Measurement of Web Surface Profiles Using Fringe Projection

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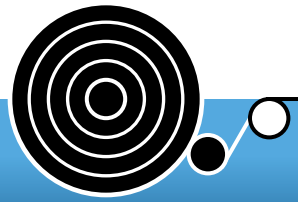
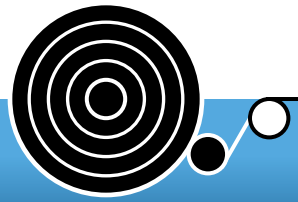


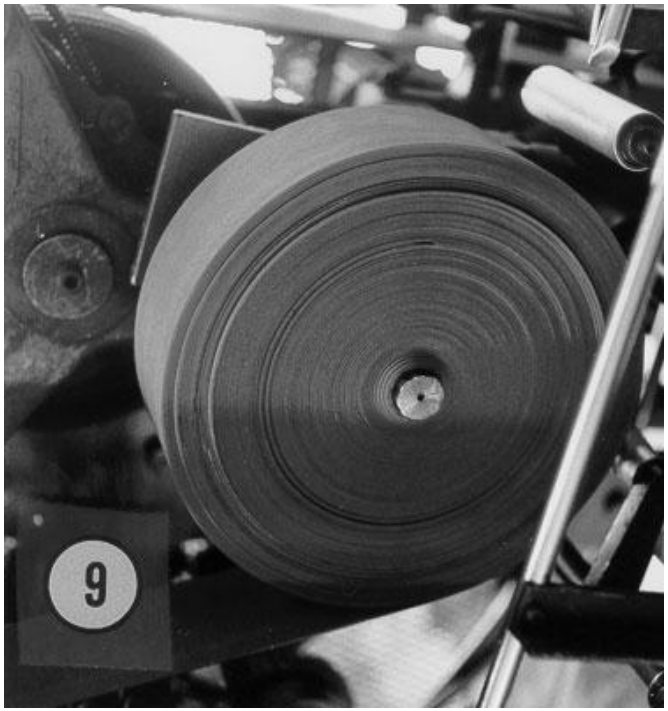
Outline

- Motivation
- Principle of Fringe Projection
- Digital Fringe Projection System
- Applications in Web Handling
- Conclusion and Future Work

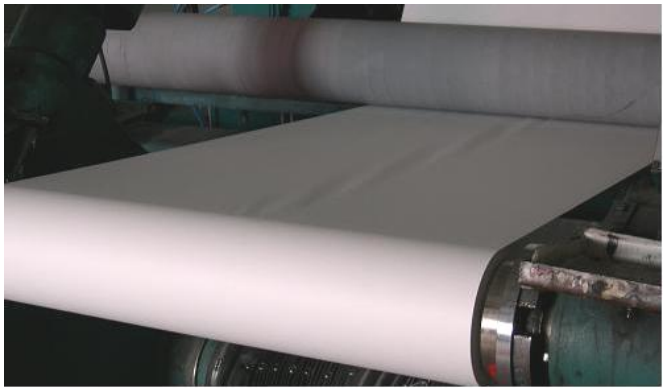


Motivation: Surface Profiling Need in Web Handling

- Industry-Quality Control.
- Research-Mechanism of Wrinkles, Baggy Lanes.



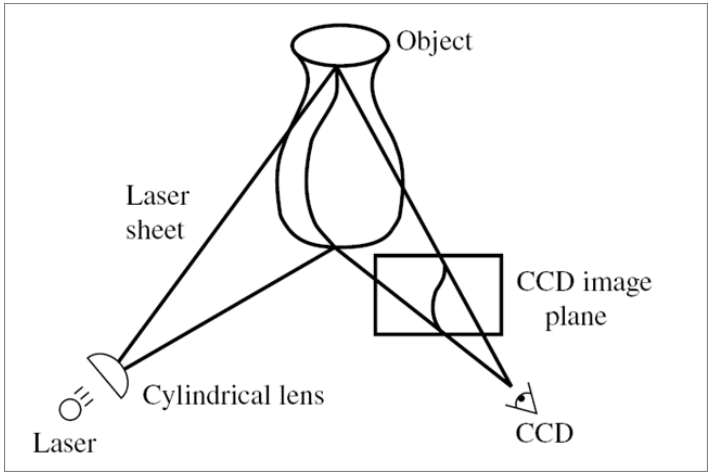
Roll Side Surface[{1}]
(http://kawbsd.net/SFAAP/pastemech/images/9.jpg)



Wrinkles and Baggy Lanes[{2},{3}]
(David Roisum, Web101 Courses, TAPPI PRESS)
(Land and Högberg, Progress in Paper Physics Seminar 2008)

