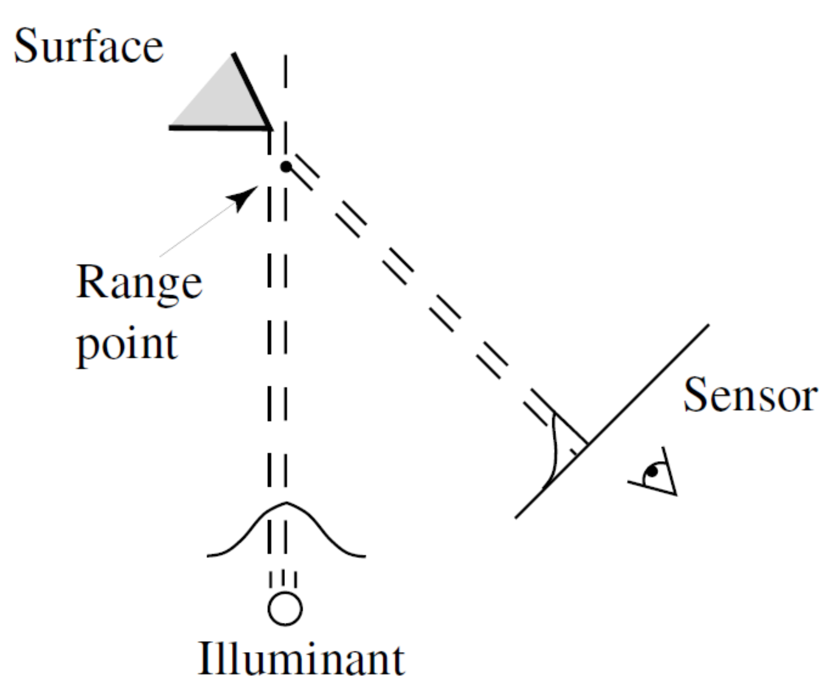
[Drouin et al., 2012]

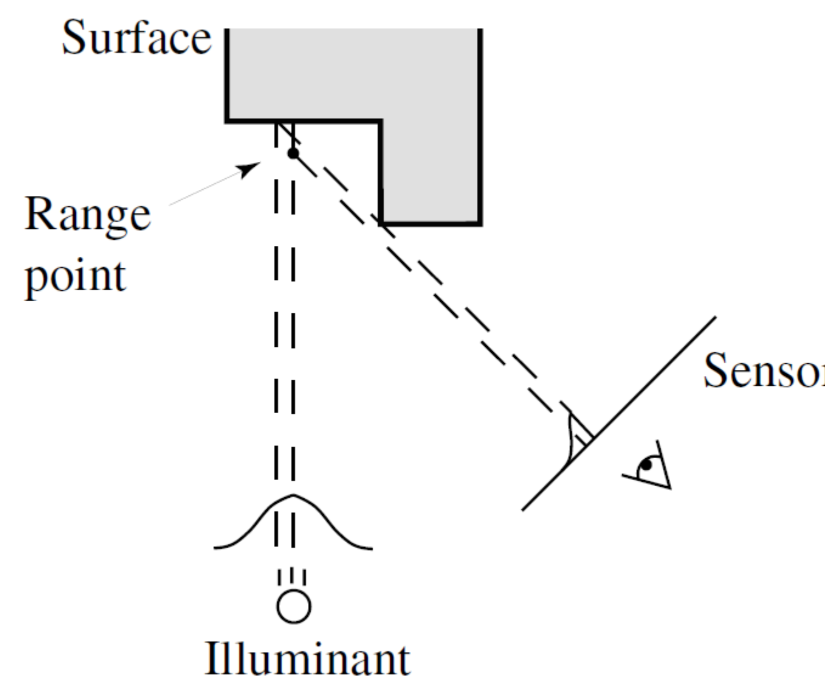
Errors in Triangulation system





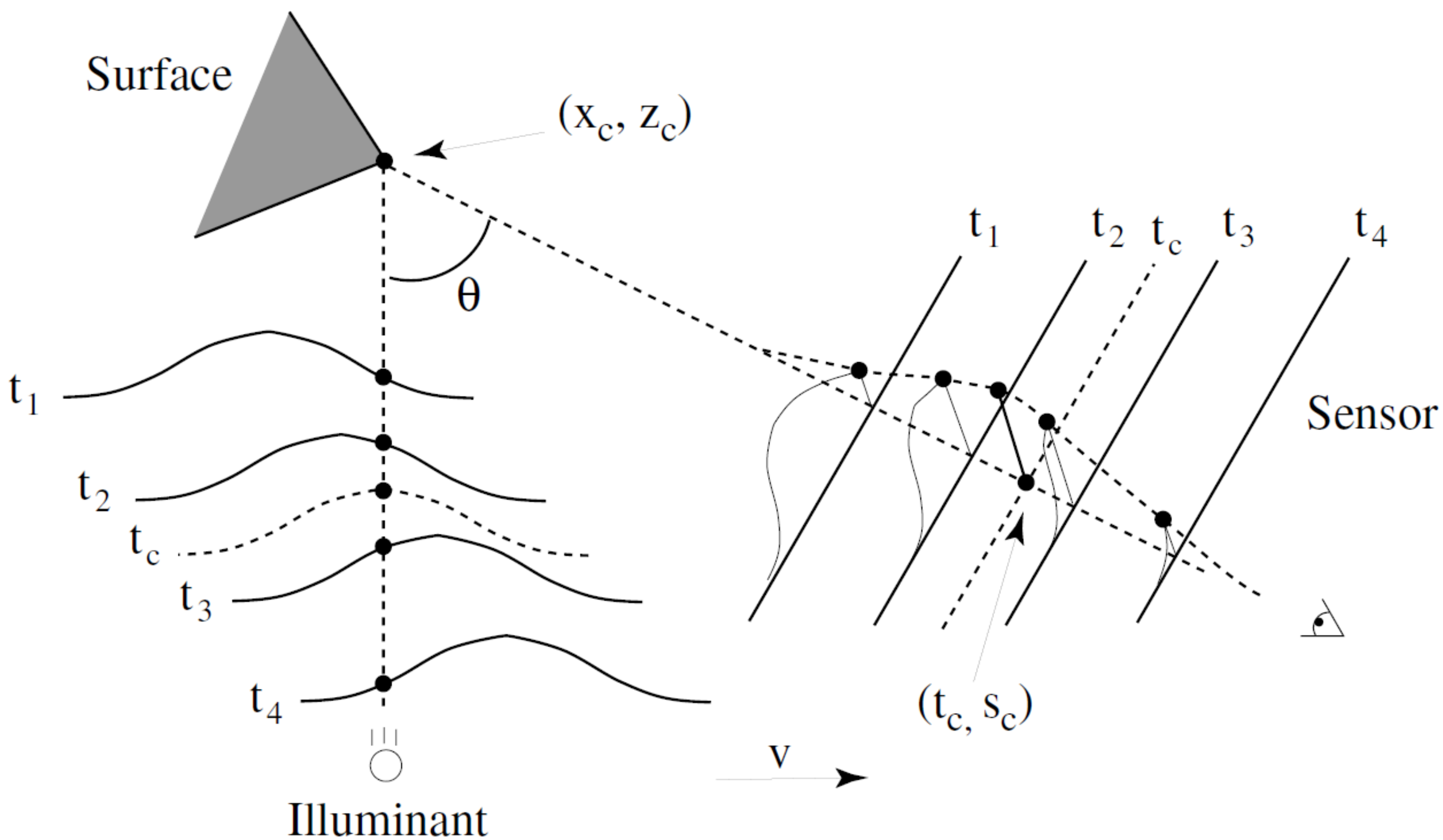
[Curless et al., ICCV 1995]





