Week 13

光學檢測
Optical Methodologies for Mechanics and Industrial Applications

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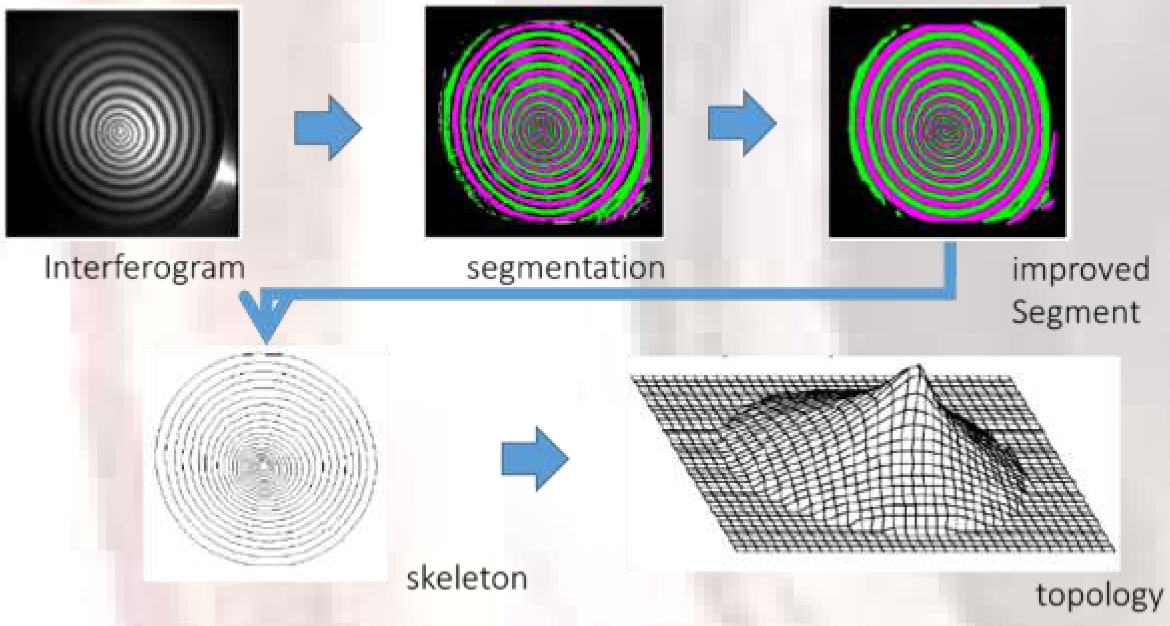
Fringe Skeleton Method

1) Intensity distribution
   1. Identification of local extrema
   2. Fringe sampling points for interpolation
2) determination of points with integer or half-integer order of interference
3) absolute order has to be identified additionally
4) Relatively low accuracy of phase measurements



Processing:

① improvement of SNR by spatial and temporal filtering
② creation of the skeleton (segmentation)
③ improvement of the skeleton shape
④ numbering the fringes
⑤ reconstruction of the phase by interpolation

Phase estimation methods

General Form of Fringe Patterns

$$\boxed{I(x,y)} = \boxed{a(x,y)} + \boxed{b(x,y)} \cos \boxed{\delta(x,y)}$$

Fringe Pattern — Measurable

Averaged/ Background — Unknown

Contrast of the fringes — Unknown

Phase to be Determined — Unknown

Imaging System & Object transmittance, Reflectivity…

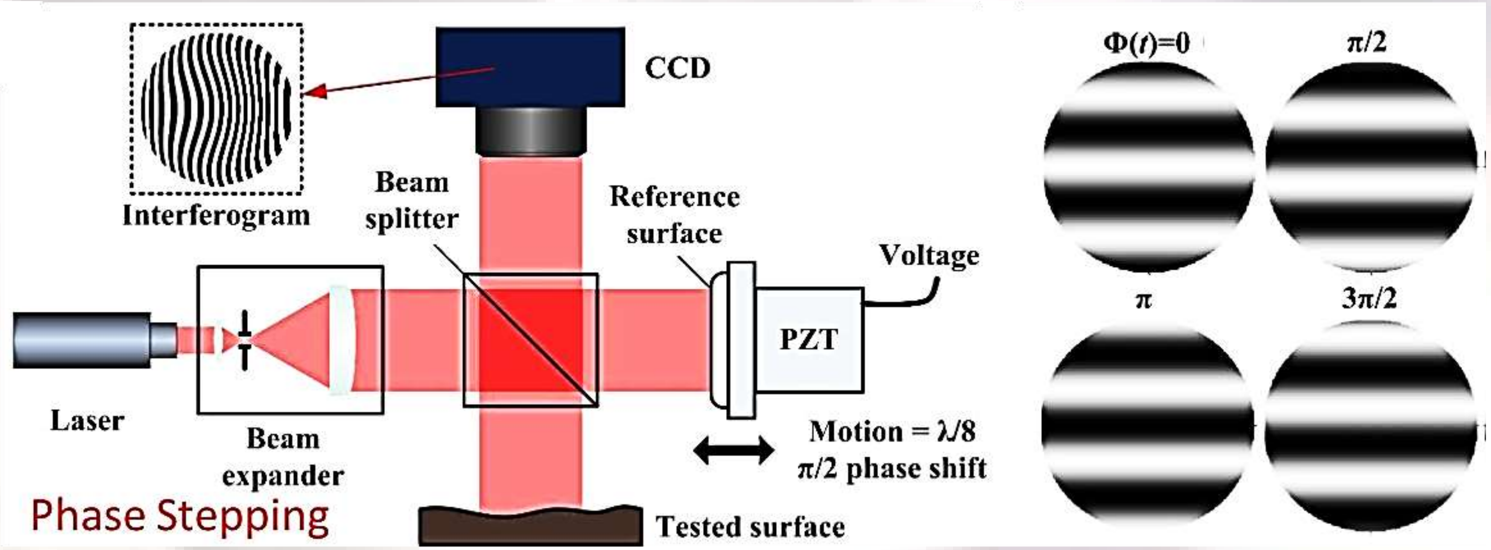
Parameters to be Measured

Generating More Information (measureable) for determining unknown parameters

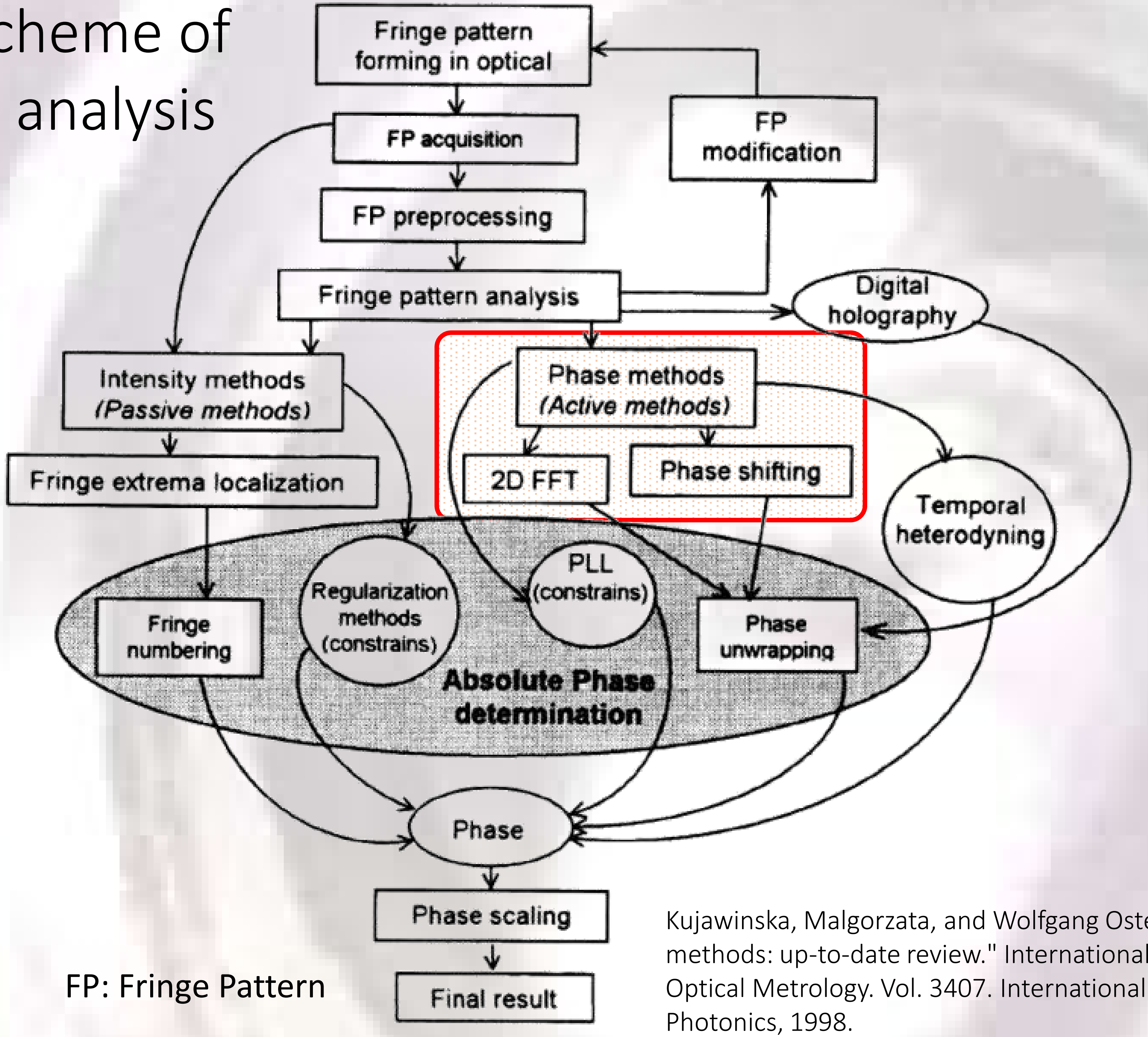
FRINGE ANALYSIS

PHASE ESTIMATION METHODS

…



The general scheme of fringe pattern analysis process



FP: Fringe Pattern

Kujawinska, Malgorzata, and Wolfgang Osten. "Fringe pattern analysis methods: up-to-date review." International Conference on Applied Optical Metrology. Vol. 3407. International Society for Optics and Photonics, 1998.

Direct Method

$$\boxed{I(x,y)} = \boxed{a(x,y)} + \boxed{b(x,y)} \cos \boxed{\delta(x,y)}$$

Fringe Pattern	Averaged/ Background	Contrast of the fringes	Phase to be Determined
Measurable	**Unknown**	**Unknown**	**Unknown**

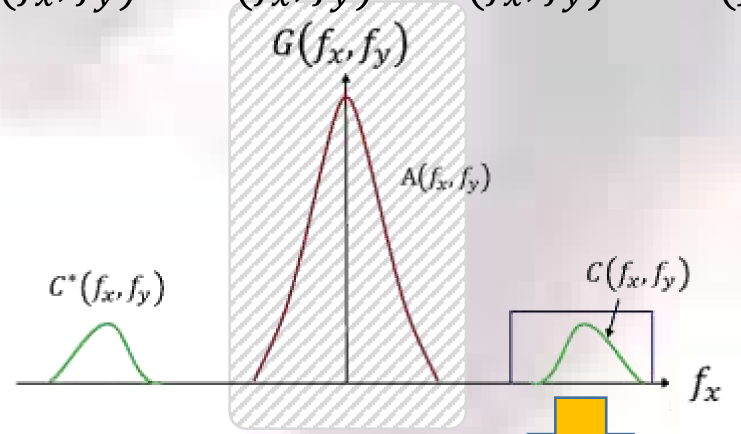
$$I(x,y) = a(x,y) + b(x,y)\cos\delta(x,y)$$
$$= a(x,y) + \boxed{\frac{1}{2}b(x,y)e^{i\delta(x,y)}} + \frac{1}{2}b(x,y)e^{-i\delta(x,y)}$$

$$\frac{1}{2}b(x,y)(\cos\delta + i\sin\delta) = Re\left[\frac{b(x,y)}{2}e^{i\delta}\right] + Im\left[\frac{b(x,y)}{2}e^{i\delta}\right]$$

$$\delta = \tan^{-1}\frac{Im\left[\frac{b(x,y)}{2}e^{i\delta}\right]}{Re\left[\frac{b(x,y)}{2}e^{i\delta}\right]}$$

Fourier Transform to 2D frequency Domain

$$\mathcal{F}(I(x,y)) = G(f_x, f_y)$$
$$\Rightarrow$$
$$G(f_x, f_y) = A(f_x, f_y) + C(f_x, f_y) + C^*(f_x, f_y)$$