Motivation: Optical Methods for 3D Measurement

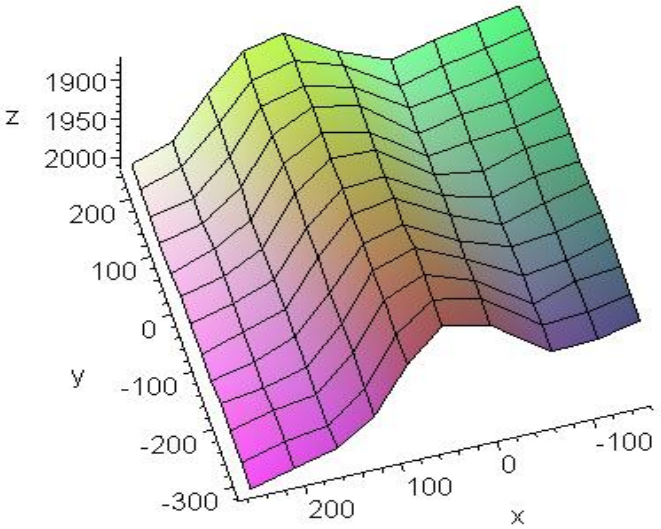
- Optical Methods
  - Laser Scanning
    - \+ High accuracy: 0.01 mm[5]
    - \- Expensive
  - Stereo Vision
    - \+ High efficiency
    - \- Less accurate than laser scanning or fringe projection
  - Fringe Projection
    - \+ High accuracy: 0.005~0.01 mm
    - \+ High efficiency
    - \+ Inexpensive
- Optical Methods vs. Traditional Methods
  - Non-contact
  - Full-field Measurement
  - High Efficiency



{5}


{5}

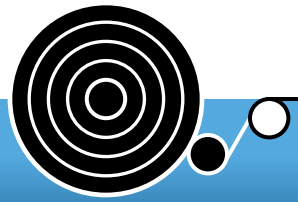
Motivation: Previous Work



"Characterization of height profile of baggy lanes using stereo vision method" by Haowen Yu and Jo-Ong Edmond Poh, 2004

Motivation: Objective

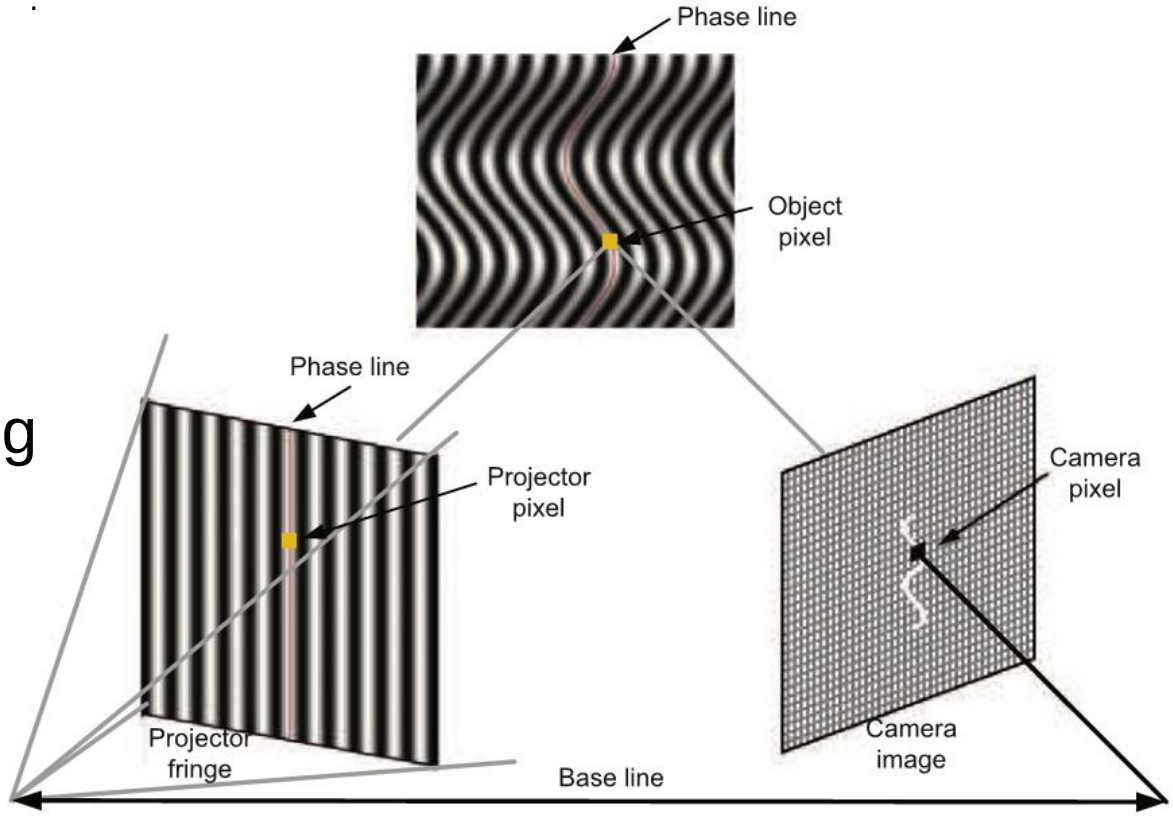
- Develop a system using Fringe Projection Technique
  - Using some off-the-shelf components
  - Evaluation of the system
- Explore application in Web Handing
  - Measurement of web wrinkles
  - Measurement of roll side walls