Errors in Triangulation system

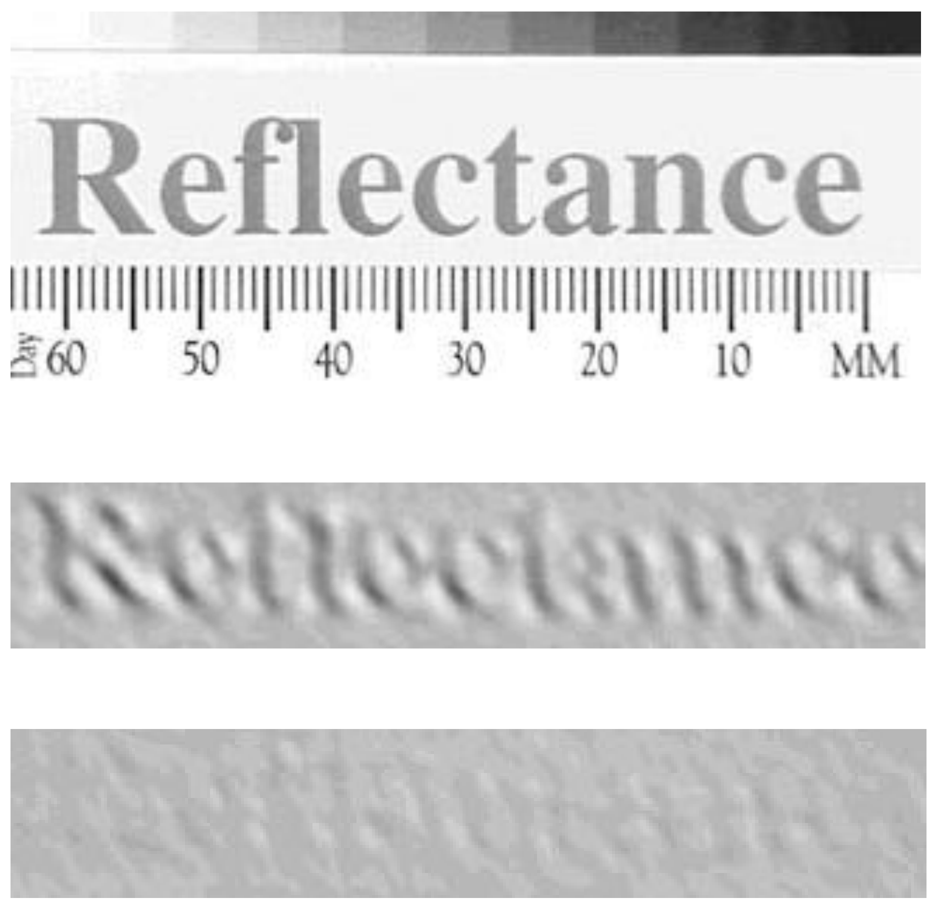
- Solution: space-time analysis [Curless et al., ICCV 1995]



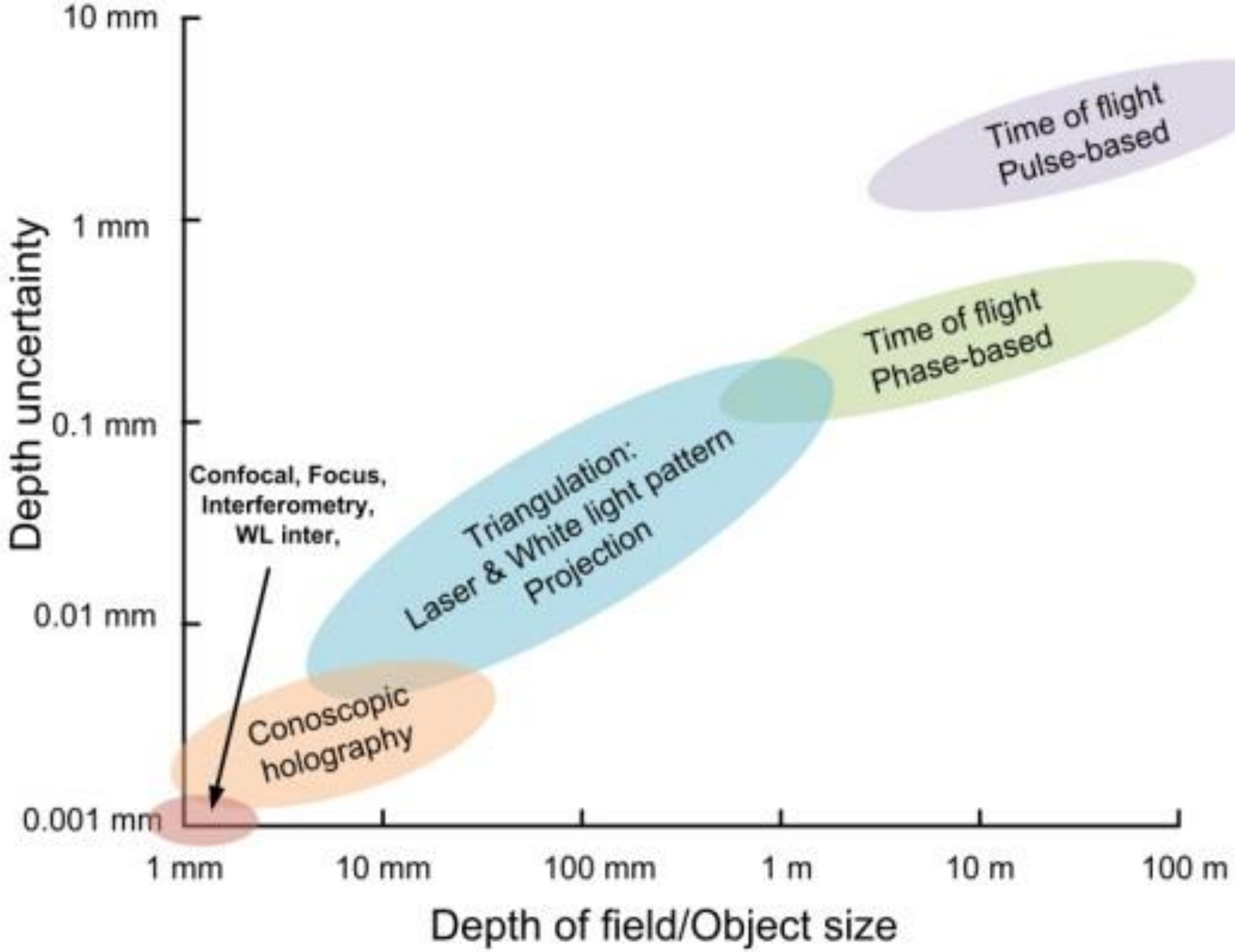
Errors in Triangulation system

- Solution: space-time analysis

[Curless et al., ICCV 1995]



Structured Light



[Drouin et al., 2012]