Shifting &
Inverse Fourier Transform

Direct Method

$$I(x,y) = a(x,y) + b(x,y)\cos\delta(x,y)$$

Fringe Pa

Measu

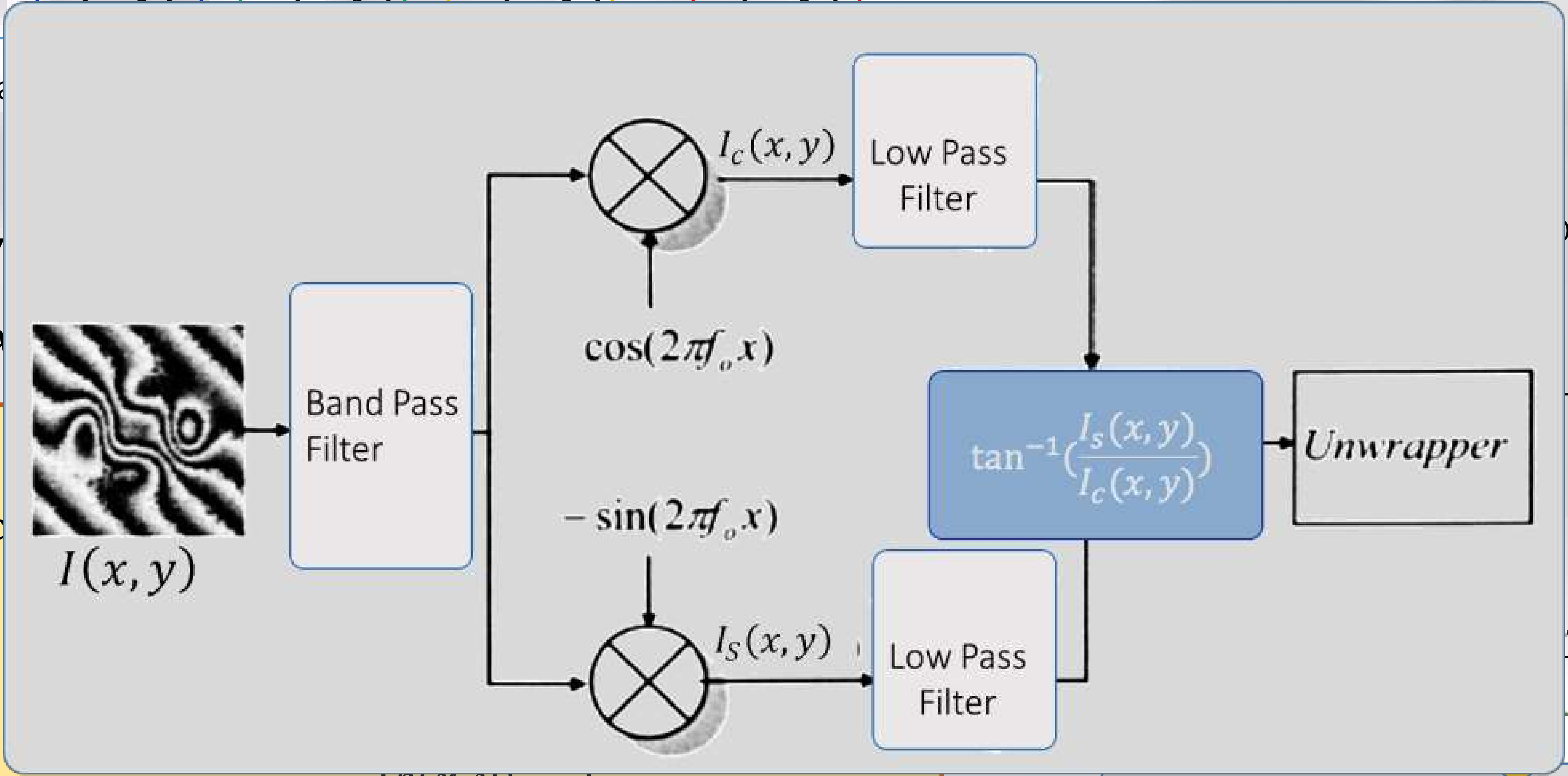
$I(x,y$

$= a(x$

omain

$C^*(f_x,f_y)$

$\frac{1}{2}b(x,y)(c$



$, f_y)$

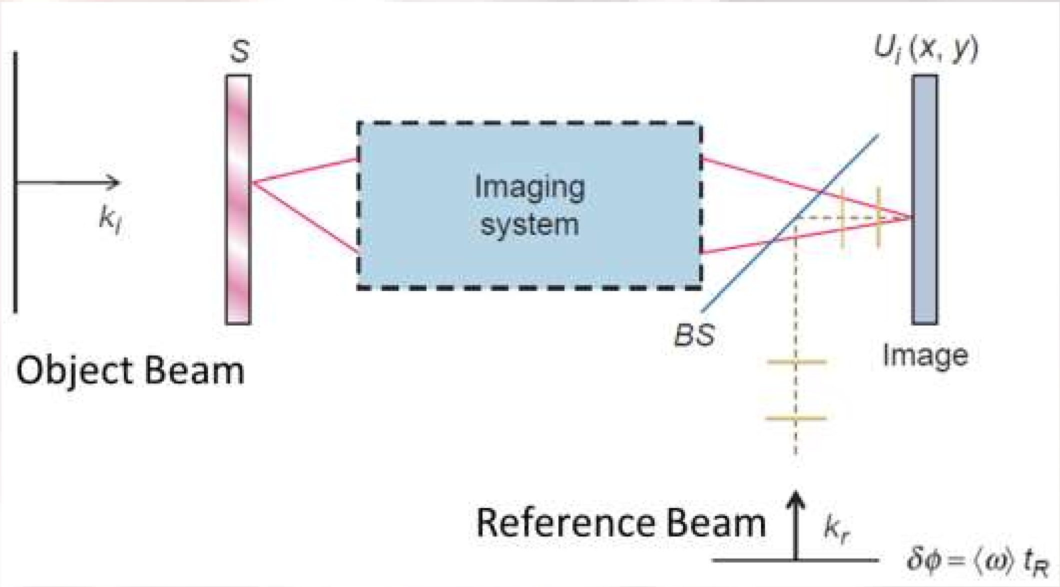
f_x

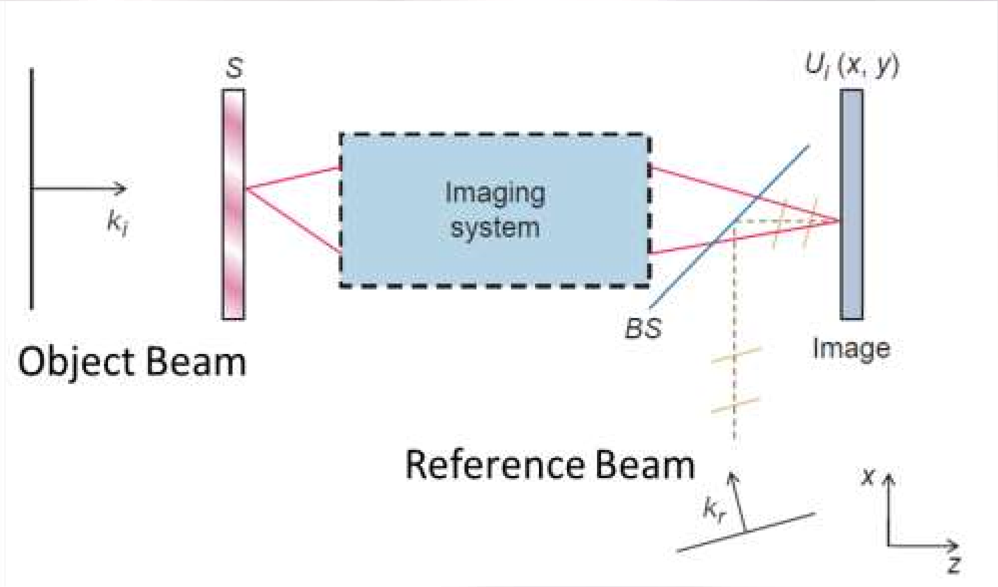
$Re\left[\frac{b(x,y)}{2}e^{i\delta}\right]$

Shifting &
Inverse Fourier Transform

Phase estimation methods

- **Temporal Phase Shifting**
  Phase shift introduced between the test and reference beams as a function of time
- **Spatial Phase Shifting**
  1) Phase shift data obtained from a single interferogram that requires a carrier pattern of almost straight fringes to either compare phases of adjacent pixels or to separate orders while performing operations in the Fourier domain.
  2) Simultaneously record multiple interferograms with appropriate relative phase shift differences separated spatially in space.





Temporal phase shifting

The phase modulation needs to generate linear and uniform phases over the field of view during the exposure time of the detector.

$$\varphi = 2\pi f t$$

$$\Longrightarrow I(x,y;t) = a(x,y) + b(x,y)\cos(\delta(x,y) + \varphi(t))$$

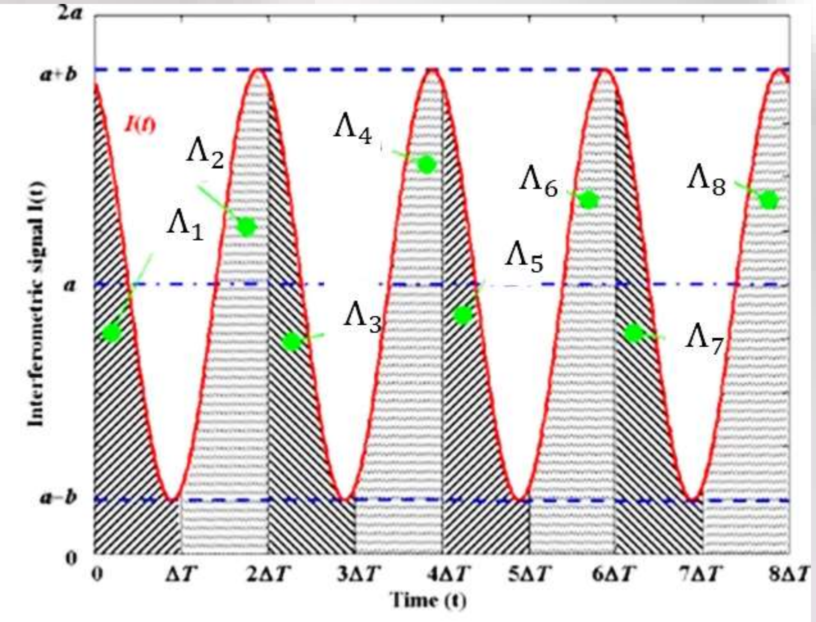
Each image is obtained by integrating over a time interval ΔT

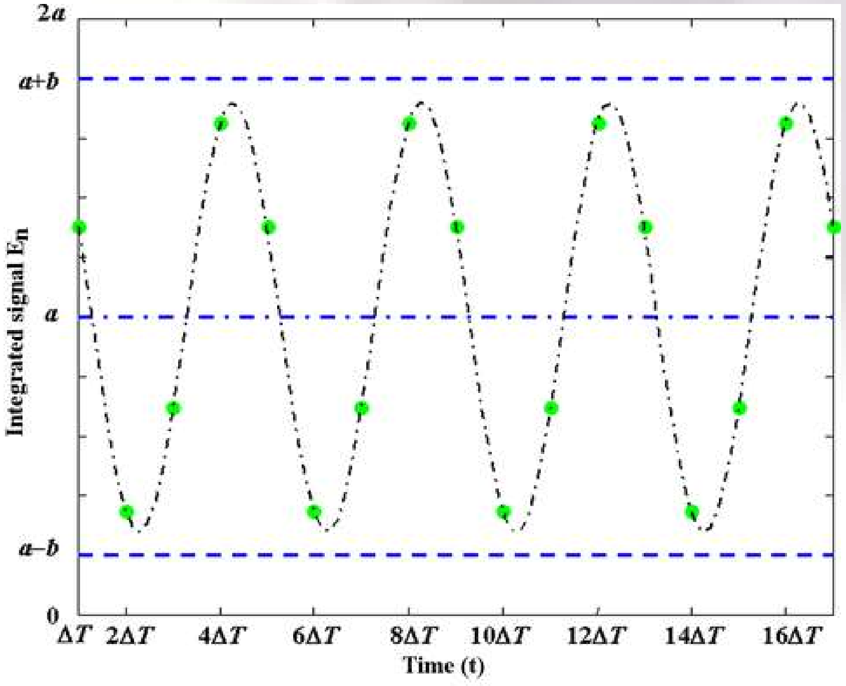
$$\Longrightarrow \Lambda_n = \frac{1}{\Delta T}\int_{(n-1)\Delta T}^{n\Delta T} I(x,y;t)dt$$

$$= a(x,y) + b(x,y)\frac{1}{\Delta T}\int_{(n-1)\Delta T}^{n\Delta T} cos(\delta(x,y) + \varphi(t))dt$$

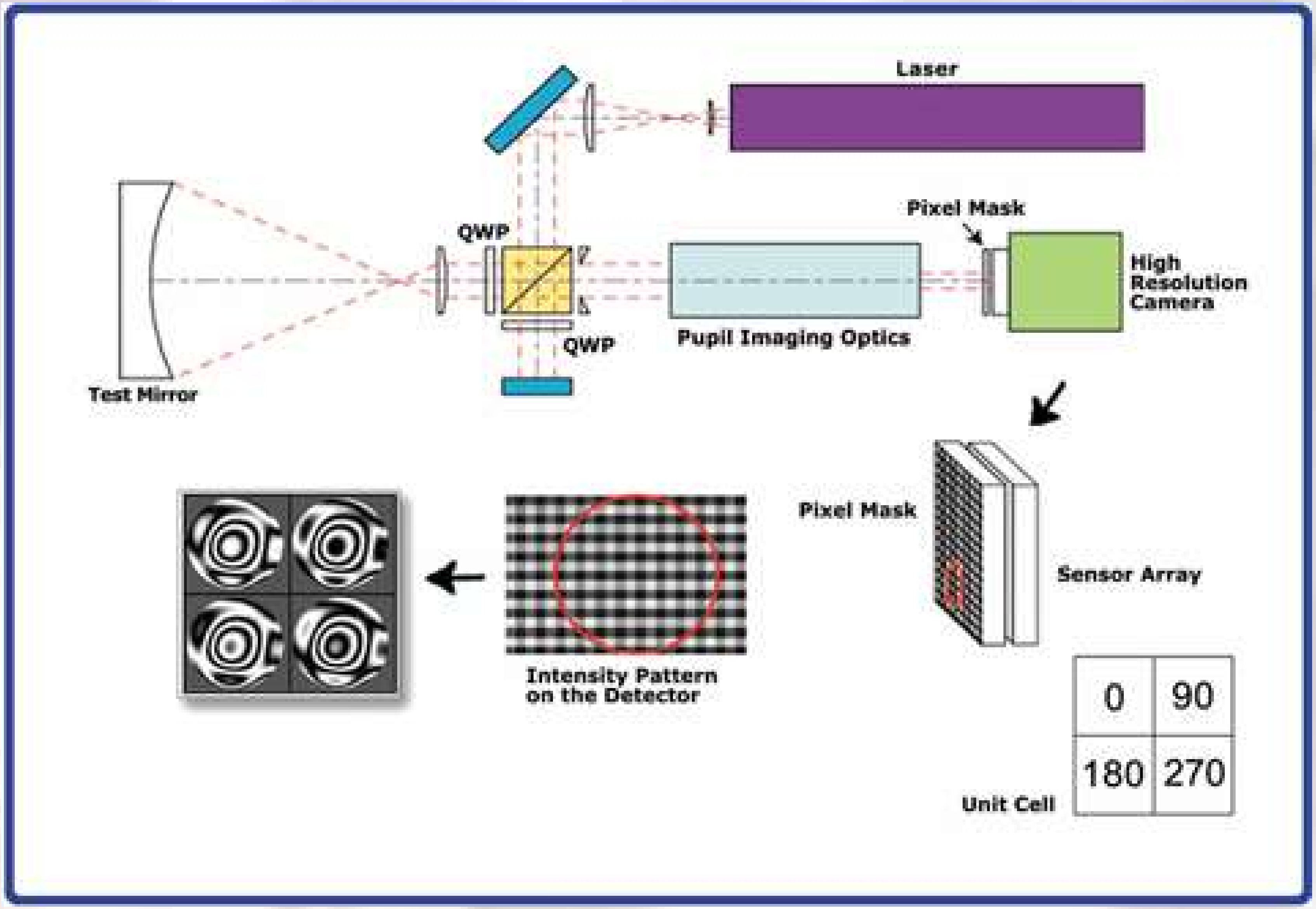
$$= a(x,y) + b(x,y)\boxed{sinc(\pi f \Delta T)}\cos\left(\delta + 2\pi\left(n - \frac{1}{2}\right)f\Delta T\right)$$

φ must be selected according to Shannon theorem thus $\varphi < \pi$





Spatial Phase-Shifting



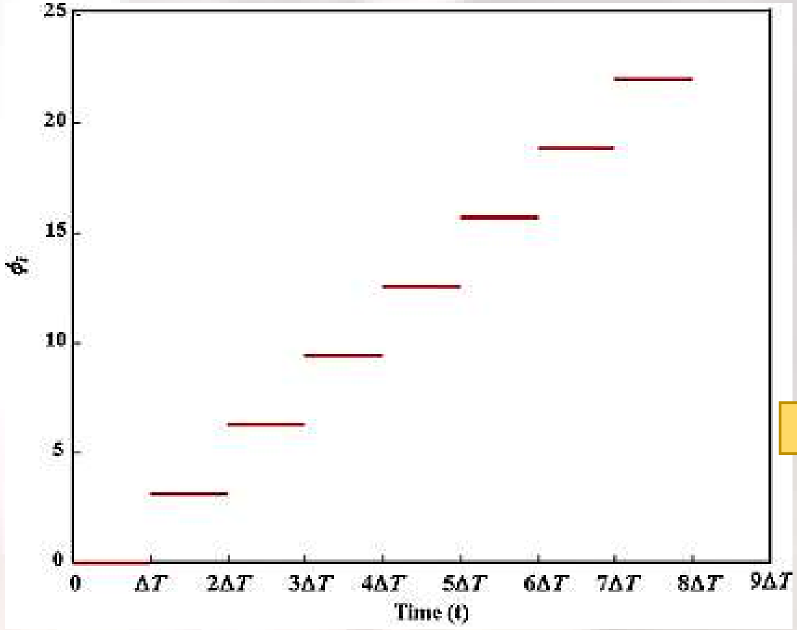
http://optiworks.jp/products_4d_phasecam6000_e.html

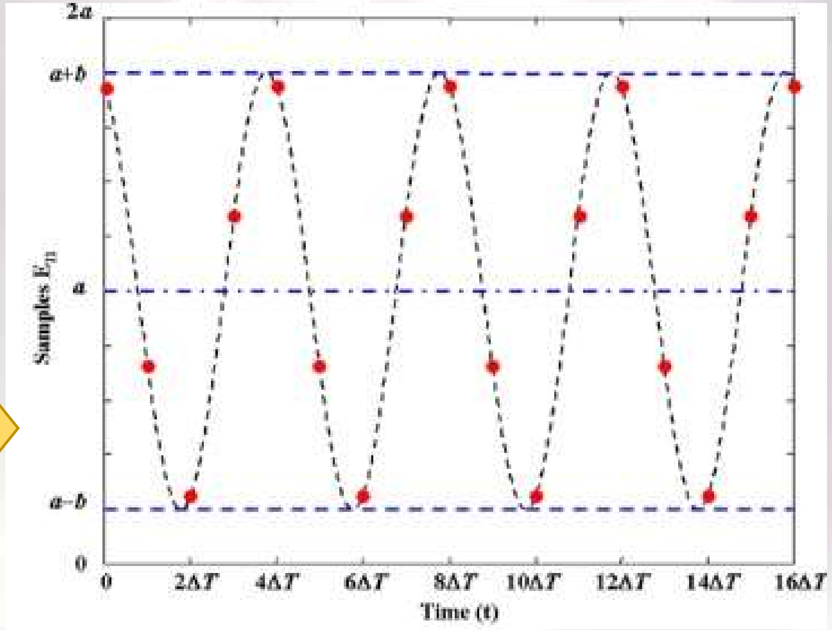
Phase Stepping

The phase modulation is a step and maintains constant during the integration time of the detector