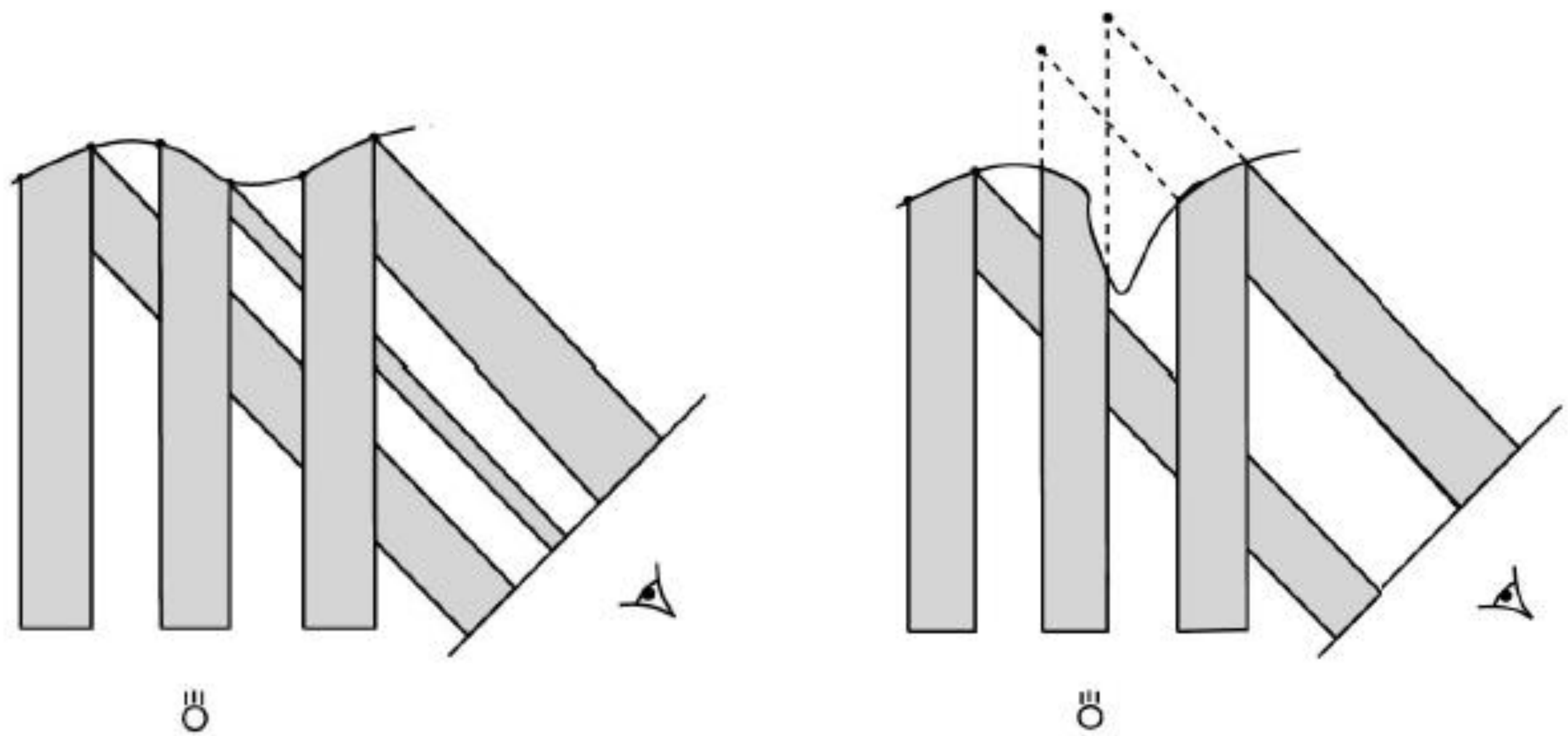
Structured light scanner

- Projection of light pattern using a digital projector and acquisition of its deformation with one o two cameras

[Drouin et al., 2012]

Structured light scanner

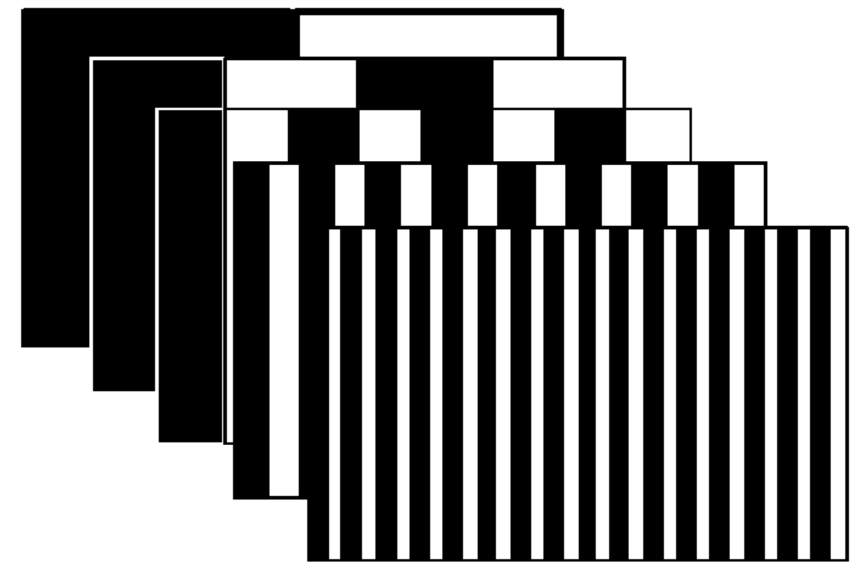
- Simple design, no sweeping/translating devices needed
- Fast acquisition (a single image for each multi-stripe pattern)
- Ambiguity problem with a single pattern to identify which stripe light each pixel



Structured light scanner

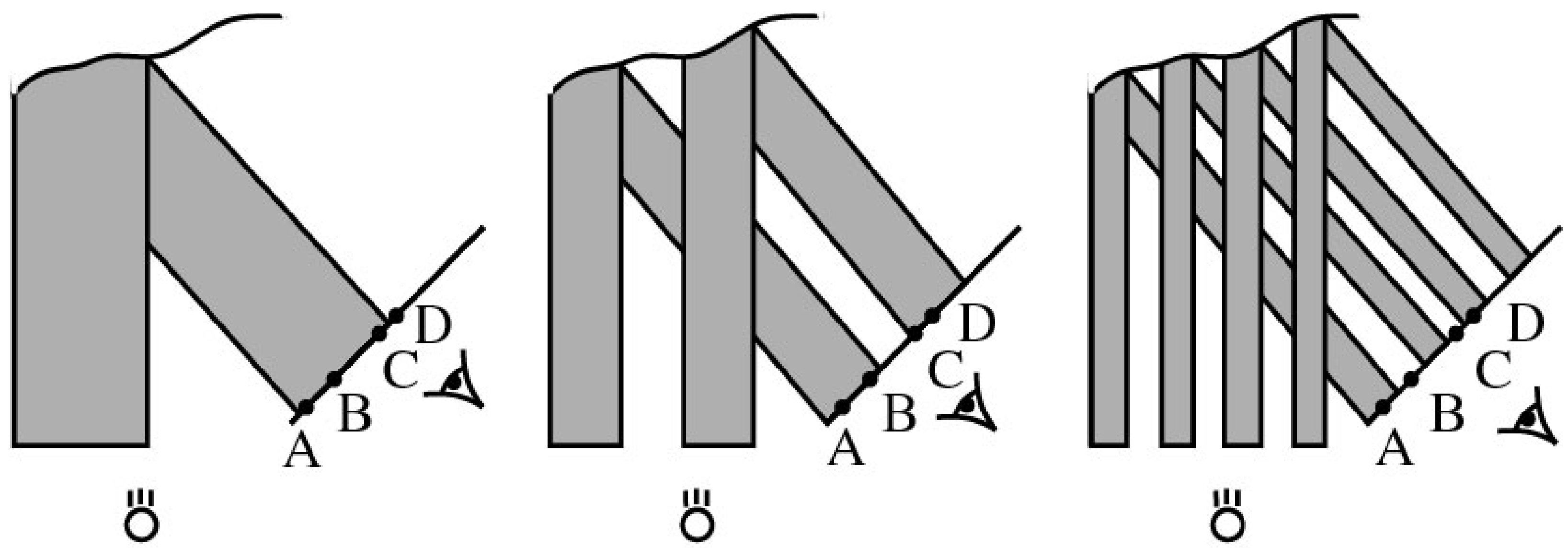
- How to solve the ambiguity?
- Many coding strategies that can be used to recover which camera pixel views the light from a given plane
  - Temporal coding – Multiple patterns in the time, matching using the time sequence of the image intensity, slower but more accurate
  - Spatial coding – A single pattern, the local neighborhood is used to perform the matching, more suitable for dynamic scene
  - Direct coding – A different code for every pixel

Temporal Coding



Binary Code

- Two illumination levels: 0 and 1
- Every point is identified by the sequence of intensities that it receives
- The resolution is limited to half the size of the finest pattern

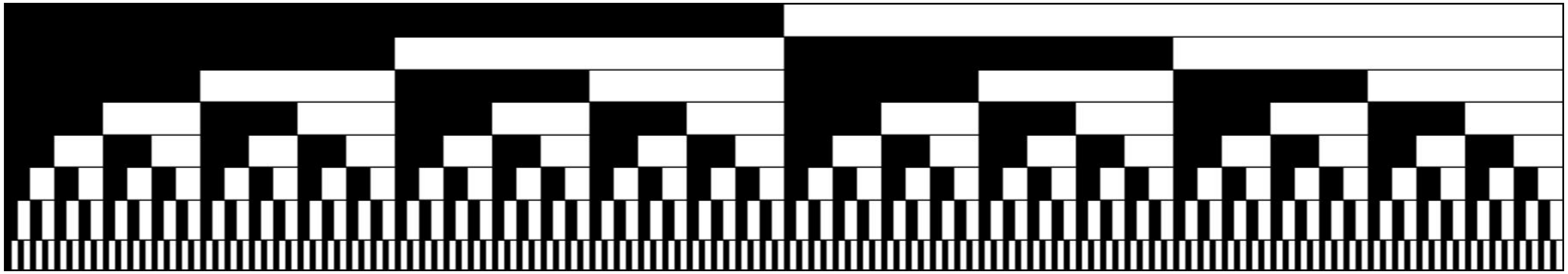


Binary codes:

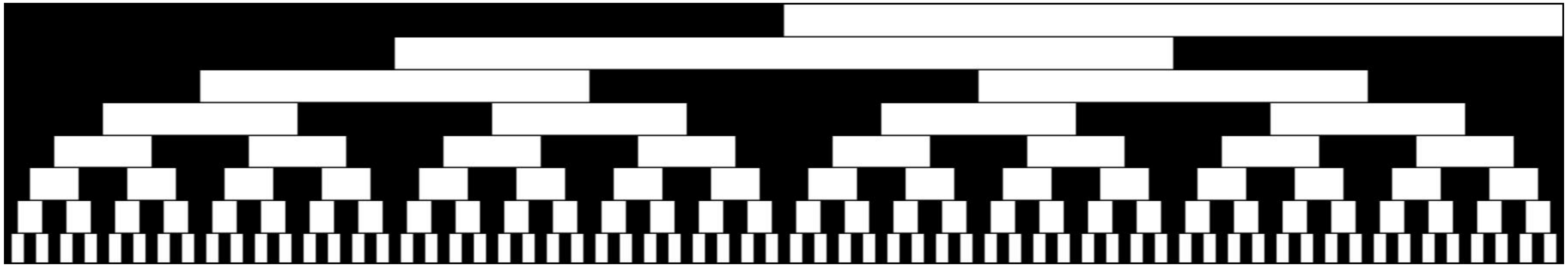
A = 1 1 1 C = 1 0 0
B = 1 1 0 D = 0 1 1

Temporal Coding

- Binary Code

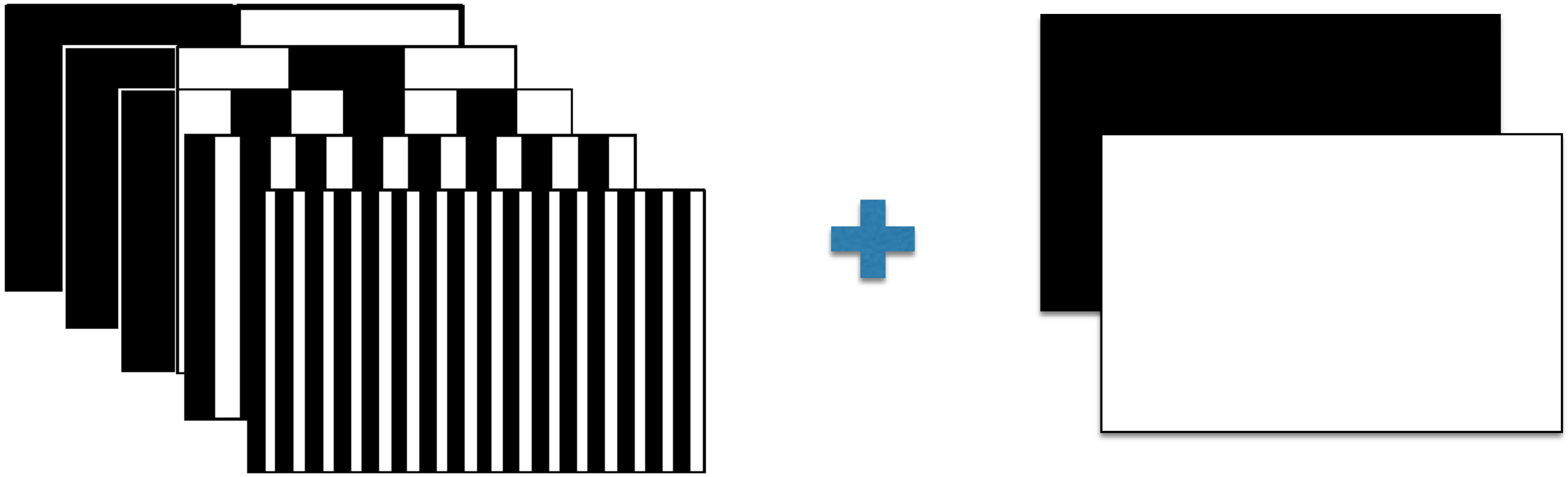


- Gray Code – Neighboring columns differ by one bit then more robust to decoding error



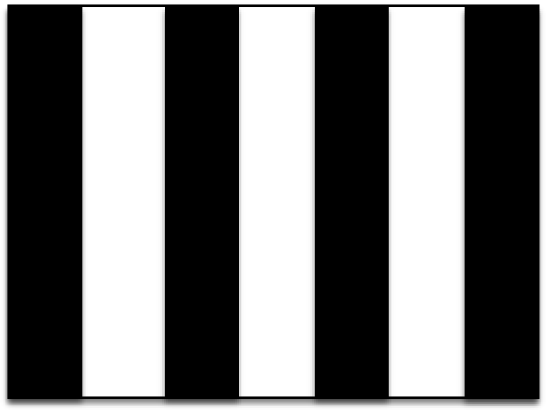
Temporal Coding

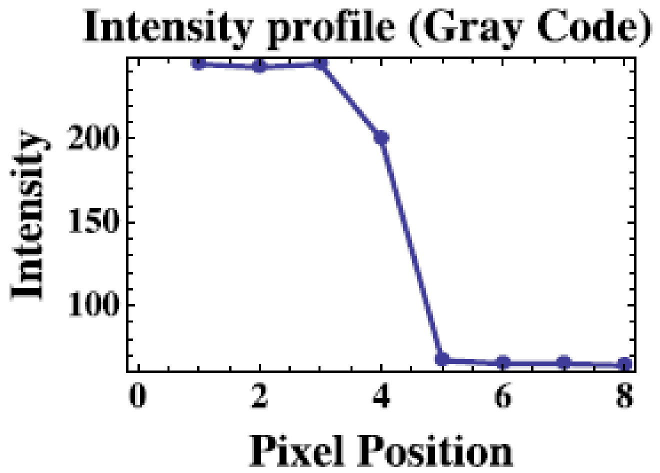
- Location of the stripes
  - Simple thresholding - Per-pixel threshold as average of two images acquired with all-white and all-black patterns – Pixel accuracy