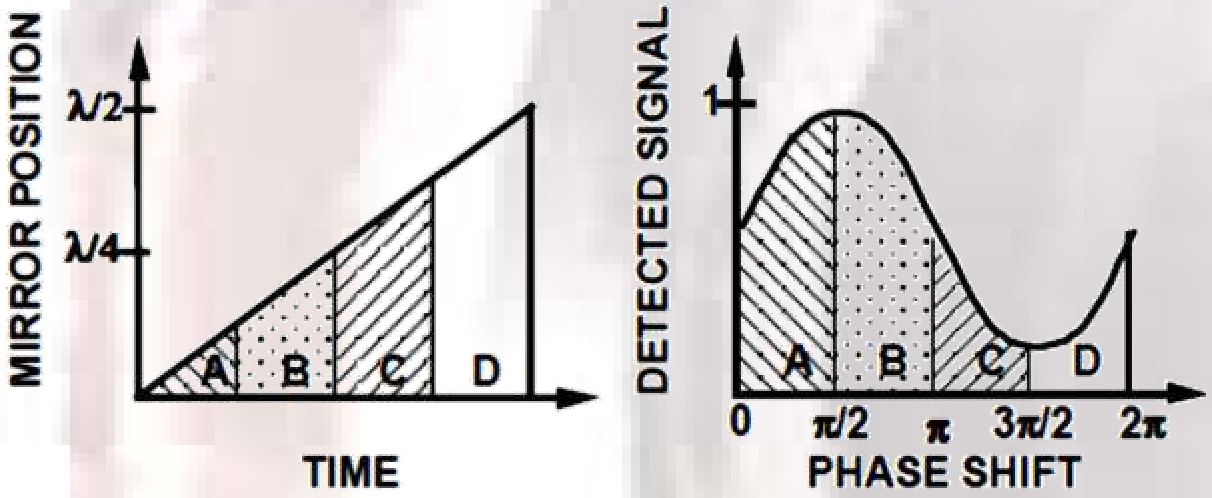
$$\varphi_n = \frac{2\pi}{N}(n-1)[u(t-(n-1)\Delta T) - u(t-n\Delta T)], n = 1, 2, \ldots$$