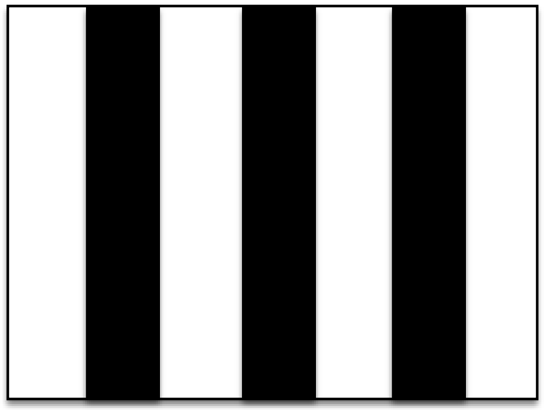


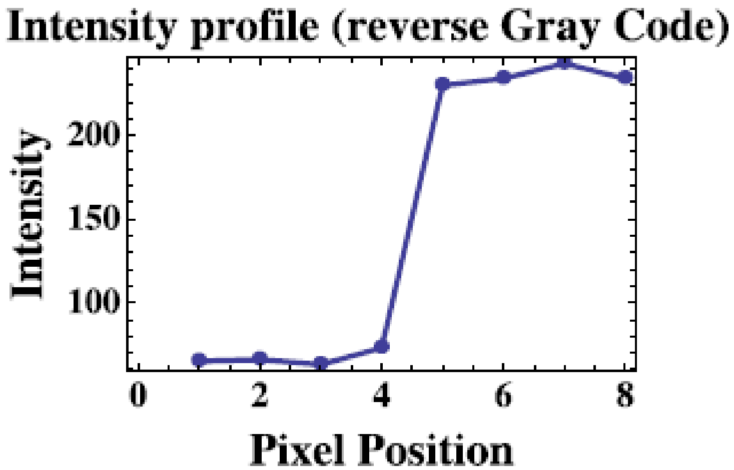
Temporal Coding

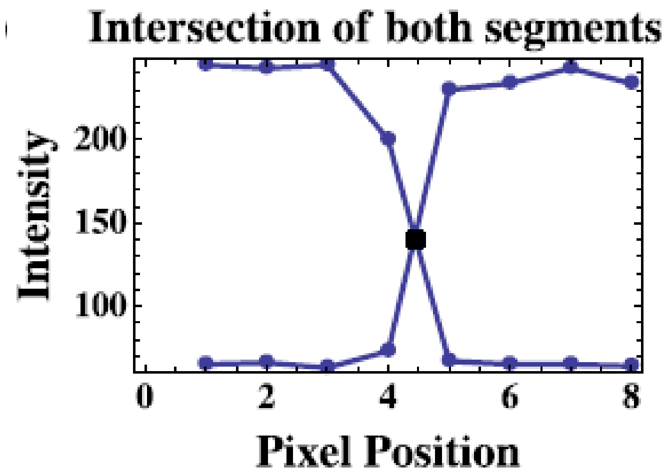
- Location of the stripes
  - Projection of Gray code and reserve Gray code and intersection of the relative intensity profile- Sub-pixel accuracy











[Drouin et al., 2012]

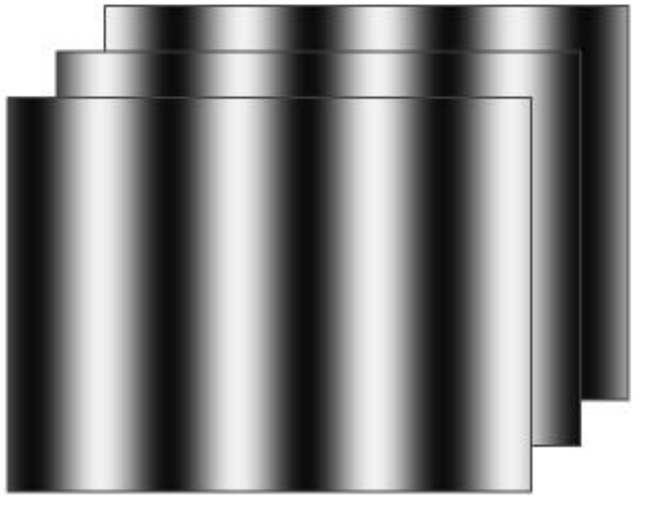
Temporal Coding

- N-ary code – Reduce the number of patterns by increasing the number of intensity levels used to encode the stripes.

Temporal Coding

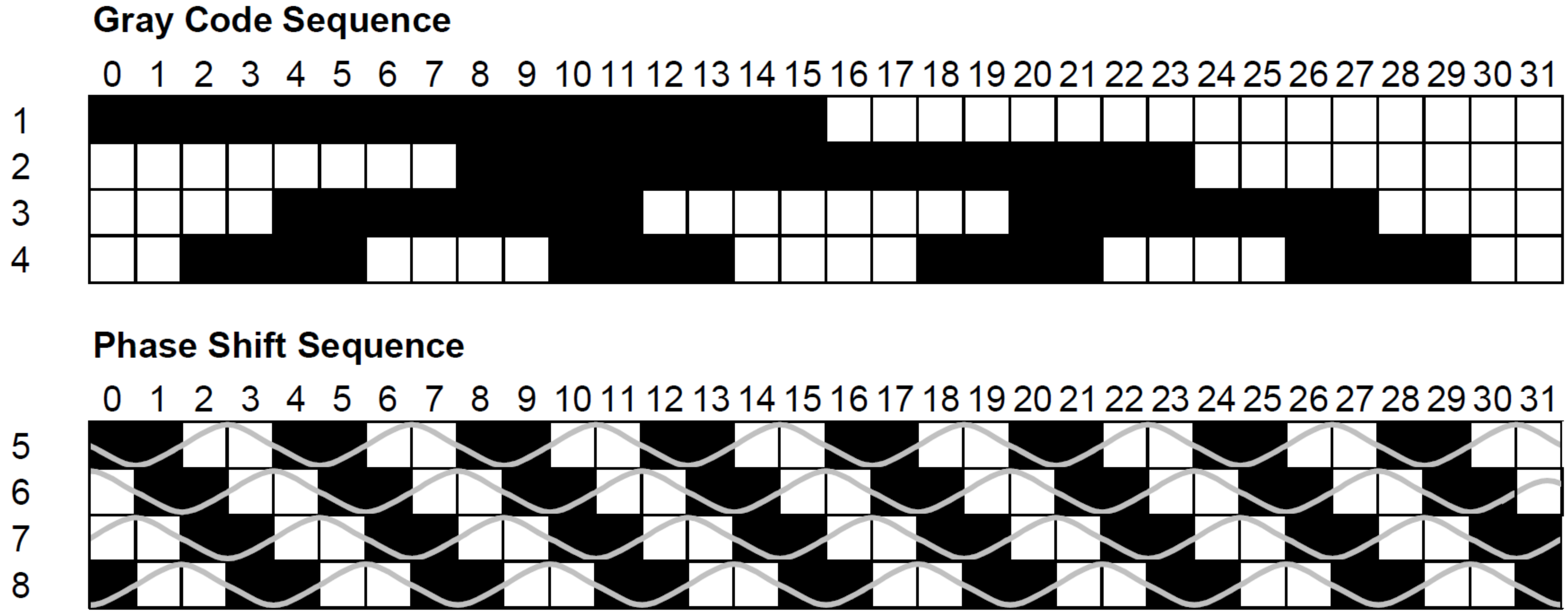
- Phase Shift
  - Projection of a set of sinusoidal pattern shifted of a constant angle
  - High resolution than Gray code
  - Ambiguity problem due the periodic nature of the pattern