$$\Lambda_n = a(x,y) + b(x,y)\cos(\delta + \varphi_n)\,, n = 1, 2, \ldots$$

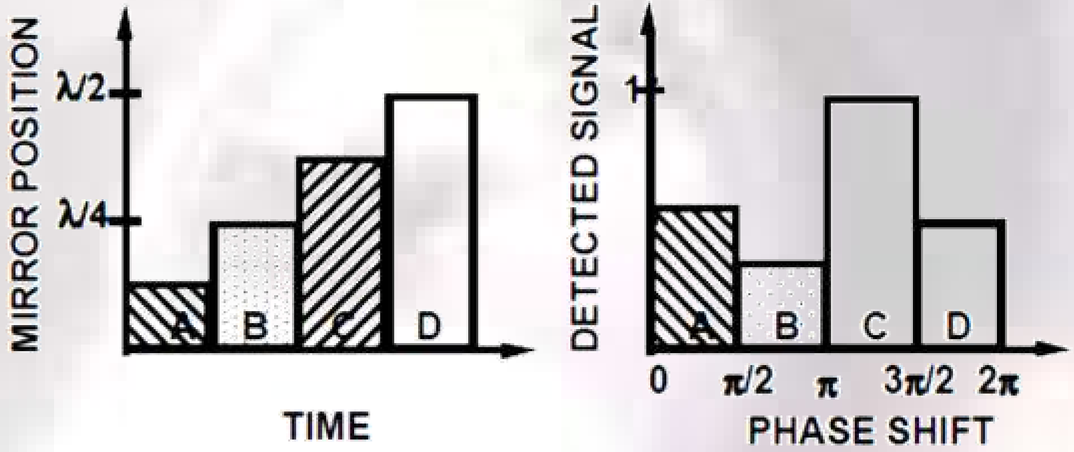




Phase Shifting vs. Phase Stepping

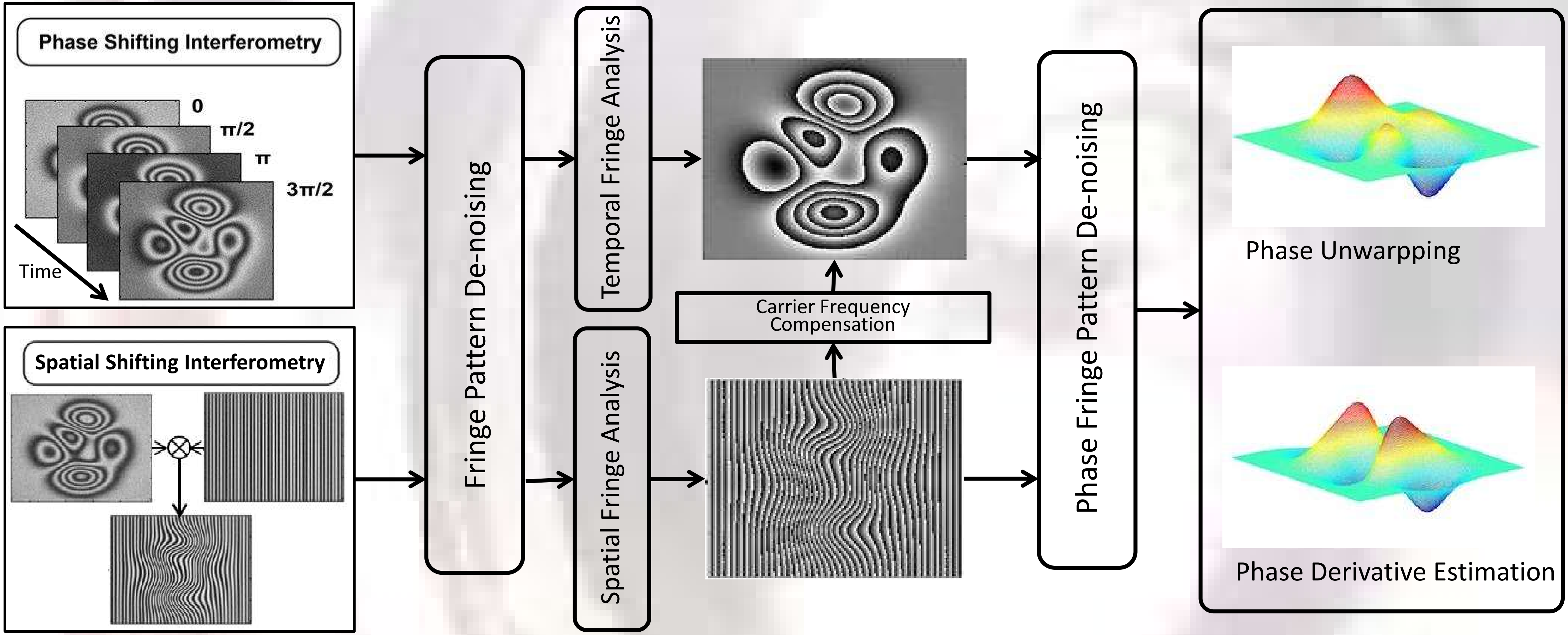


Phase Shifting

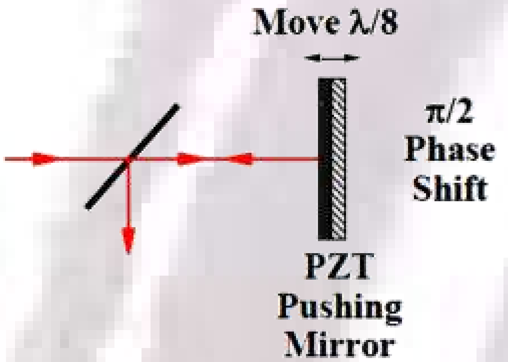


Phase Stepping

Phase estimation methods

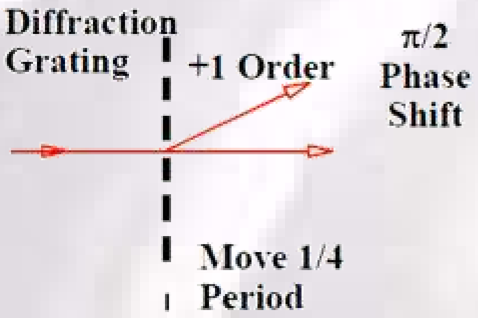


Mechanisms for Phase Shifting/ Phase Stepping



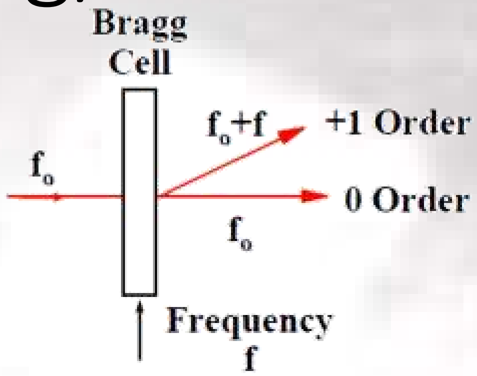
Moving Mirror

$\delta = 2 \times \lambda/8$

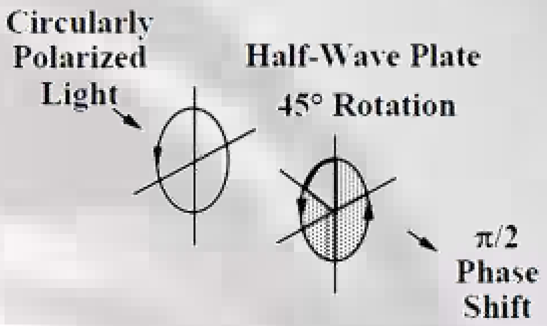


Diffraction Grating

$\delta = p/4$

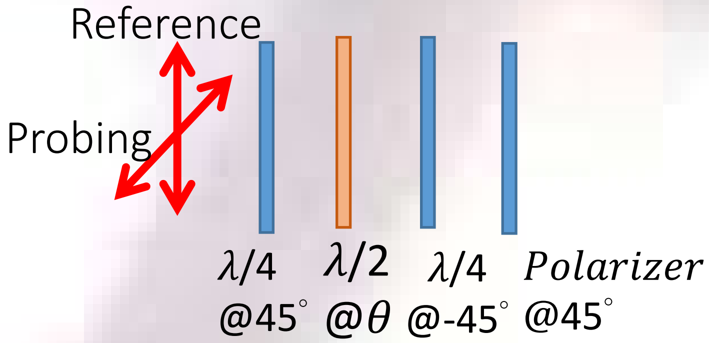


Bragg Cell/ Acousto-optical modulator



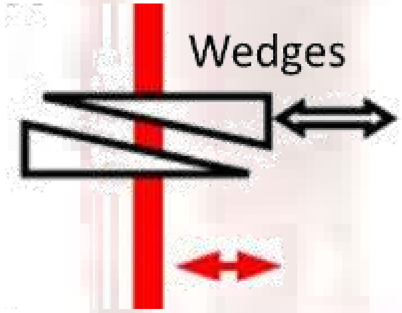
Rotating Half-Wave Plate

$\Delta\text{Ø} = 2\theta$



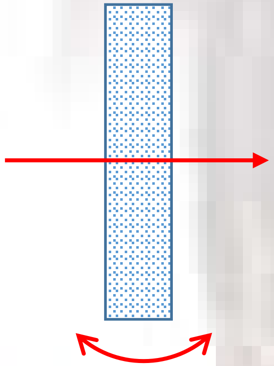
$\Delta\text{Ø} = 4\theta$

Geometric Phase Shifter

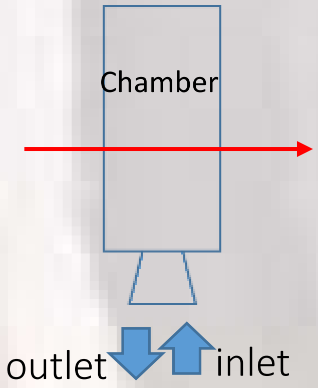


Wedge Compensator

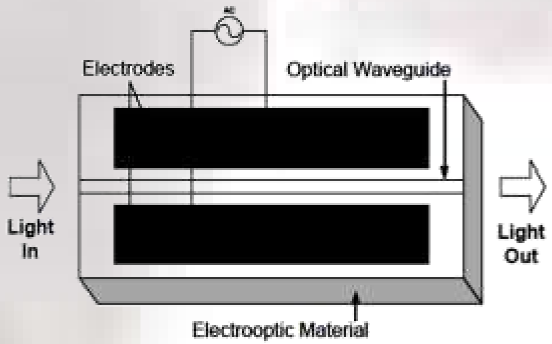
$\delta = (n-1)\Delta l \tan\theta$



Titling Plane-Parallel plate



Pressure Chamber

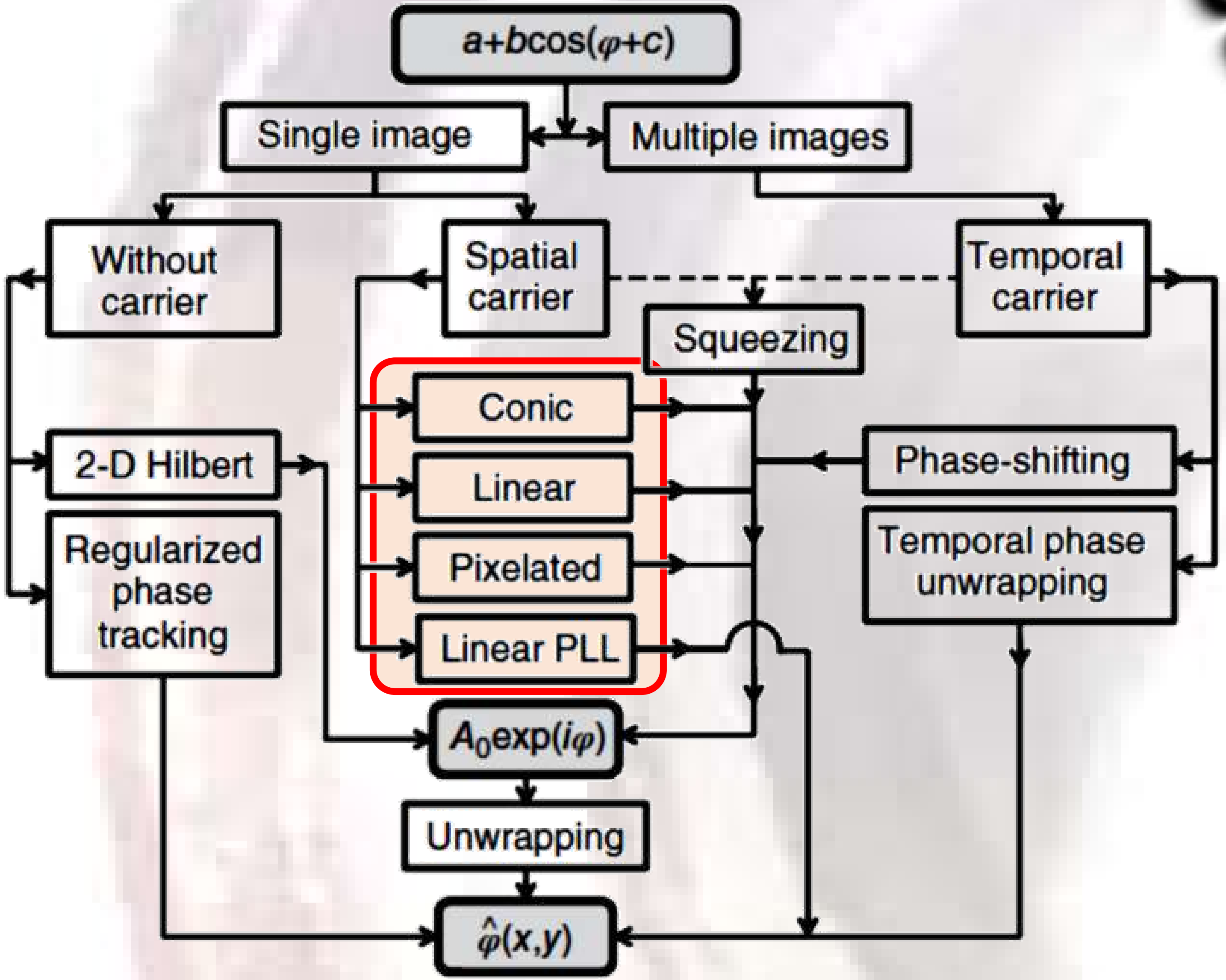


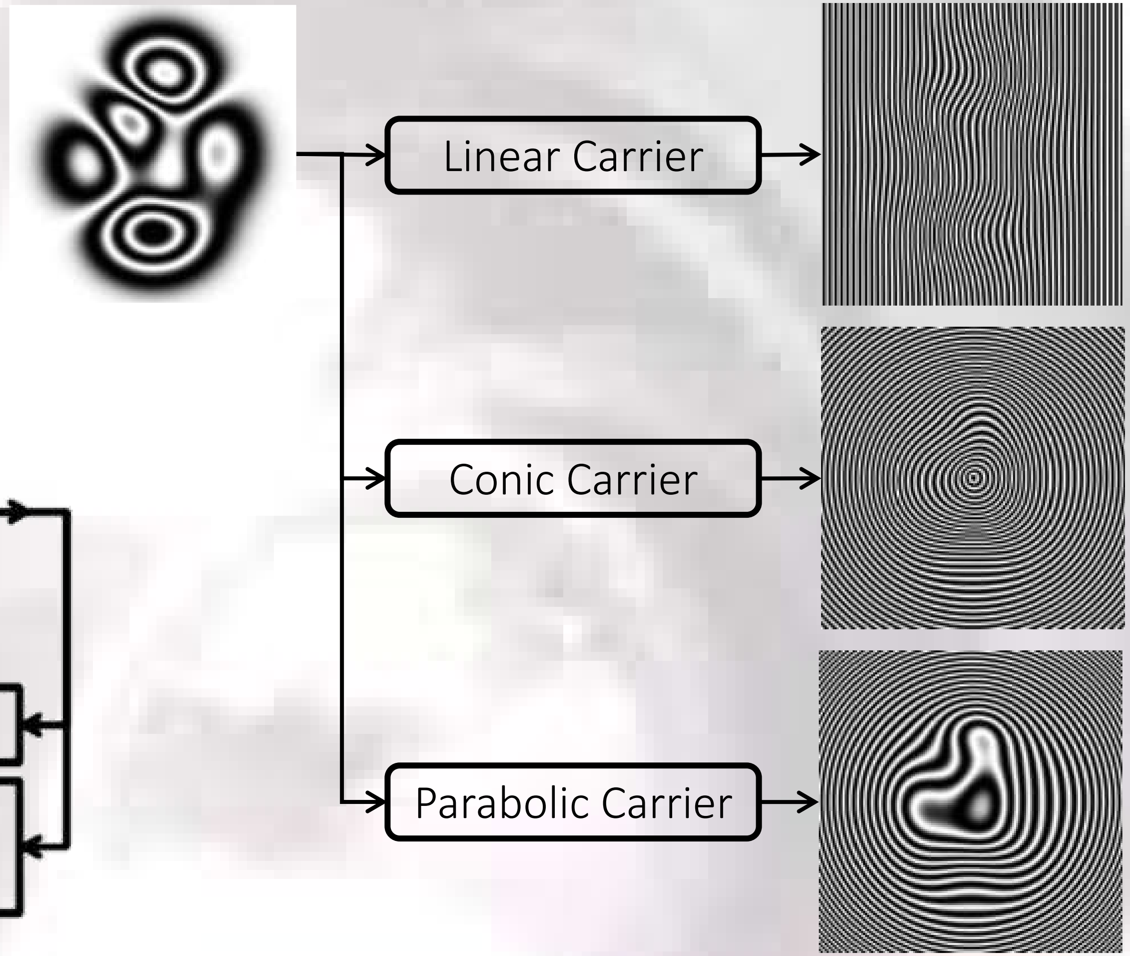
electro-optic modulator

$\varphi = n(E)koL$

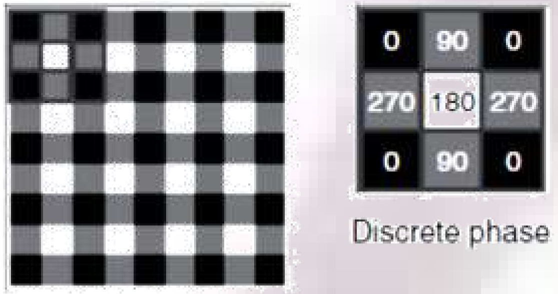
$= 2\pi n(E)L/\lambda o$

Classification of phase estimation methods

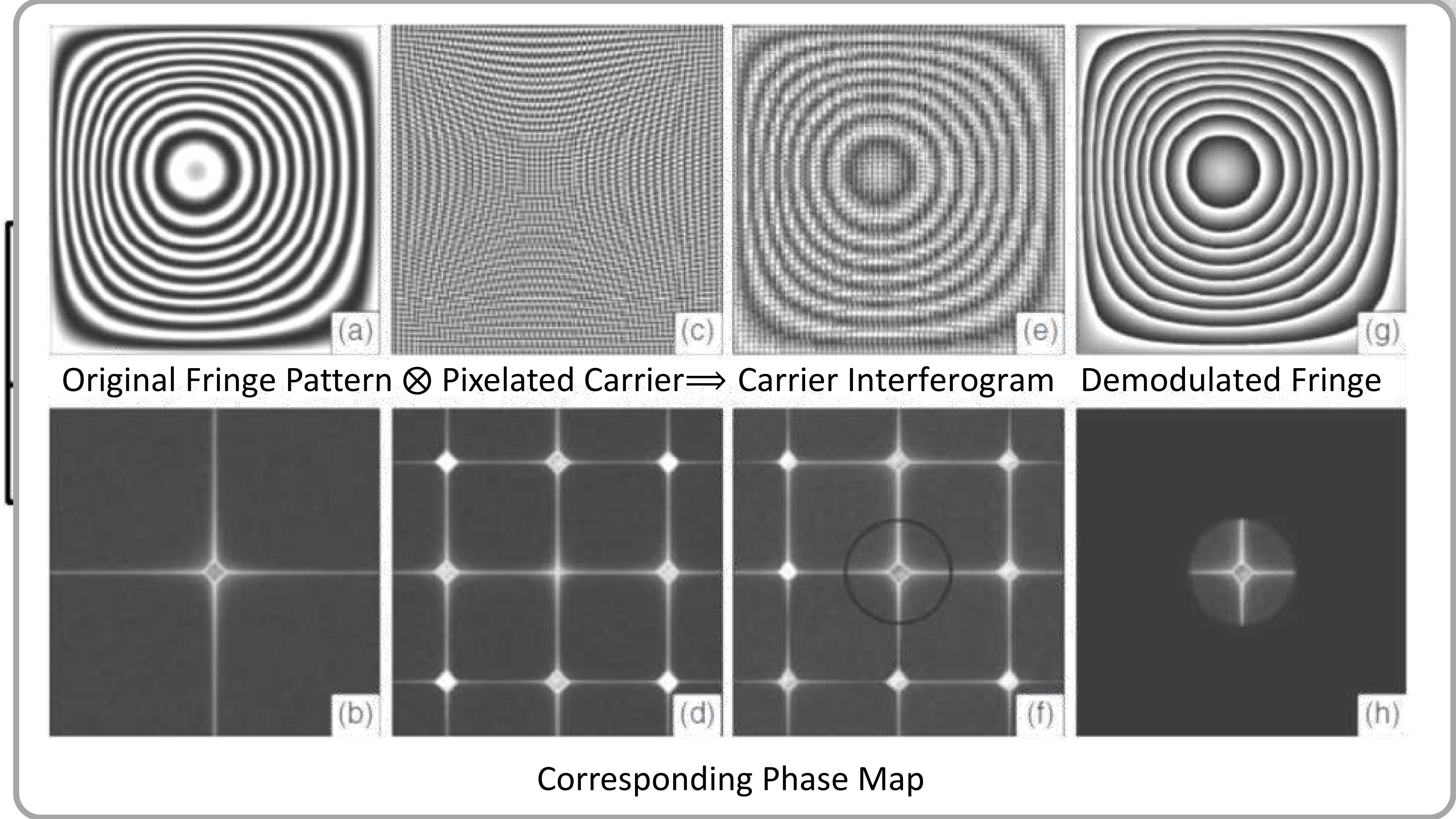


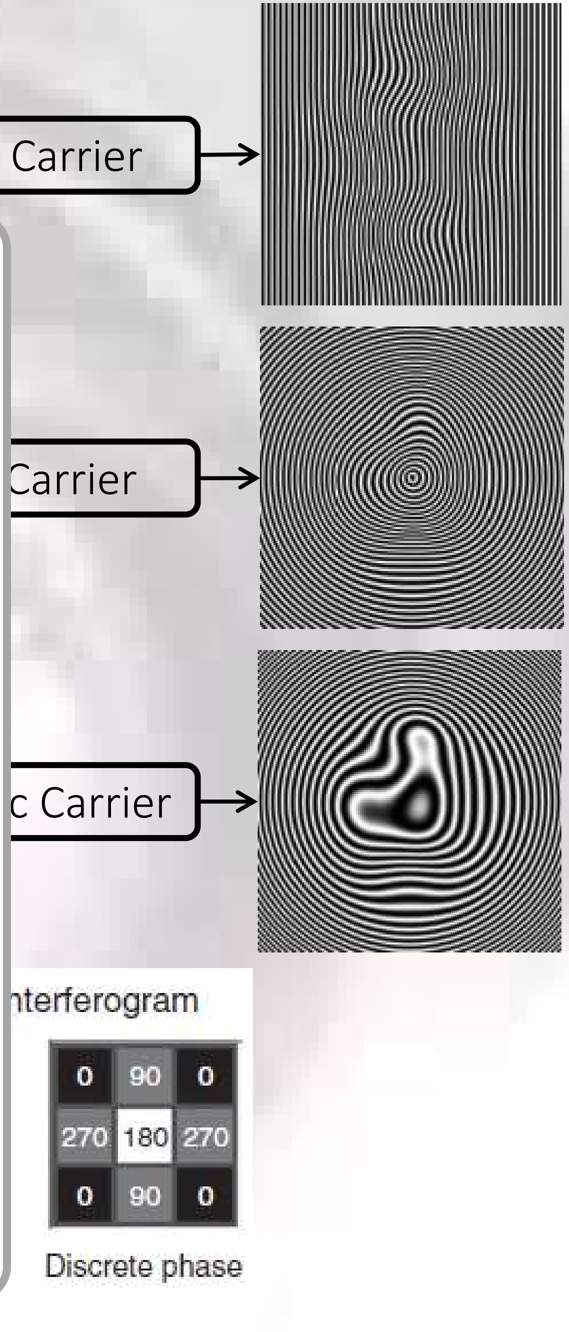


Pixelated carrier interferogram



Classification of phase estimation methods





Procedures for Extracting Phase Map from Spatial Carrier Fringes

① Capturing Fringe Patterns With Spatial Carrier

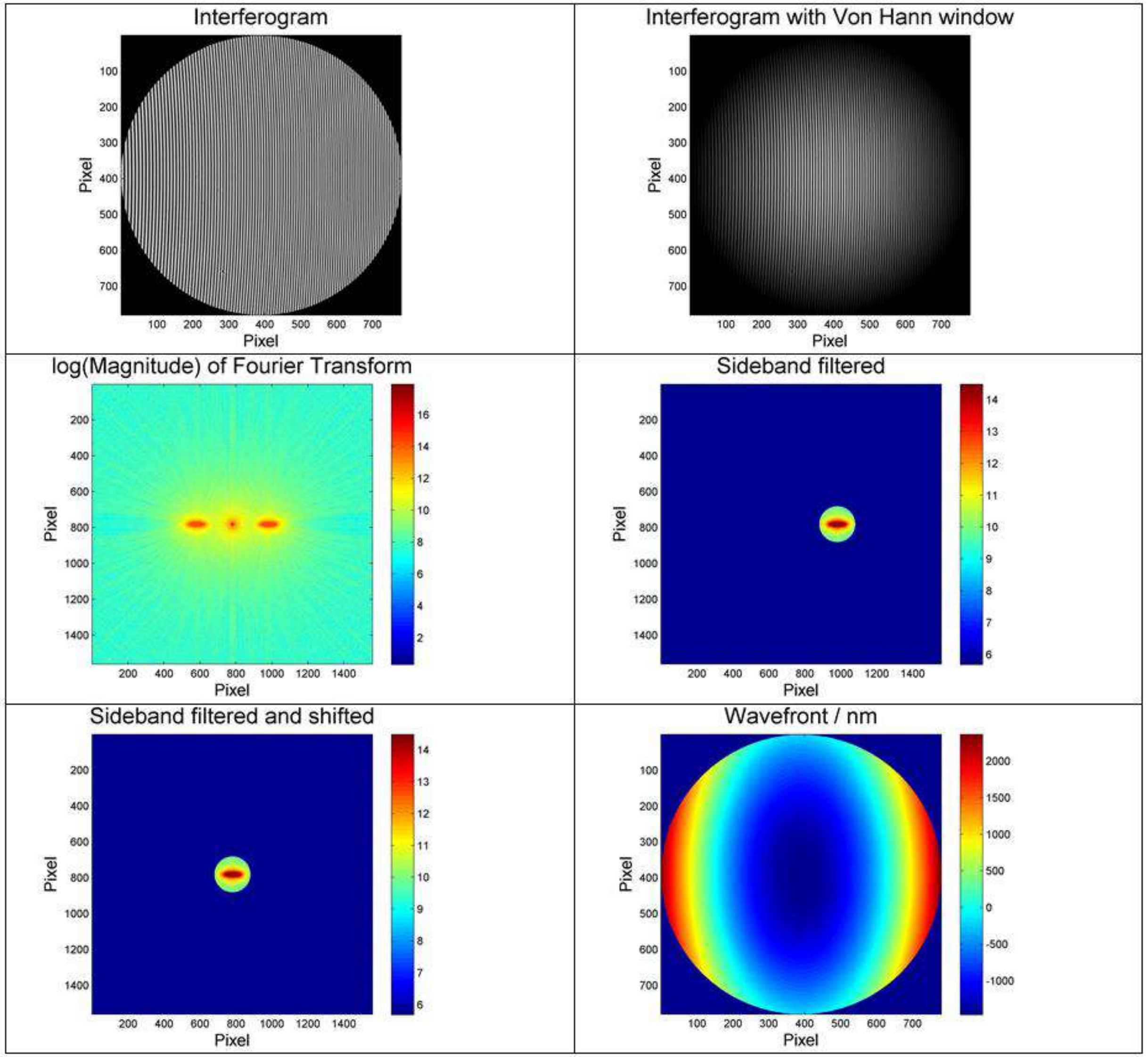
$$I(x,y) = a(x,y) + b(x,y)\cos\delta\,(x,y)$$

③ Fourier transform

$$\mathcal{F}(I(x,y)) = G(f_x,f_y) = \mathrm{A}(f_x,f_y) + C(f_x,f_y) + C^*(f_x,f_y)$$

⑤ Centering the fileted Spectrum

$$G'(f_x,f_y) = \begin{cases} C(f_x,f_y); & \|(f_x,f_y)-(0,0)\| \le \mathrm{R} \\ & 0;\text{otherwise} \end{cases}$$



② Fringe Pattern De-noising

④ Filtering with bandpass

$$G'(f_x,f_y) = \begin{cases} C(f_x,f_y); & \|(f_x,f_y)-(\mu,\nu)\| \le \mathrm{R} \\ & 0;\text{otherwise} \end{cases}$$

⑥ reconstructed phase and Unwrapped

$$\mathcal{F}^{-1}\left(G'(f_x,f_y)\right) = C(x,y) = \frac{1}{2}b(x,y)e^{i\delta}$$

$$\Rightarrow \delta(x,y) = \tan^{-1}\left(\frac{ImC(x,y)}{ReC(x,y)}\right)$$

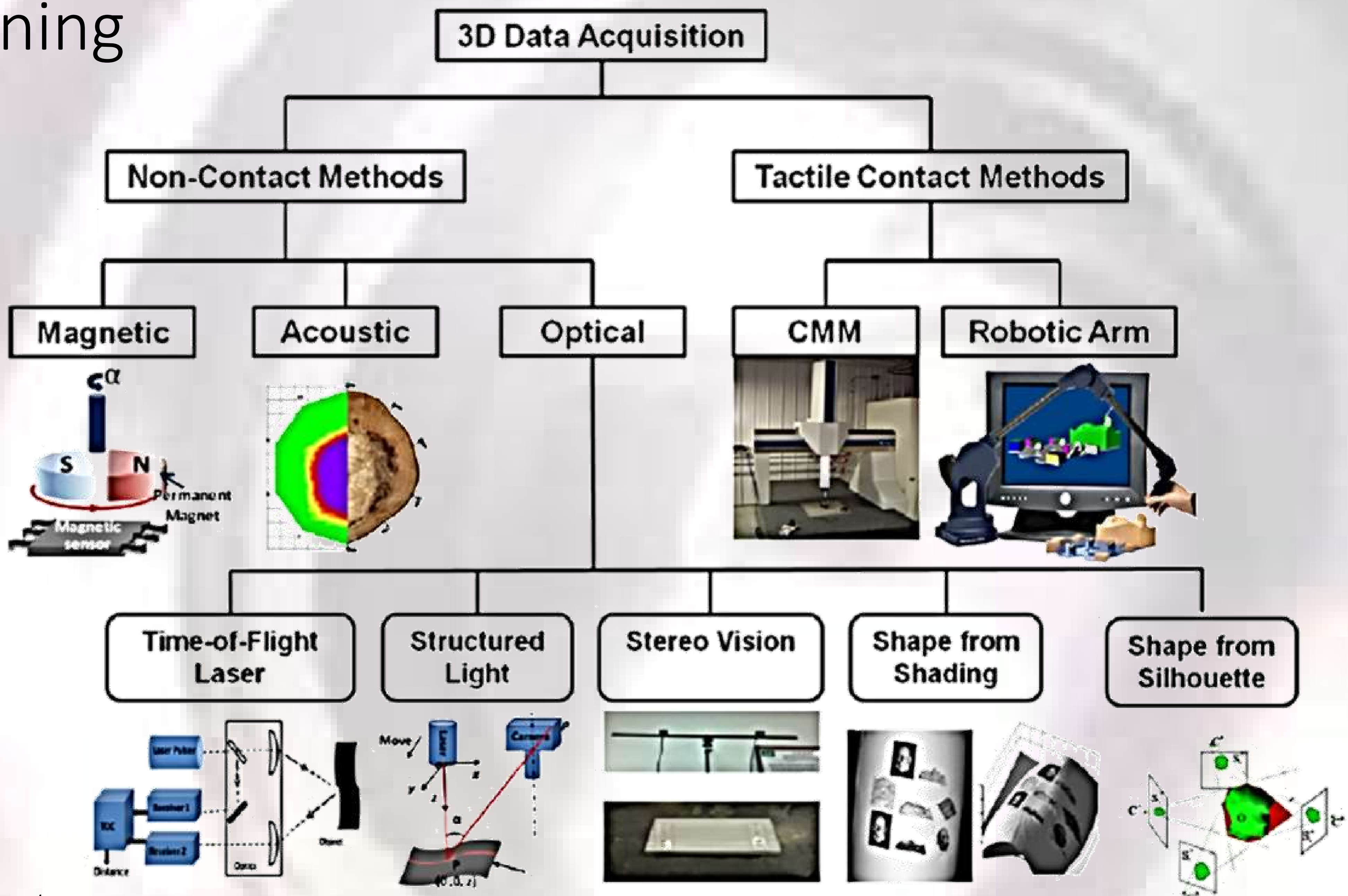
Phase-Measurement Algorithms

# of Frames	Phase Shift	Phase
3	$\pi/2$	$\emptyset = \tan^{-1}(\frac{I_1 - I_2}{I_2 - I_3})$
4	$\pi/2$	$\emptyset = \tan^{-1}(\frac{I_2 - I_4}{I_2 - I_3})$
Carré Equation	$\pi/2$	$\emptyset = \tan^{-1}(\frac{\sqrt{3[(I_2 - I_3) - (I_1 - I_4)][(I_2 - I_3) + (I_1 - I_4)]}}{(I_2 + I_3) - (I_1 + I_4)})$
5 (Schwider-Hariharan)	$\pi/2$	$\emptyset = \tan^{-1}(\frac{-2I_2 + 2I_4}{I_1 - 2I_3 + I_5})$
7	$\pi/3$	$\emptyset = \tan^{-1}(\frac{\sqrt{3}(I_2 + I_3 - I_5 - I_6)}{-I_1 - I_2 + I_3 + 2I_4 + I_5 - I_6 - I_7})$
8	$\pi/2$	$\emptyset = \tan^{-1}(\frac{I_1 + 5\, I_2 - 11I_3 - 15I_4 + 15I_5 + 11I_6 - 5I_7 - I_8}{I_1 - 5\, I_2 - 11I_3 + 15I_4 + 15I_5 - 11I_6 - 5I_7 + I_8})$
12	$\pi/3$	$\emptyset = \tan^{-1}(\frac{\sqrt{3}(-3I_2 - 3I_3 + 3I_4 + 9I_5 + 6I_6 - 6I_7 - 9I_8 - 3I_9 + 3I_{10} + 3I_{11}}{2I_1 + I_2 - 7I_3 - 11I_4 - I_5 + 16I_6 + 16I_7 - I_8 - 11I_9 - 7I_{10} + I_{11} + 2I_{12}})$
N (synchronous detection)	$\alpha_i = \frac{2\pi i}{N}$, $i = 1,2 \ldots\ldots$	$\emptyset = -\tan^{-1}\left[\frac{\sum_{i=1}^{N} \sin \alpha_i}{\sum_{i=1}^{N} \cos \alpha_i}\right]$

Topics

- Introduction
- Why optical methodologies?
- Define Requirement-Knowing Limitation of a Method
- Key Elements of Optics
  - Light Source
  - Sensors
  - Optical Lens& Optical Components
- Principle of Basic Interferometry
- Spectrum and Its Applications
- Laser Triangulation Measurement Method
- Moiré Method/ Sampling Moiré Method
- **Structured Light and Its Application**
- Astigmatic Method and Applications
- Principle of White Light Scanning Interferometer and its Applications
- Principle of Confocal Microscopy and its applications
- Principle of Conoscopic Holography and its applications

3D Scanning



http://dx.doi.org/10.1016/j.cirp.2013.05.005

	Time of Flight (ToF)	Stereoscopic vision	Fixed structured light	Programmable structured light (DLP)
Location	✓	✓		✓
Identification	✓	✓	✓	✓
Measurement & inspection	✓	✓	✓	✓
Biometrics				✓
UI control / gaming	✓		✓	
Augmented reality	✓	✓		✓

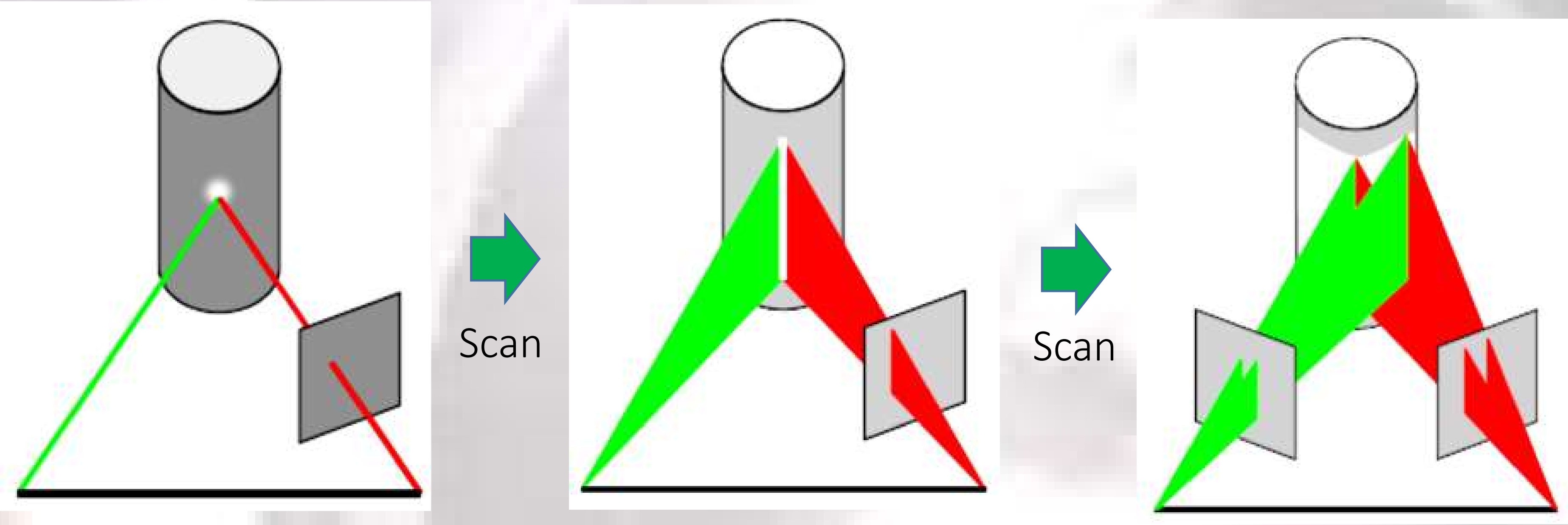
https://blog.cometlabs.io/depth-sensors-are-the-key-to-unlocking-next-level-computer-vision-applications-3499533d3246

Comparison of 3D imaging technologies

	Time of Flight (ToF)	Stereoscopic vision	Fixed structured light	Programmable structured light (DLP)
Operational principle	**IR pulse, measure light transit time**	**Two 2D sensors emulate human eyes**	**Single pattern visible or IR illumination, detects distortion**	**Multiple pattern visible or IR illumination, detects distortion**
Point cloud generation	Direct out of chipset	High SW Processing	Medium SW processing	SW processing scales with # of patterns
Latency	Low	Medium	Medium	Medium
Active illumination	Yes	No	Yes	Yes – customizable spectrum
Low light performance	Good	Weak	Good	Good
Bright light performance	Medium	Good	Medium / weak *Depends on illumination power*	Medium / weak *Depends on illumination power*
Power consumption	Medium/high *Scales w/ distance*	Low	Medium	Medium *Scales with distance*
Range	Short to long range *Depends on laser power & modulation*	Mid range *Depends on spacing between cameras*	Very short to mid range *Depends on illumination power*	Very short to mid range *Depends on illumination power*
Resolution	QQVGA, QVGA -> Roadmap to VGA	Camera Dependent	Projected pattern dependent	WVGA to 1080p -> Roadmap to WQXGA
Depth accuracy	mm to cm *Depends on resolution of sensor*	mm to cm *Difficulty with smooth surface*	mm to cm	μm to cm
Scanning speed	Fast *Limited by sensor speed*	Medium *Limited by software complexity*	Medium *Limited by SW complexity*	Fast / medium *Limited by camera speed*

https://blog.cometlabs.io/depth-sensors-are-the-key-to-unlocking-next-level-computer-vision-applications-3499533d3246

Triangulation

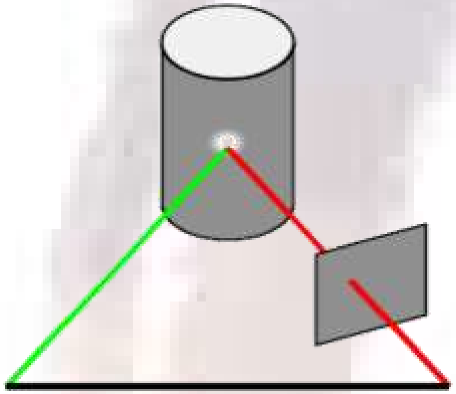


Light Source Sensor
Single Point Measurement

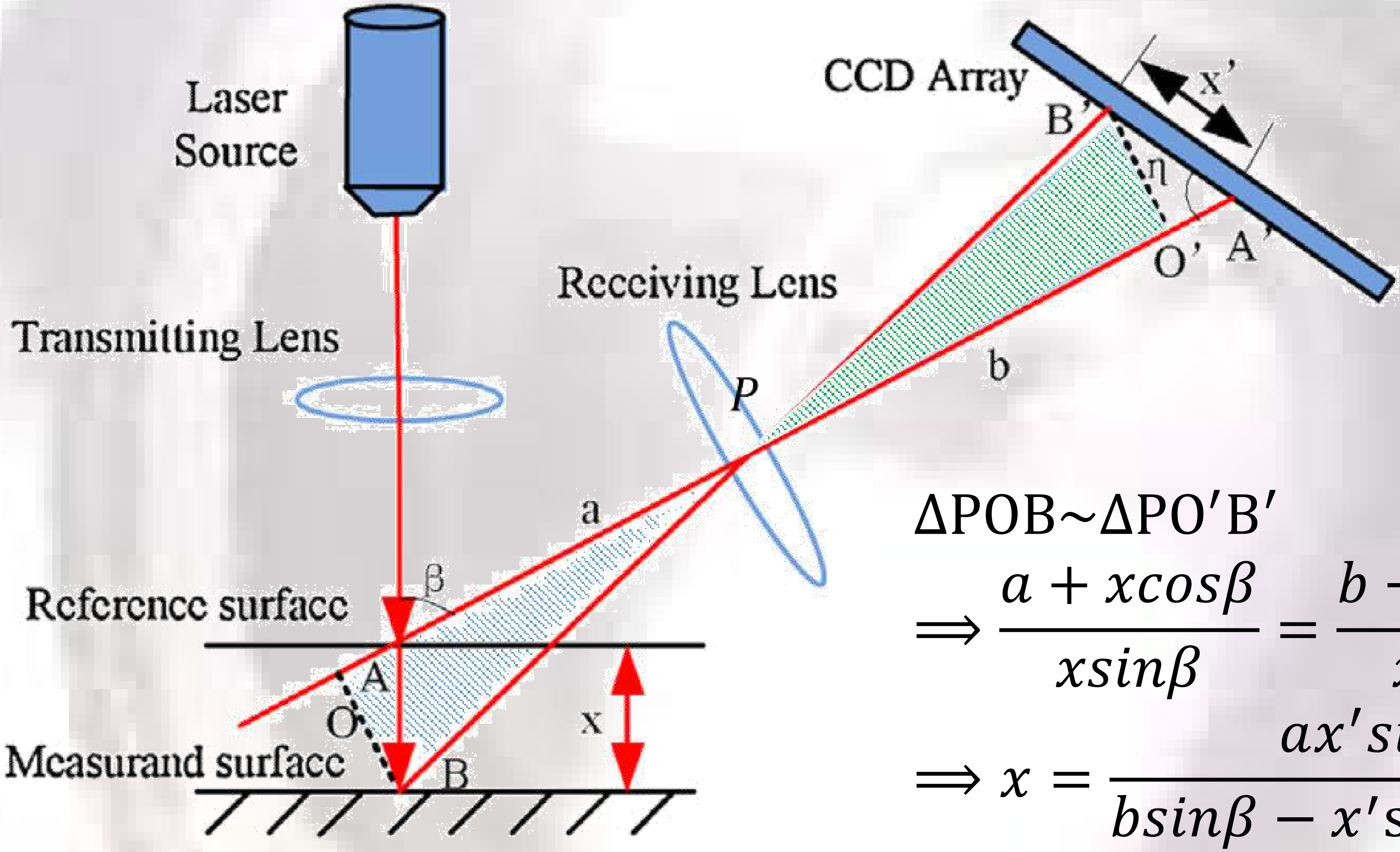
Light Source Sensor
Profile Measurement

Light Source Sensor
Surface Measurement

General Mathematical Model for Single Point Measurement



Single Point Measurement

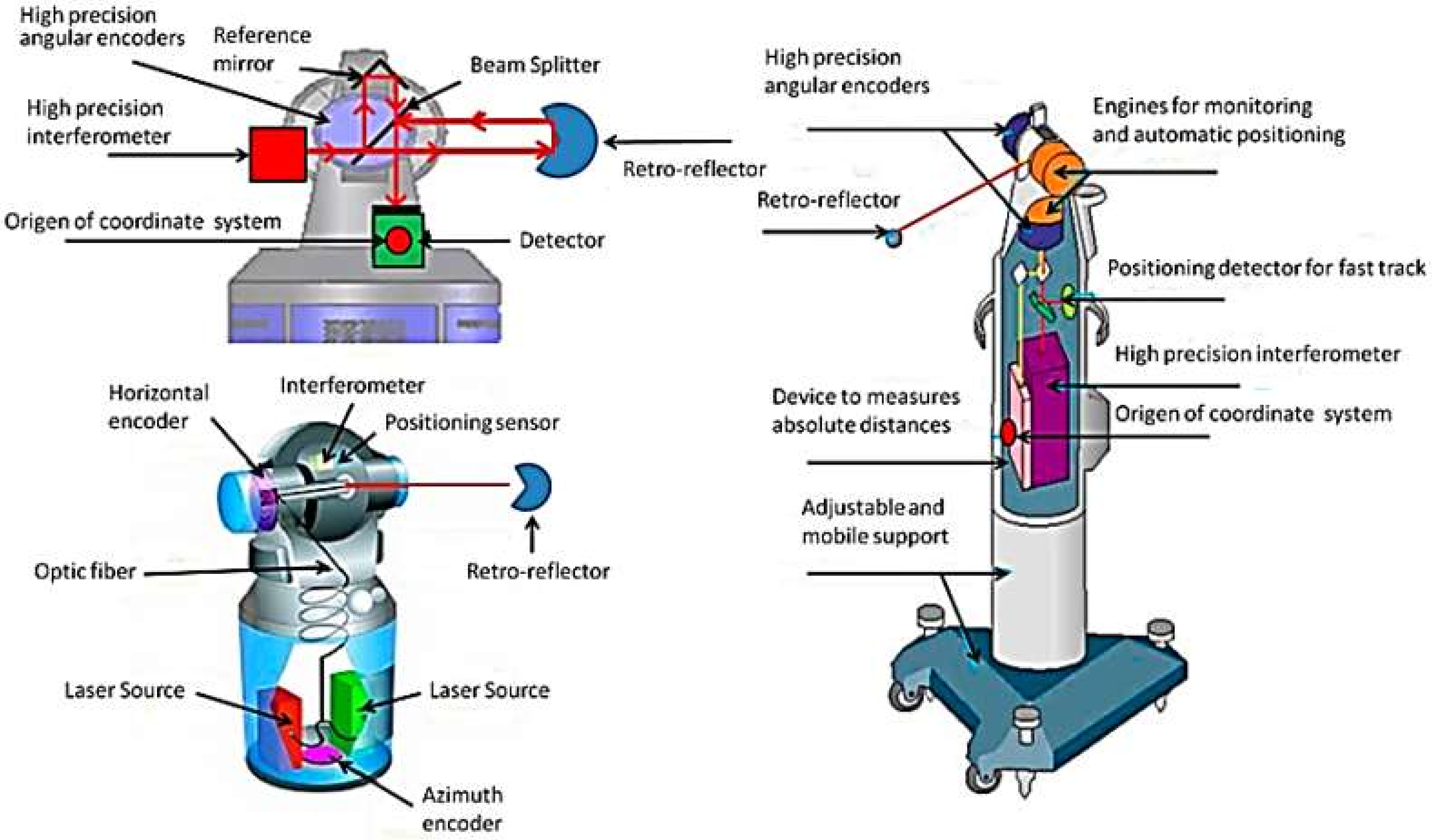


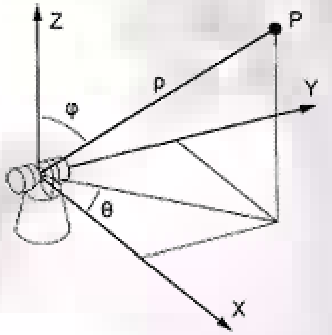
$$\Delta \mathrm{POB} \sim \Delta \mathrm{PO'B'}$$

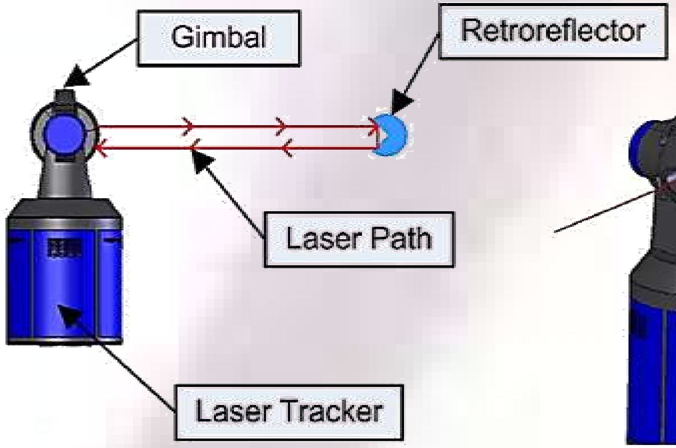
$$\Rightarrow \frac{a + x cos\beta}{x sin\beta} = \frac{b - x' cos\eta}{x' sin\eta}$$

$$\Rightarrow x = \frac{a x' sin\eta}{b sin\beta - x' \sin(\beta + \eta)}$$

Laser Trackers—Single Point Measurement

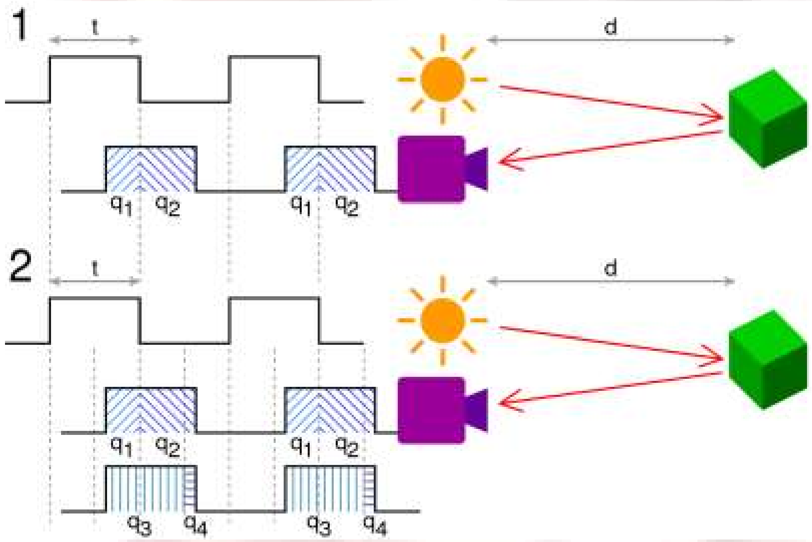






Laser scanners

Basic principle:
Depending on the technique used, the 3D laser scanner are defined 'time of flight' (TOF) when calculating the distance according to the time elapsed between the emission of the laser and the reception of the return signal, or 'phase shift based' when the calculation is performed by comparing the phases of the output signal and the return.