$$I(x) = A + B\cos\left(\frac{2\pi}{\omega}(x \bmod \omega) - \theta\right)$$



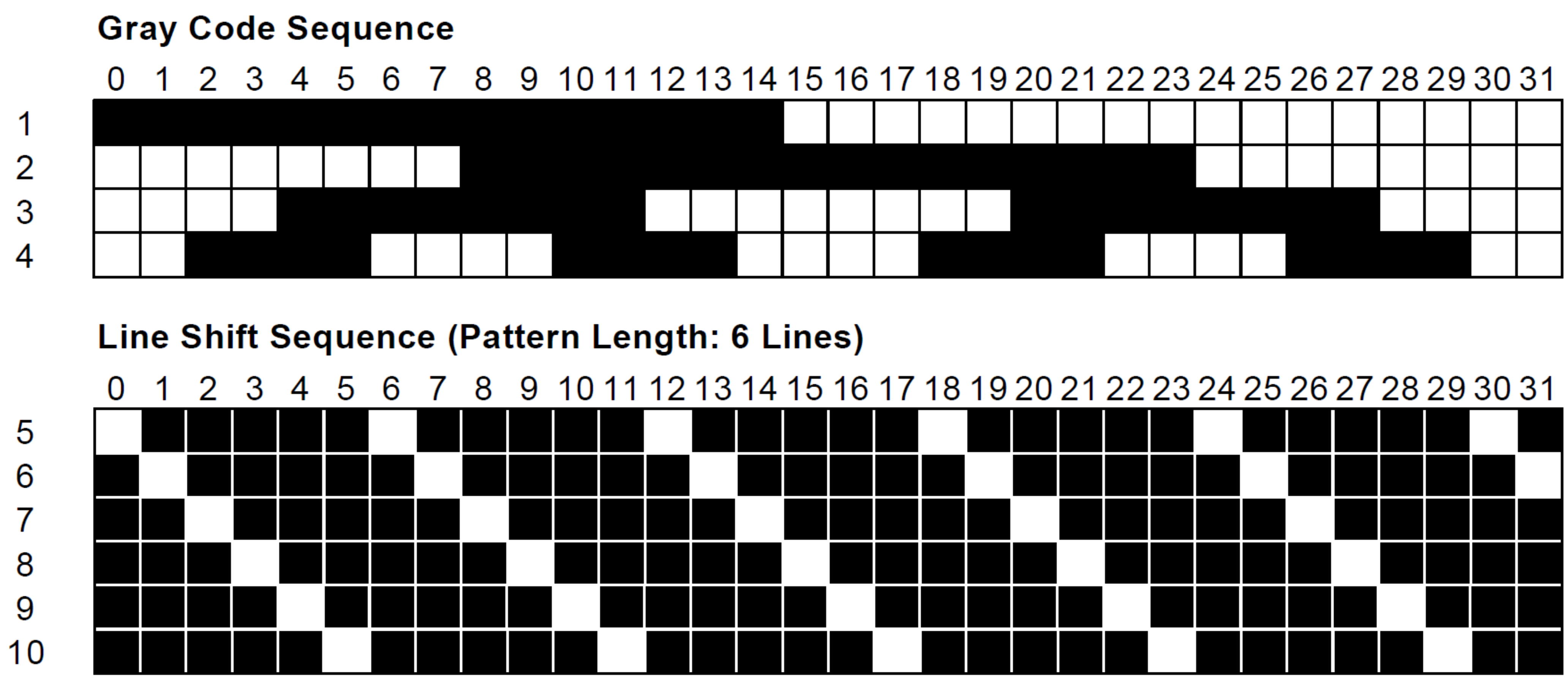
Temporal Coding

- Gray Code + Phase Shift [Gühring , 2000]
  - Corse correspondence projector-camera with Gray code to remove ambiguity
  - Refinement with phase shift
  - Problem with non-constant albedo surface



Temporal Coding

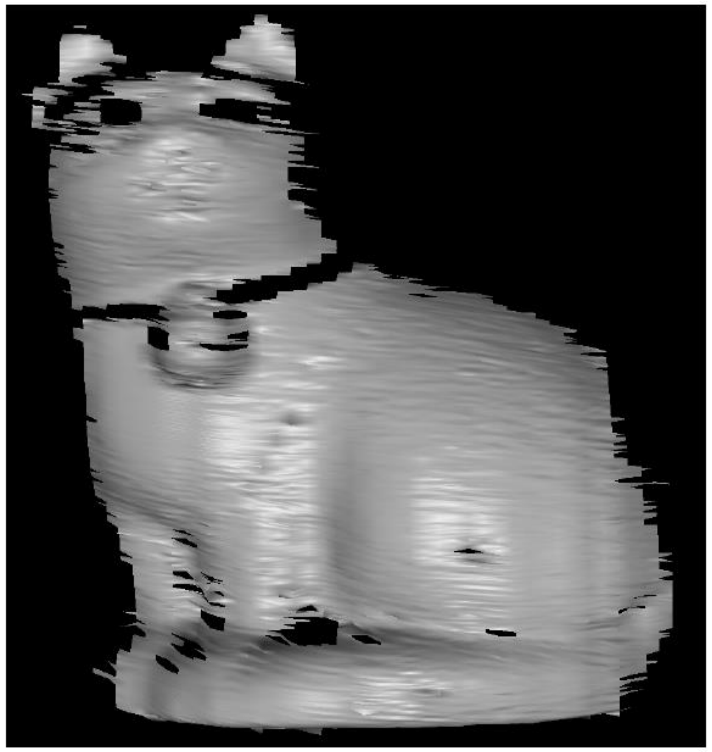
- Gray Code + Line Shift [Gühring , 2000]
  - Substitution the sinusoidal pattern with a pattern of equally spaced vertical line



Spatial Coding

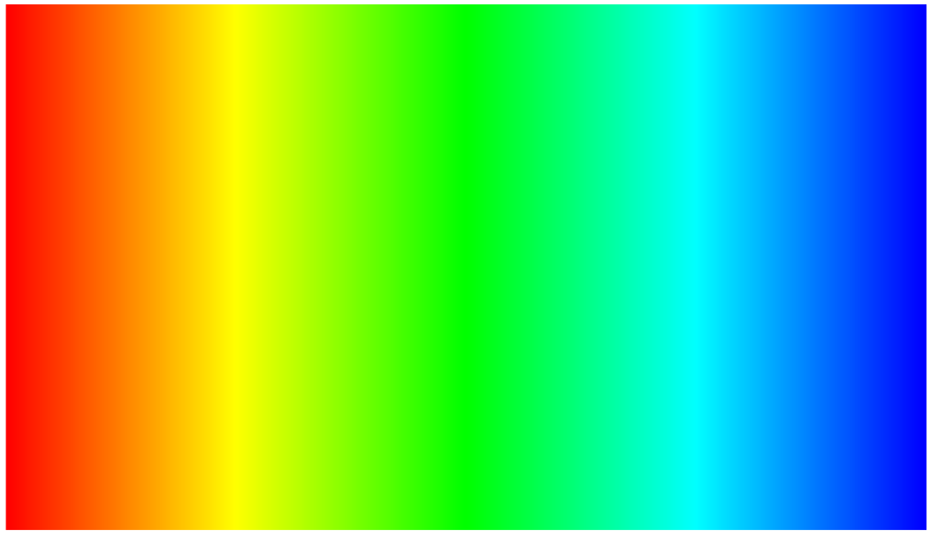
- The label of a point of the pattern is obtained from a neighborhood around it.
- The decoding stage more difficult since the spatial neighborhood cannot always be recovered (fringe not visible from the camera due to occlusion)

[Zhang et al., 3DPVT 2002]

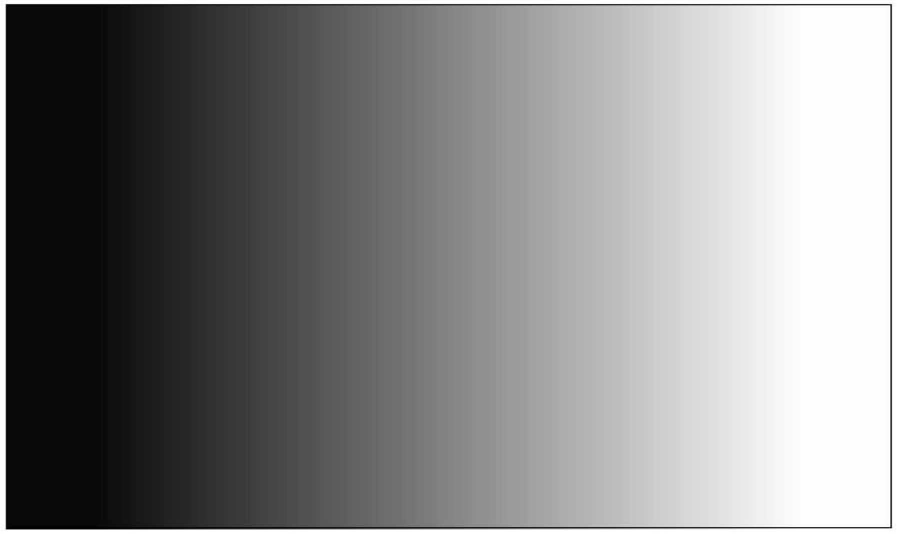


Direct Coding

- Every encoded pixel is identified by its own intensity/color
- The spectrum of intensities/colors used is very large
- Sensible to the reflective properties of the object, low accuracy, need accurate calibration