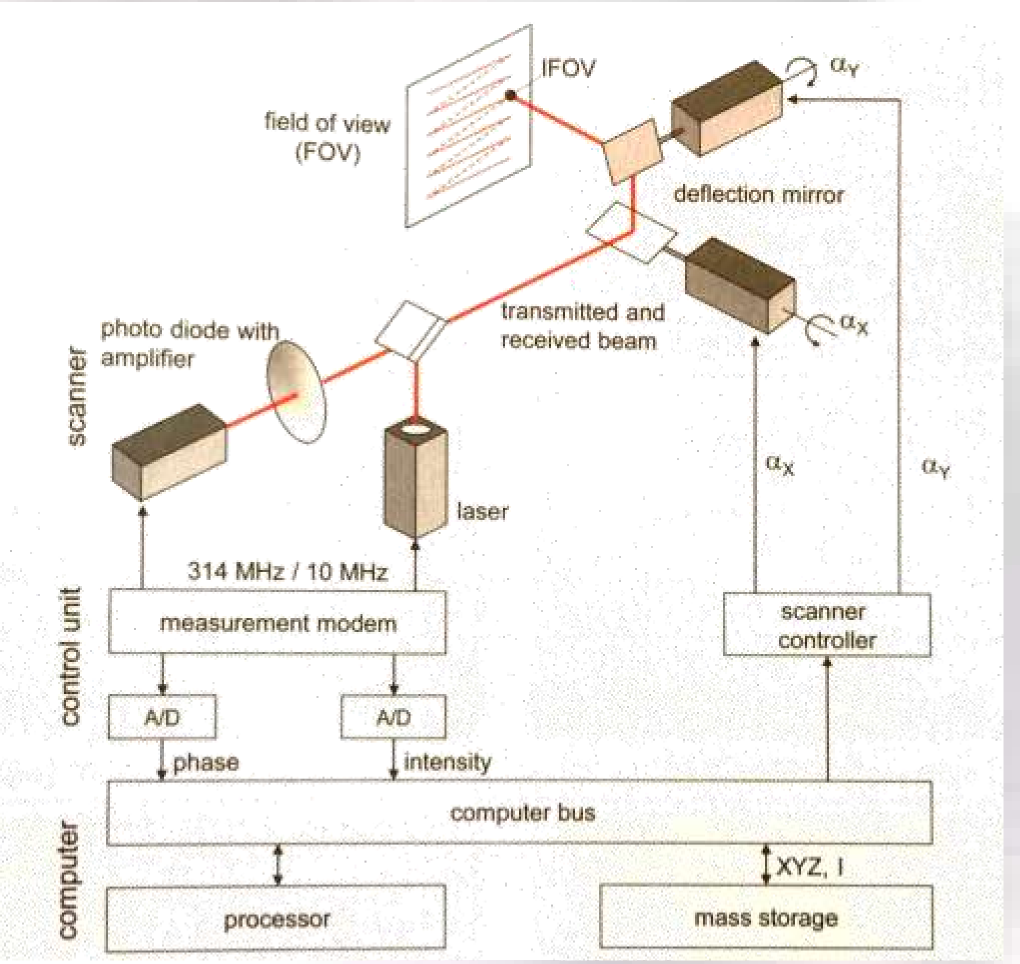


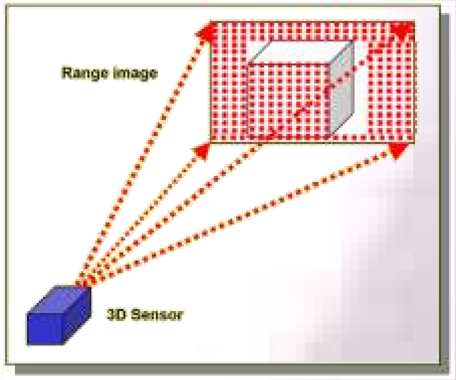
$(1) pulsed\ mode,$

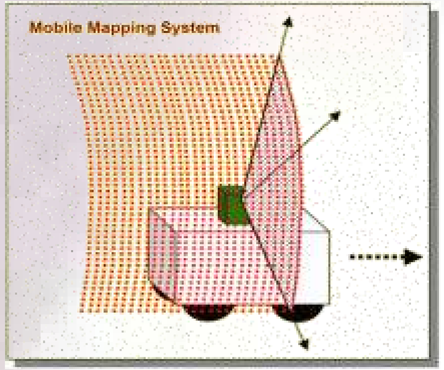
$$d = \frac{Ct}{2} \frac{q_2}{q_1 + q_2}$$

$(2) continuous - wave,$

$$d = \frac{Ct}{2\pi} tan^{-1} \frac{q_3 - q_3}{q_1 - q_2}$$

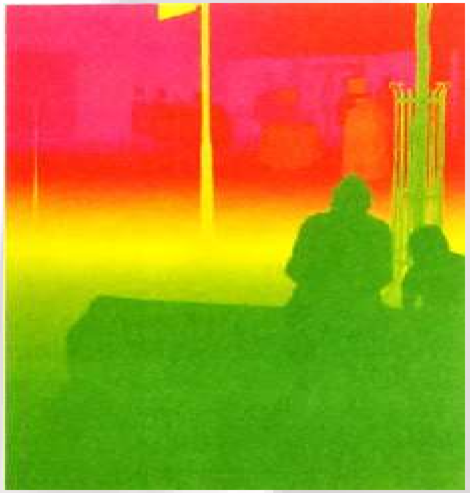






Laser scanners

Grey-Value Range Image

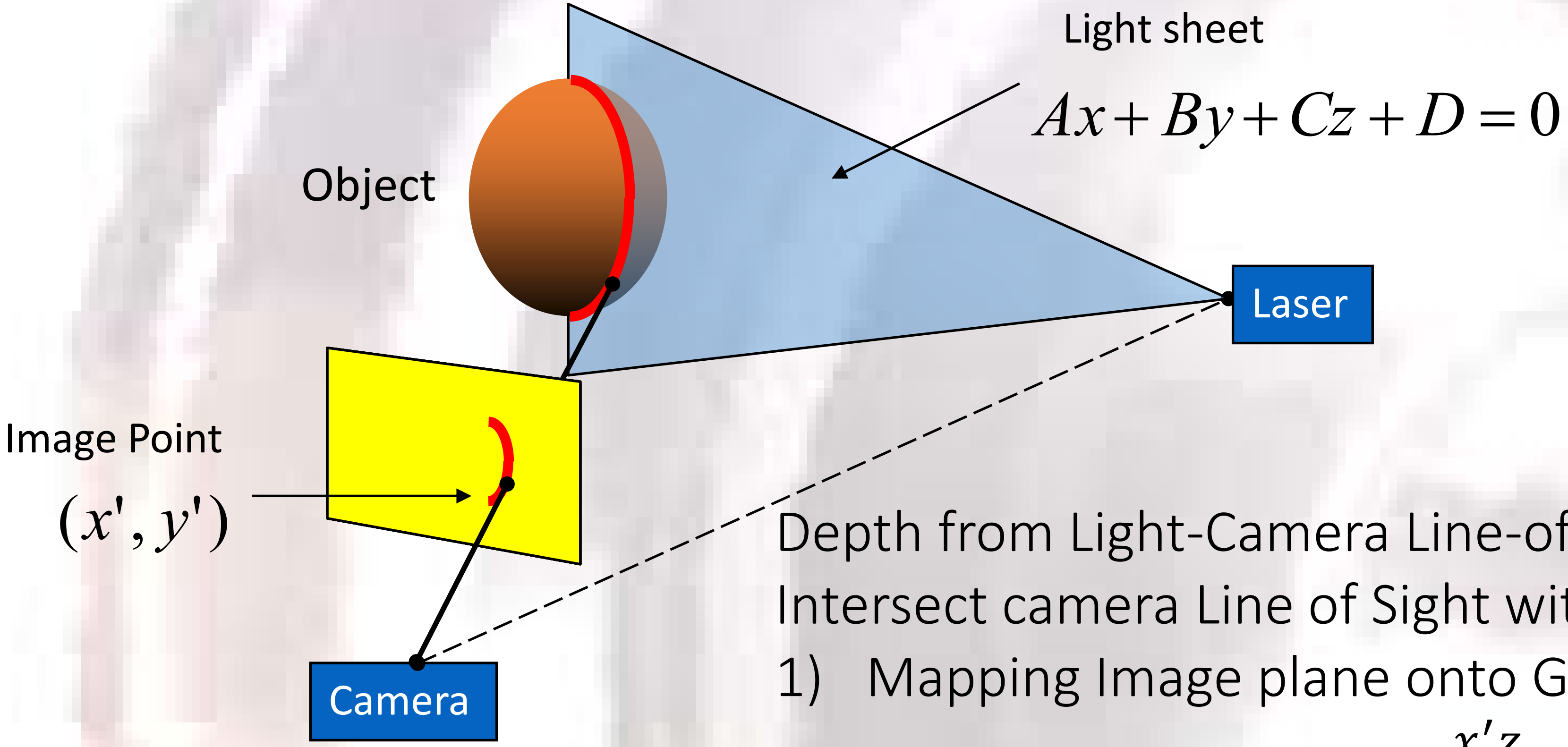


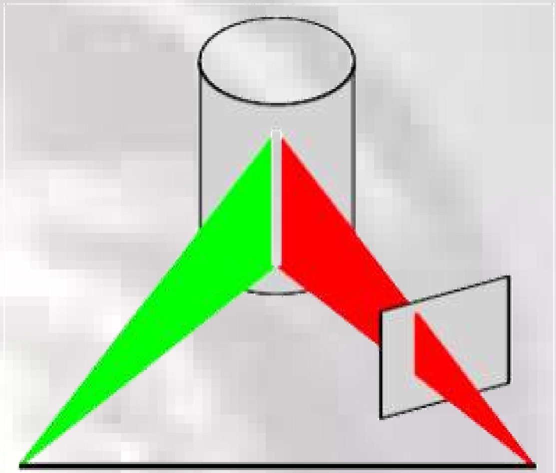
Colour-Coded Range Image

Intensity Image

RGB Image Overlay

General Mathematical Model for Light Sheet Illumination





Profile Measurement

Depth from Light-Camera Line-of-Sight-plane triangulation:
Intersect camera Line of Sight with light Sheet

1) Mapping Image plane onto Global Space (object space)

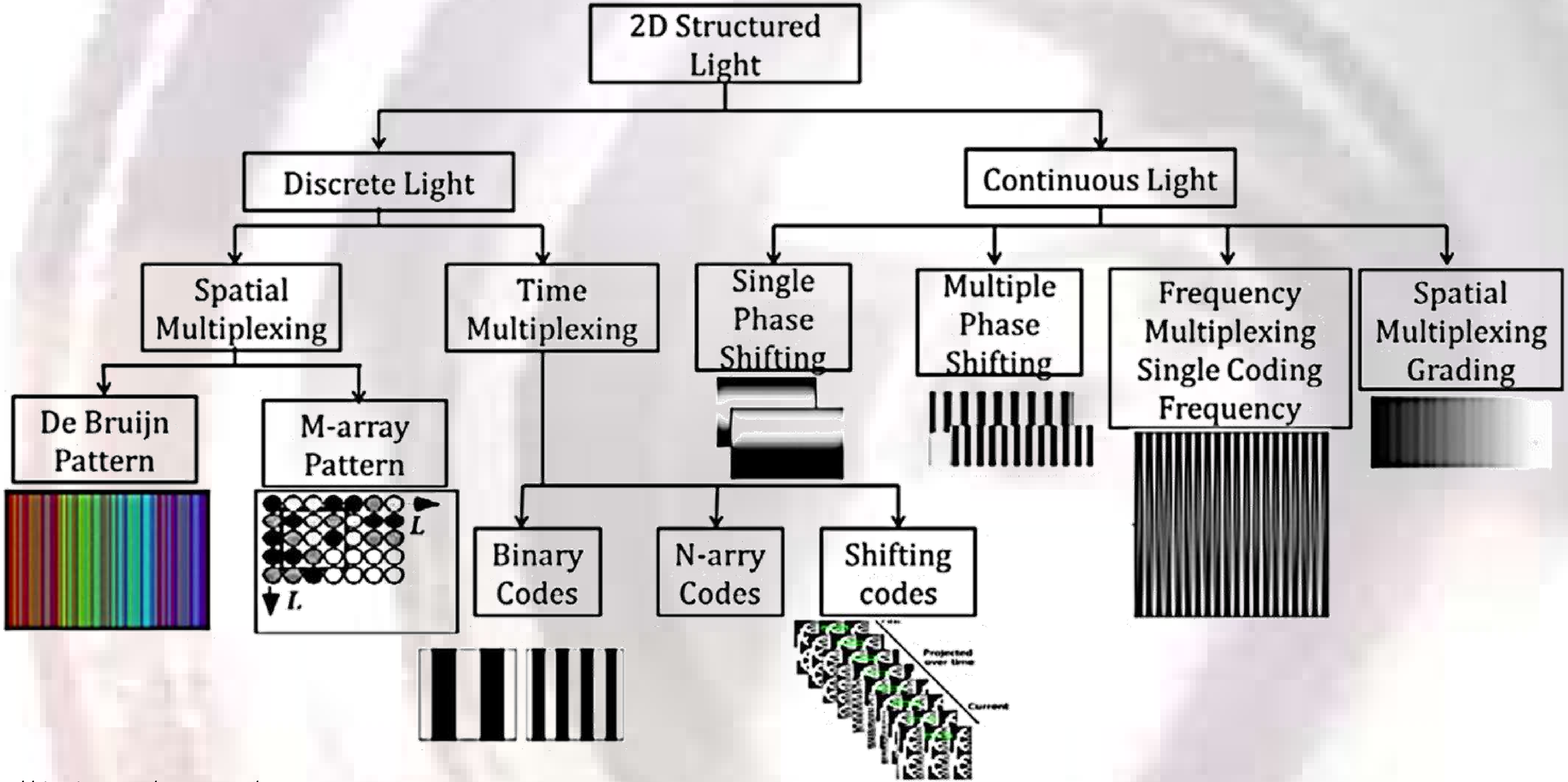
$$x = \frac{x'z}{f}; y = \frac{y'z}{f}$$

2) Determining depth by considering

$$(x, y, z) \in Ax + By + Cz + D = 0$$

$$\Rightarrow z = \frac{-Df}{Ax' + By' + Cf}$$

Classification of 2D structured light coding methods

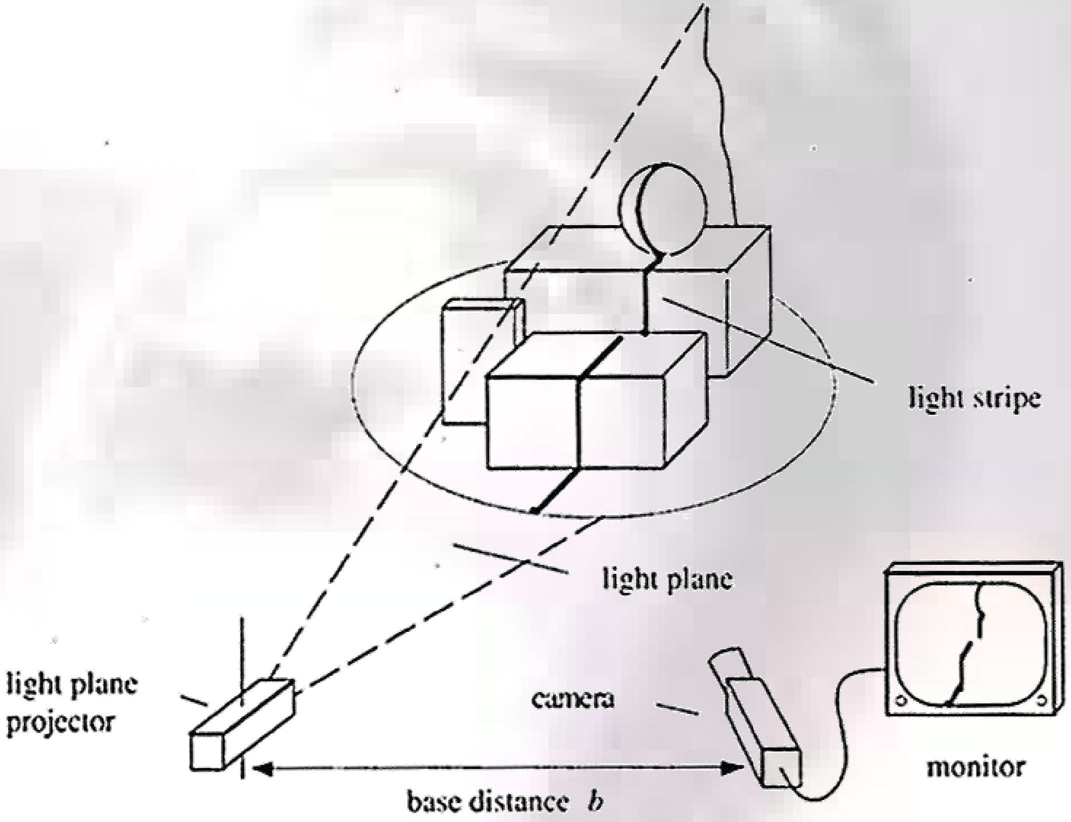


http://dx.doi.org/10.1016/j.cirp.2013.05.005

Techniques		Pros	Cons
Stereo vision		No need for active lighting; lowcost; easy to implement	Correspondence between different views and reconstruction of 3D shape with high resolution in real time are difficult
Shape from shading		Able to reconstruct a 3D shape from a single image	Difficult to implement algorithms for 3D shape reconstruction in the real world
Shape from silhouette		Computationally simple; able to reconstruct 3D shapes efficiently	Accuracy is relatively low
Time of flight		Able to provide high accuracy at a reasonable price	Data acquisition time is relatively high
structured light	1D structured light	Able to provide high accuracy; no need for complicated correspondence calculation	Laser scanning is time consuming; equipment is relatively expensive
	2D structured light	No need for scanning or complicated correspondence calculation	Less accurate than 1D structured light technique

Structured Lighting

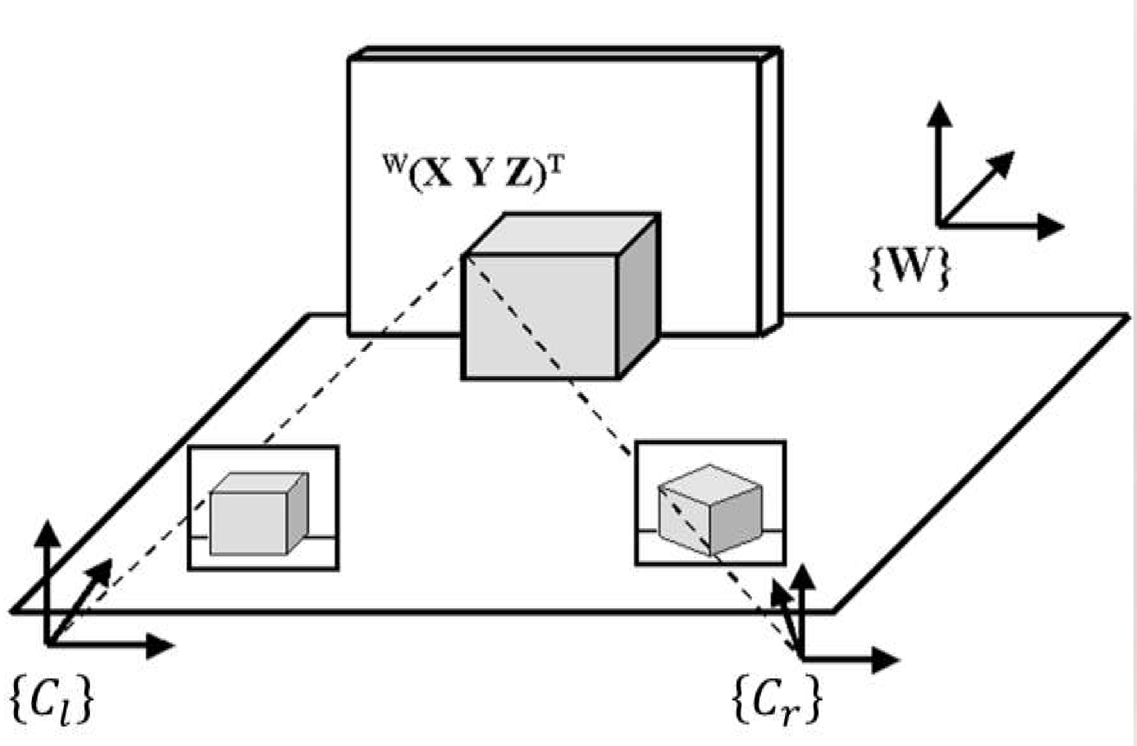
- The projection of patterns into a scene is called structured lighting.
- The patterns projected onto the objects within the field of view of a camera.
- The distance of object to the camera or the location of an object in space can be determined by analyzing the observed light patterns in the images.
- Structured lighting consists in intersecting the ray I, projected by a light source at point (X,Y,Z) and imaged at point (x,y); with an additional ray I' or an additional plane π which leads to a unique reconstruction of the object point (X,Y,Z).



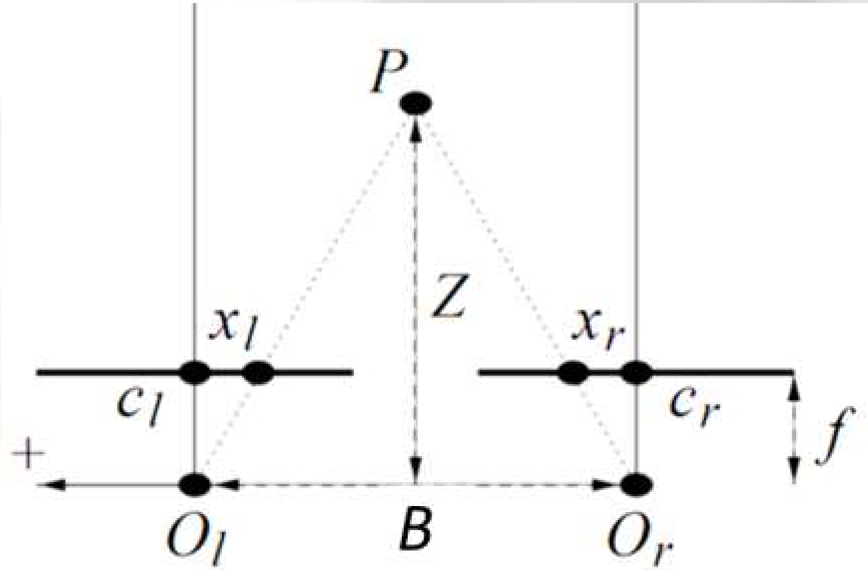
Applications of Structure Light

Stereo Imaging method

- Need 2 or more views of the scene
- Scene texture used to identify correspondences across views



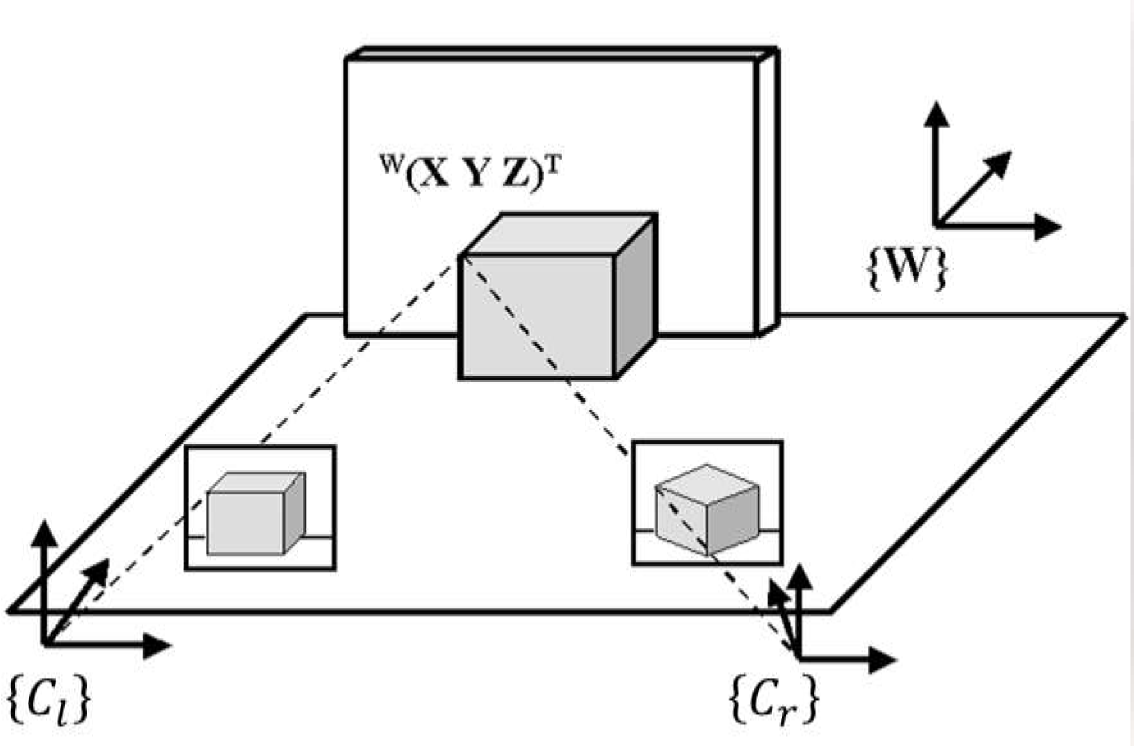
Coordinate Systems



Geometrical Model

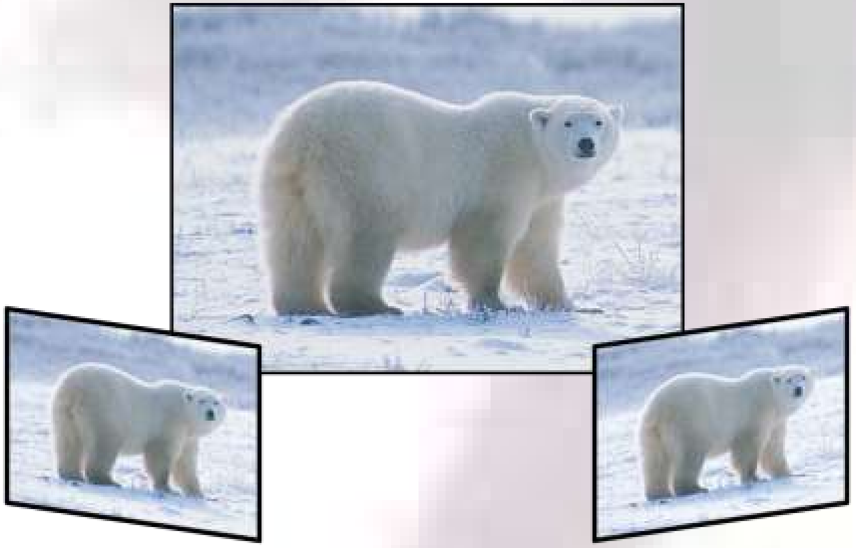
$$\frac{B - |x_r + x_l|}{Z - f} = \frac{B}{Z} \Longrightarrow Z = \frac{fB}{|x_r + x_l|}$$

Stereo Imaging method



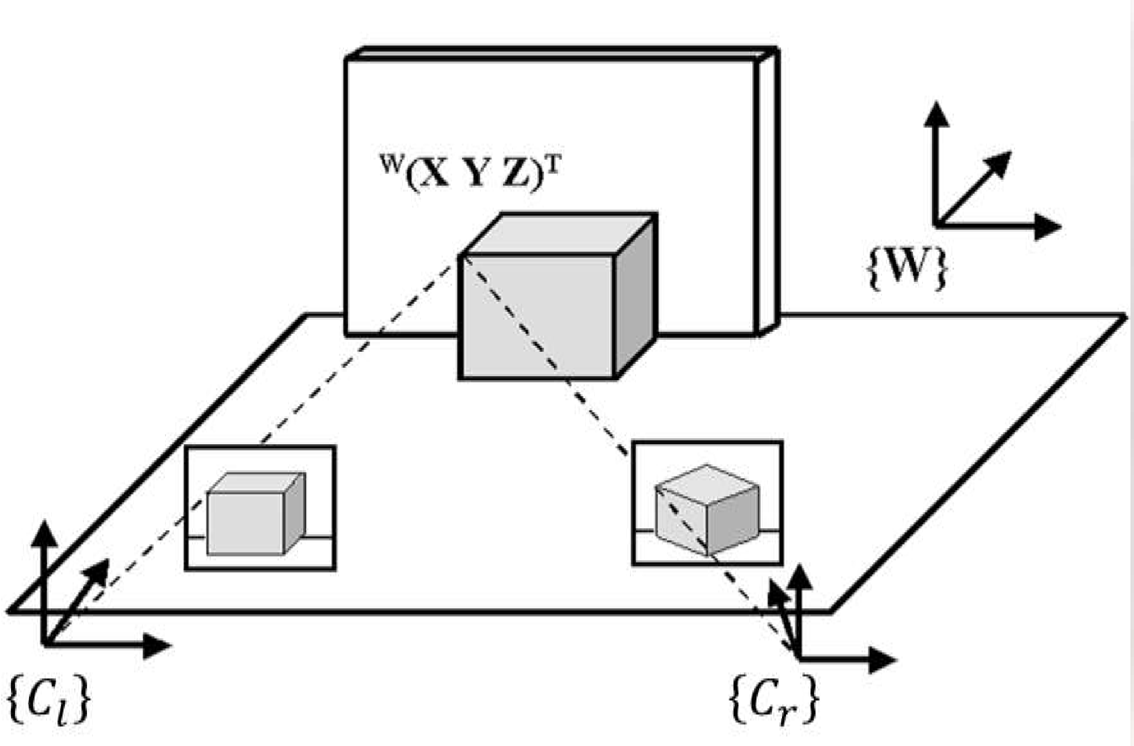
Coordinate Systems

Stereo works well on “textured” images

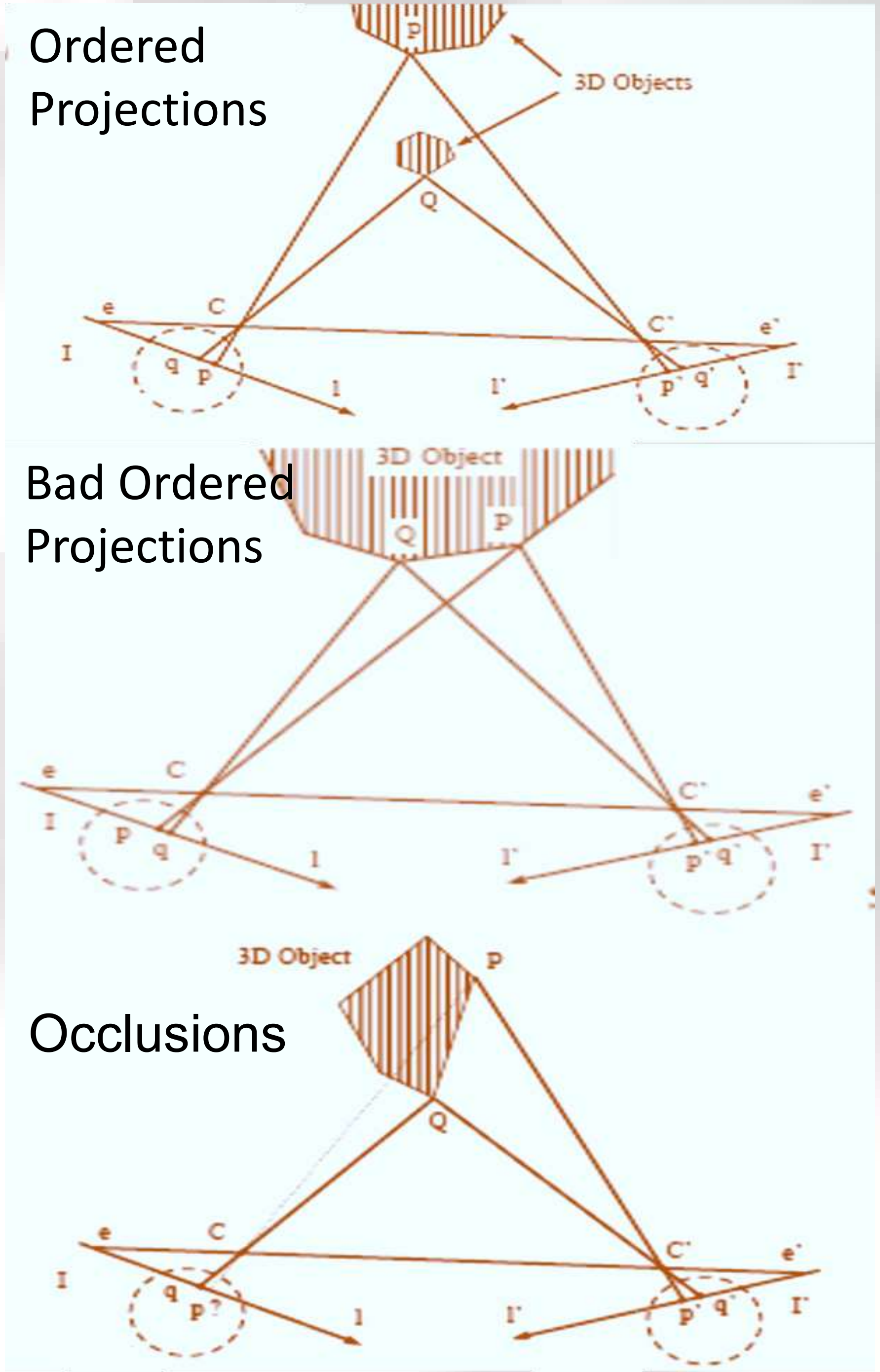


Stereo can fail with lack of texture

Stereo Imaging method



Coordinate Systems

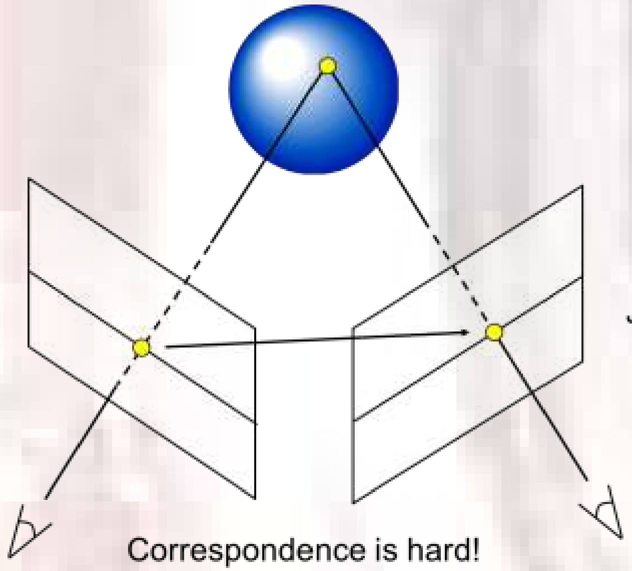


Stereo Vision vs. Structured Light

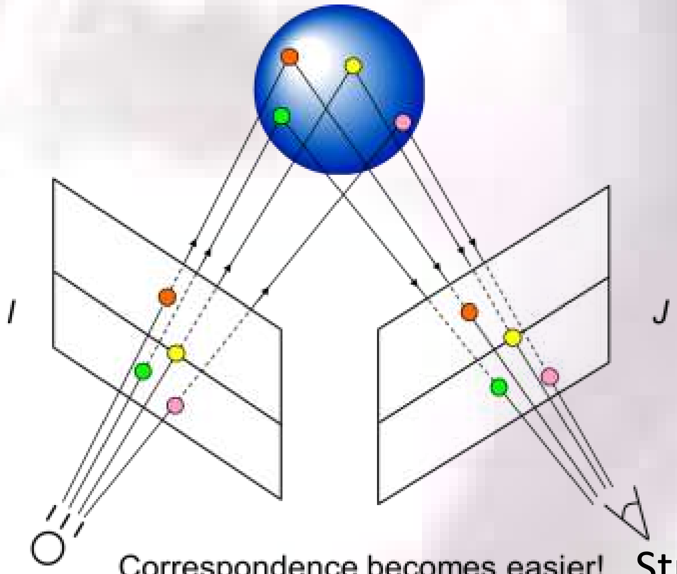
General Problems for Stereo Vision

- Recovering shape from multiple views of s scene, finding correspondence between images are needed
- Matching correspondence problem is complex
- 3D cannot be reconstructed in image regions without well-defined points

- Avoid problems due to correspondence
- Avoid problems due to surface appearance
- Much more accurate
- Very popular in industrial settings



Stereo Imaging



Structured Light

Coded structured light

Single dot:

- No correspondence problem.
- Scanning both axis.