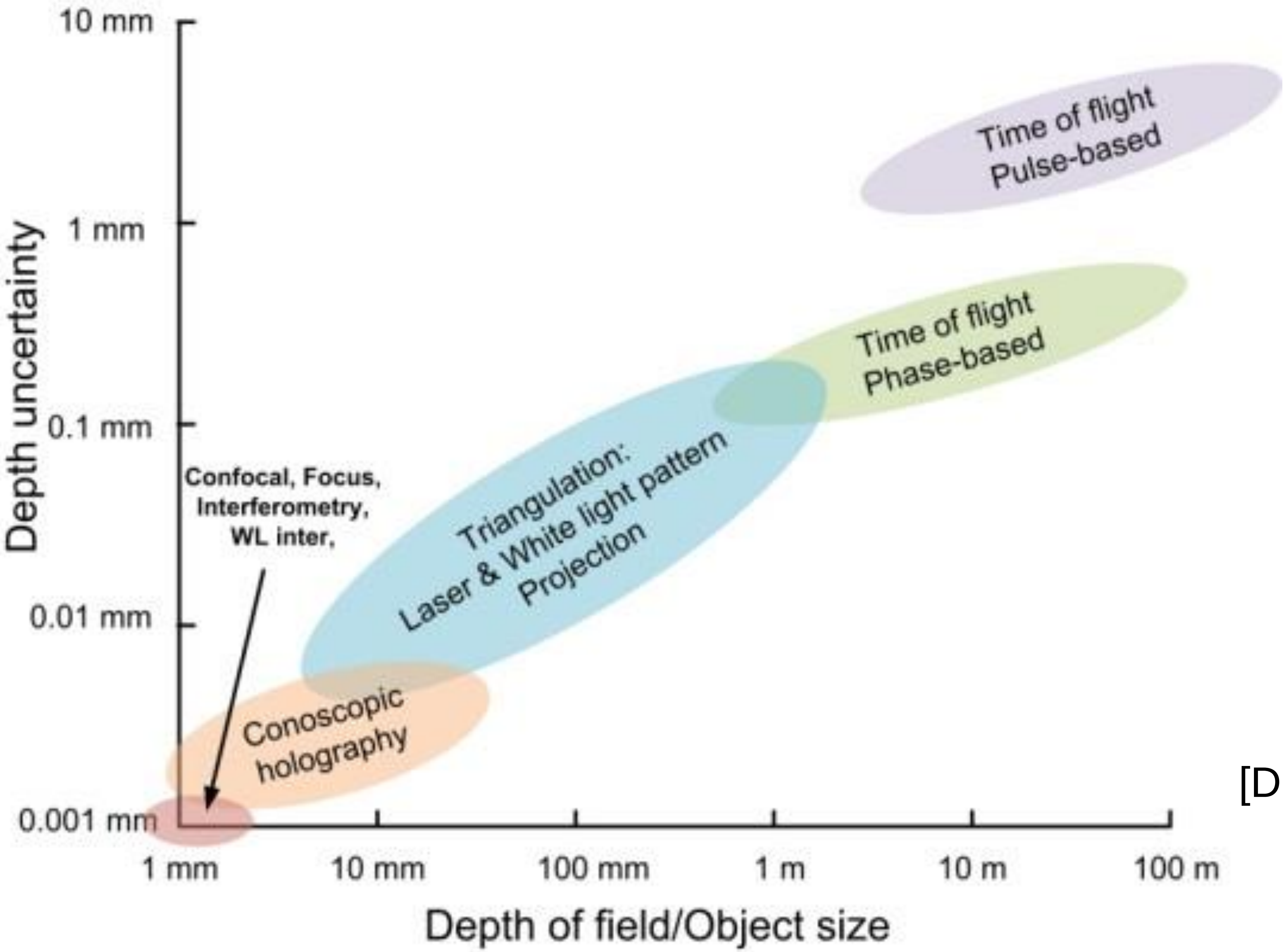


RAINBOW PATTERN



GREY LEVEL SCALE PATTERN

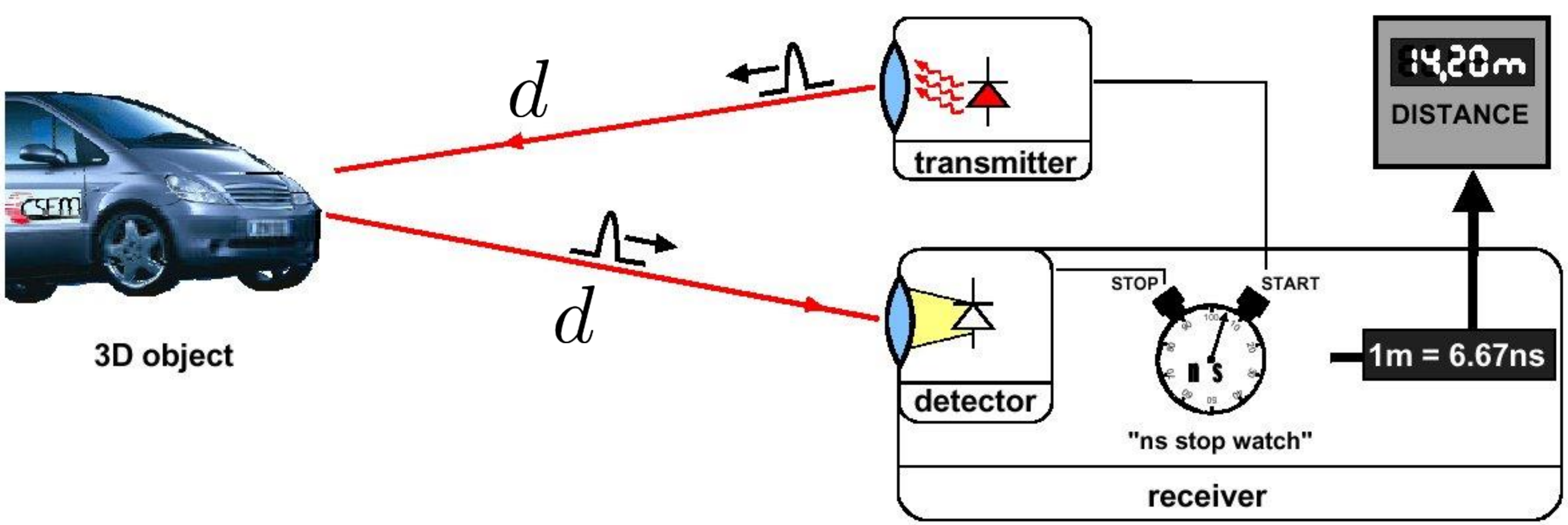
Time of Flight



[Drouin et al., 2012]

Pulse-based Time of Flight Scanning

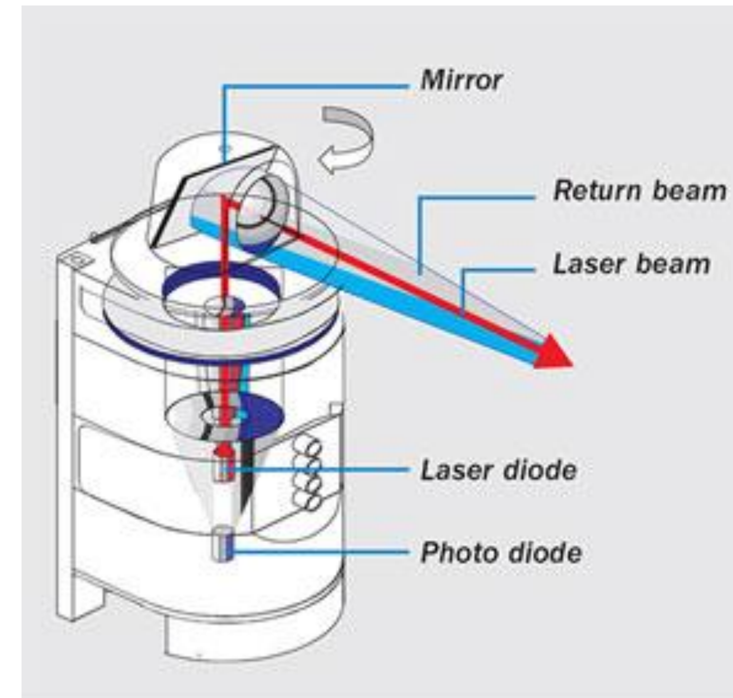
- Measure the time a light impulse needs to travel from emitter to target
  - Source: emits a light pulse and starts a nanosecond watch (1m = 6.67ns
  - Sensor: detects the reflected light, stops the watch (roundtrip time)