Single slit:

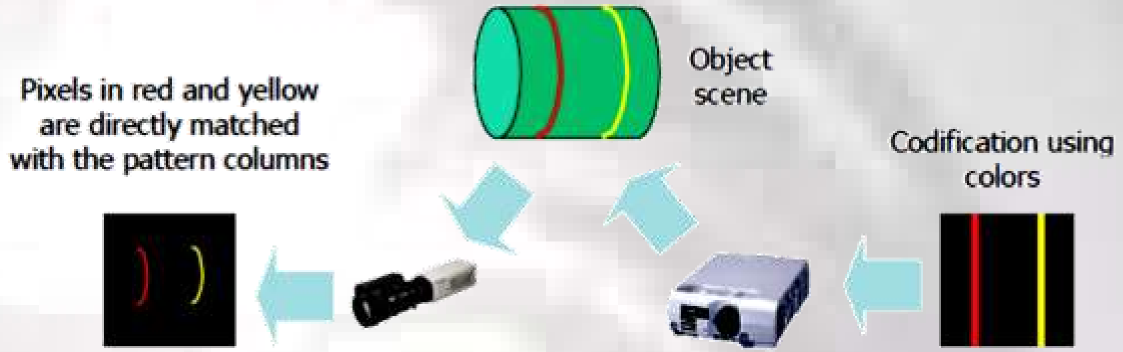
- No correspondence problem.
- Scanning the axis orthogonal to the slit.

Stripe patterns:

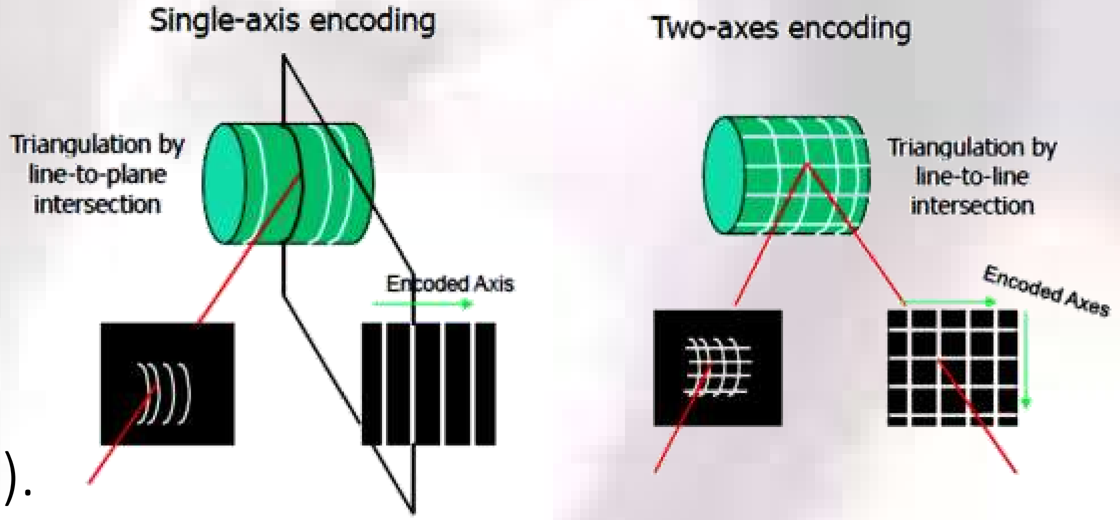
- No scanning.
- Correspondence problem among

Grid, multiple dots:

- No scanning.
- Correspondence problem among all the imaged features (points, dots, segments,…).



pattern with two-encoded-columns



Classes of patterns : Temporal/ Spatial/ Other

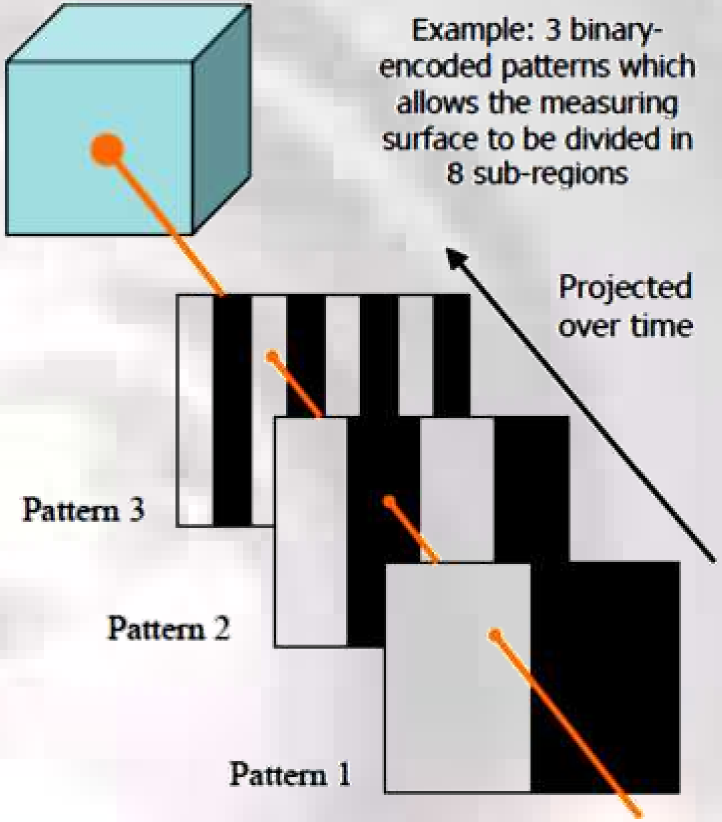
Coded structured light

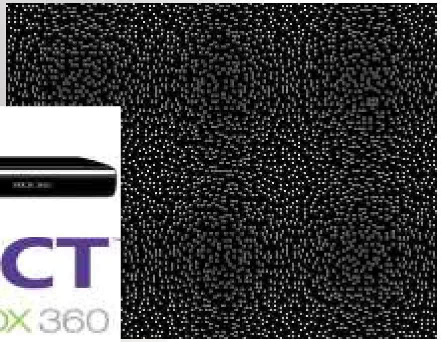
Temporal Coding

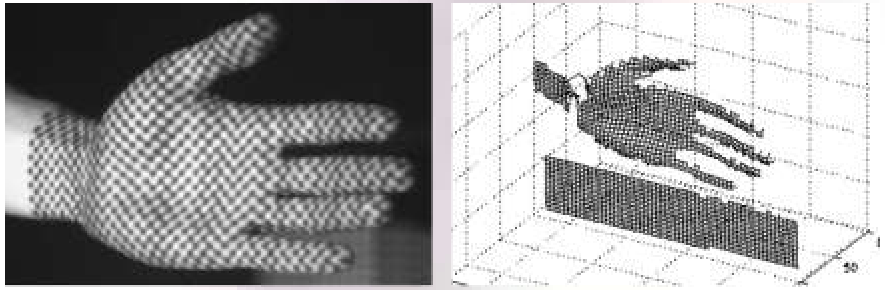
1. Multiple frames are projected to identify scene regions
2. Camera pixel's intensity change used for correspondence
3. Scene assumed to be static

Spatial Coding

1. Coding in a single frame.
2. Spatial Coherence can be local or global.
3. The minimum number of pixels used to identify the projected code defines the accuracy of details to be recovered in the scene.

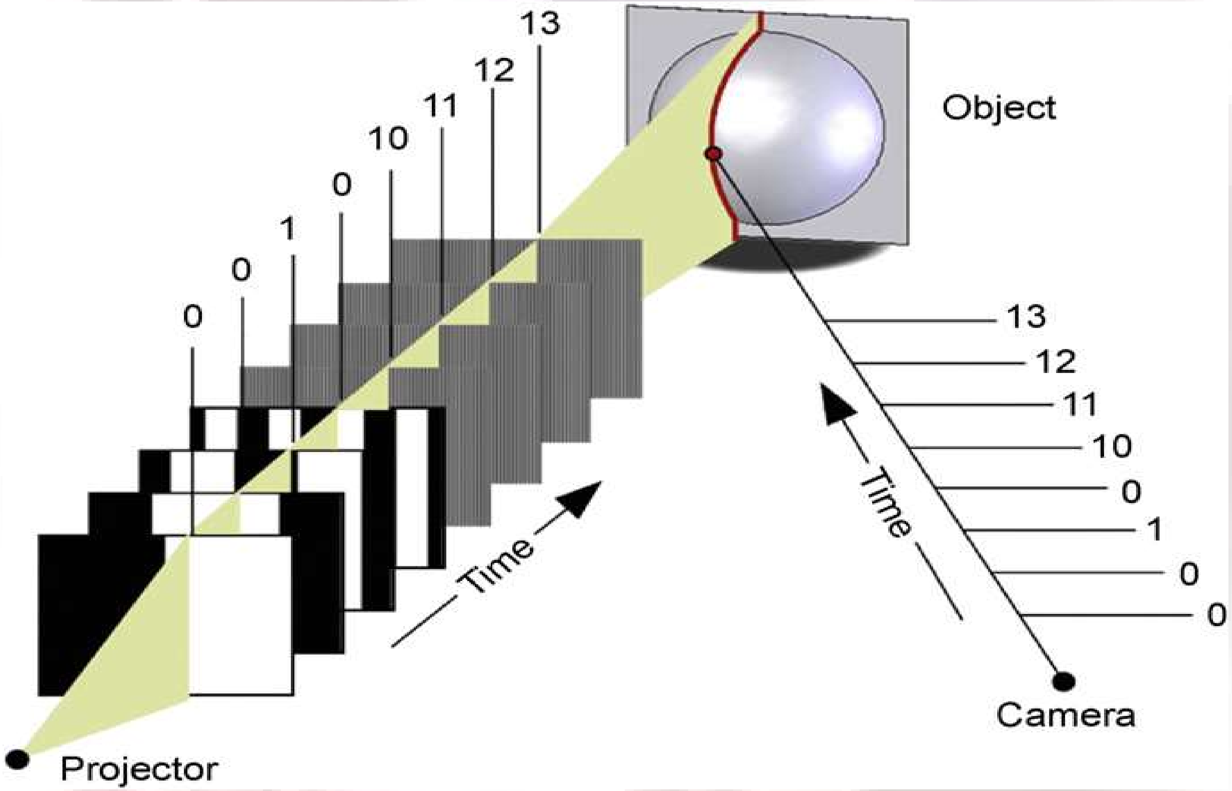


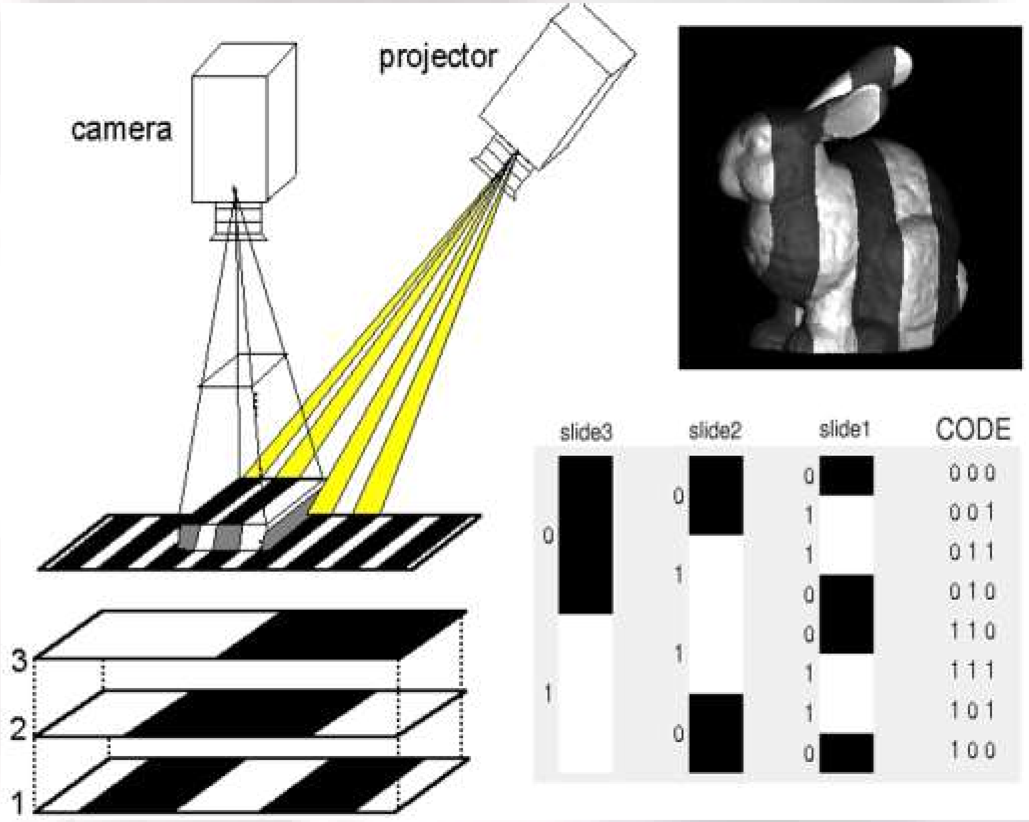




http://cmp.felk.cvut.cz/cmp/demos/RangeAcquisition.html

Binary Coding

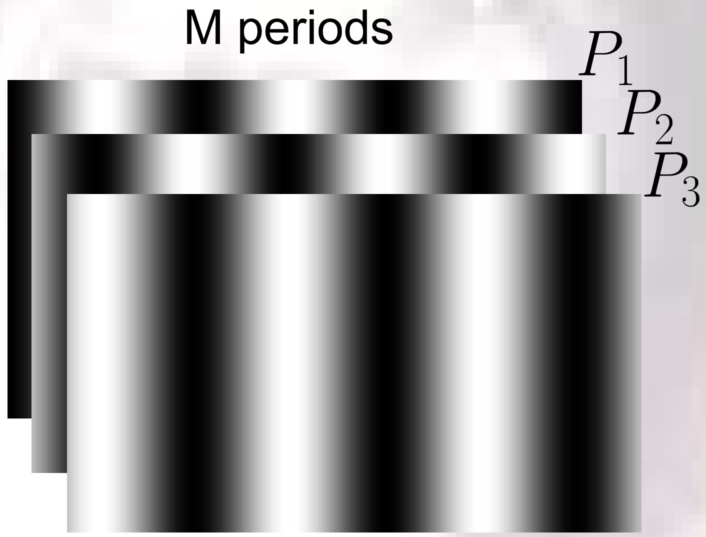




Projecting Binary Code w.r.t. frame time

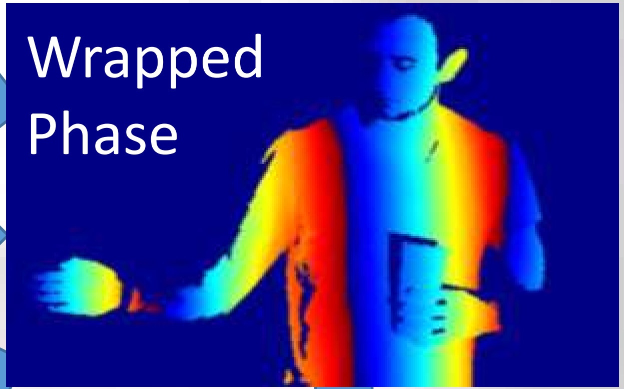
Phase Shifted Structured Light (SL) Systems

- Project patterns to find correspondences between camera and projector
- Phase shifted sinusoidal patterns:
  - Fast capture: 3 shots
  - Simple to decode
  - Insensitive to blur
  - Used in optical metrology



Scene Illuminated with Phase-Shifted Sinusoids

$$\phi(x, y) = \tan^{-1}\left(\frac{\sqrt{3}(I_1(x,y) - I_3(x,y))}{2I_2(x,y) - I_1(x,y) - I_3(x,y)}\right)$$



M periods in sinusoid ➔
Need to unwrap phase