$$d = c\frac{\Delta t}{2}$$

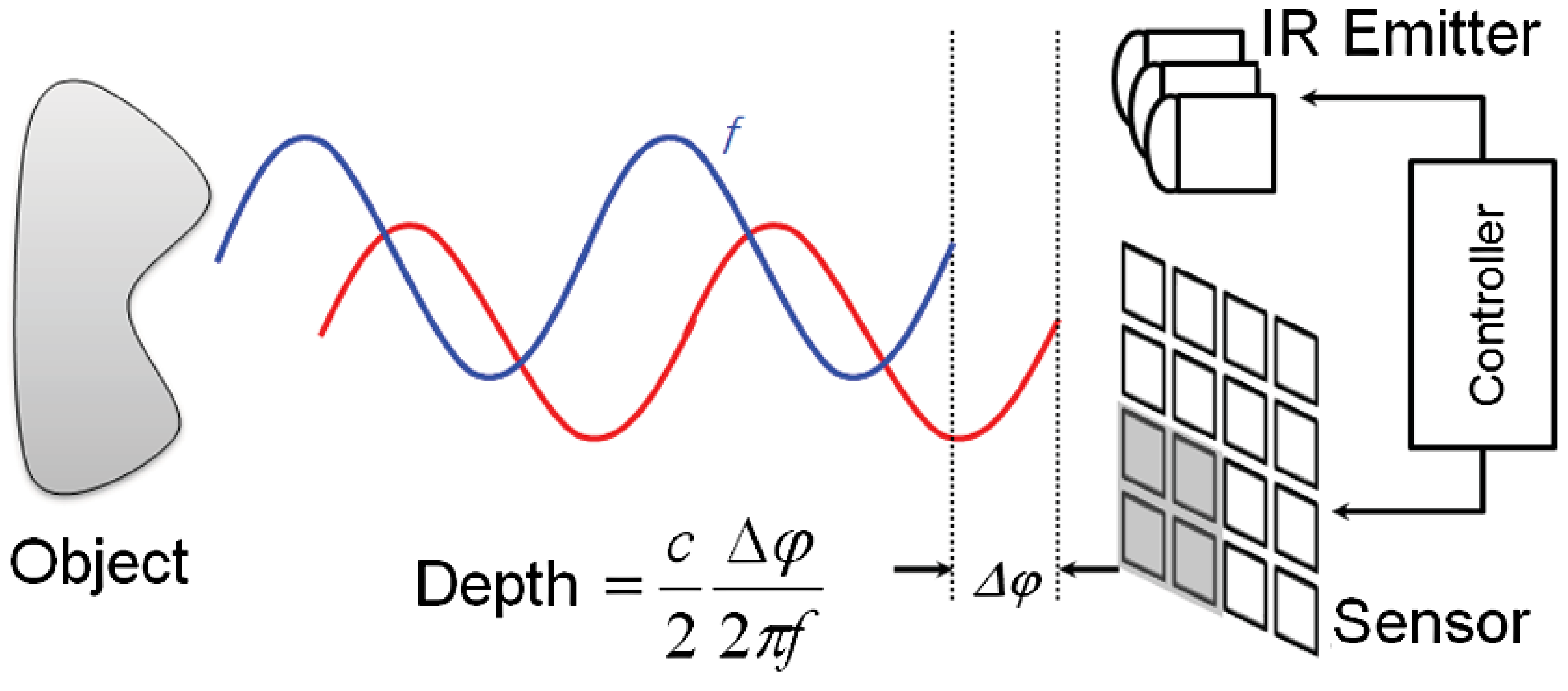
Pulse-based Time of Flight Scanning

- Scanning
  - Single spot measure
  - Range map obtained by rotating mirrors or motorized 2 DOF head
- Advantages
  - No triangulation, source and detector on the same axis (no shadow effect)



Phase-based Time of Flight Scanning

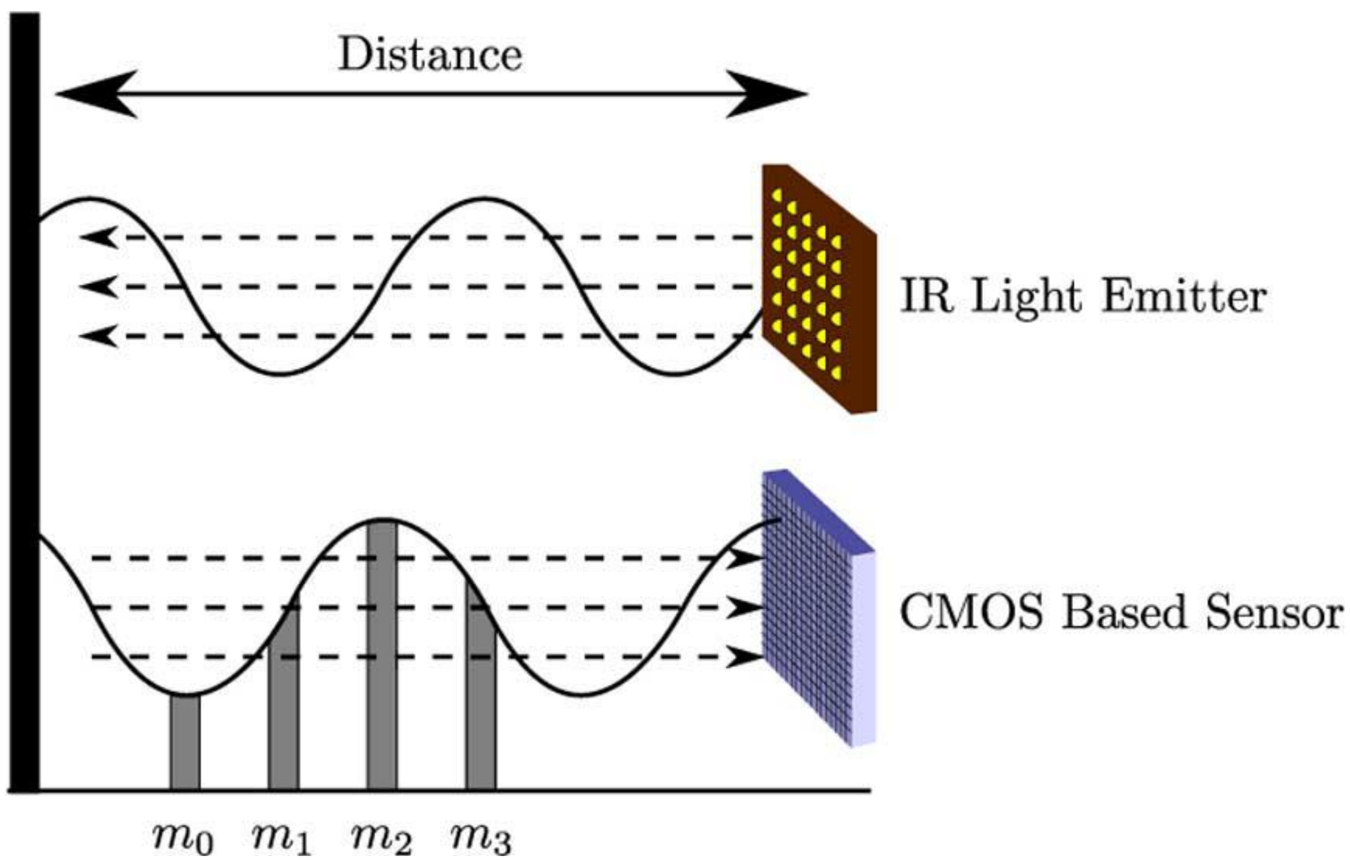
- A laser beam with sinusoidal modulated optical power is sent to a target. The phase of the reflected light is compared with that of the sent light



Phase-based Time of Flight Scanning

[Foix et al., 2011]

- Ambiguity of the phase shift. When $\Delta\phi = 2\pi$, the unambiguous distance measurement is limited to $c/(2f)$ (e.g. with frequency 16.66 MHz a maximum distance of 9m)



$$\Delta\phi = \arctan\frac{m_3 - m_1}{m_0 - m_2}$$

Time of Flight Scanning

In principle is an easy approach, but:

- maximum distance range limited by the amount of light received by the detector (power of the emitter, environment illumination)
- accuracy depends on : optical noise, thermal noise, ratio between reflected signal intensity and ambient light intensity
- Accurate and fast systems are still expensive (70K-100K Euro)
- Cost depends on mechanical components (high-quality rotation unit, to span the spherical space around the scanner)

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