Principle of Fringe Projection

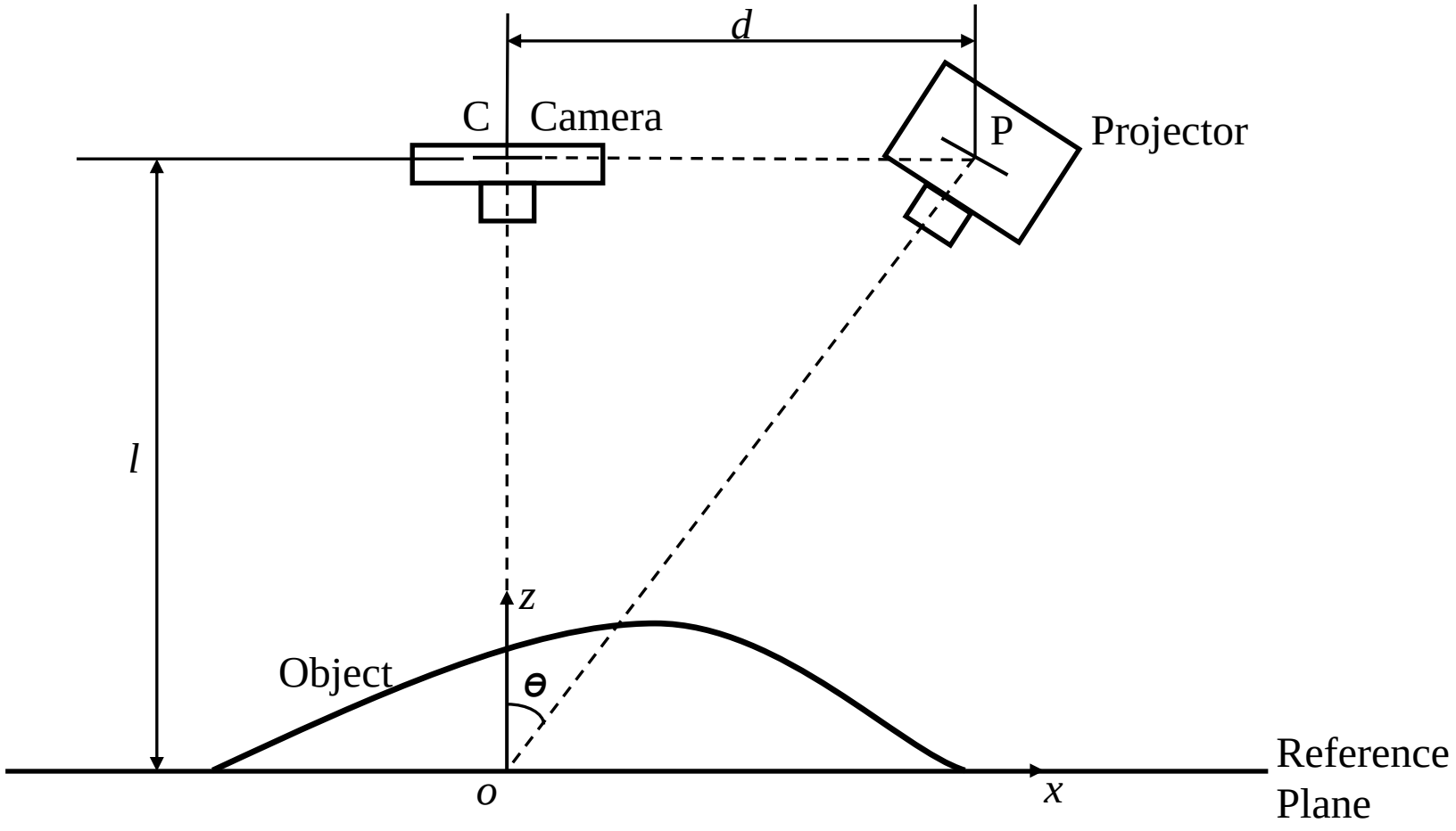
The first use of fringe projection for determining surface profile was presented by Rowe and Welford in 1967[{6}].

- Triangulation
- Phase to Length
- Phase Extraction
- Phase Unwrapping

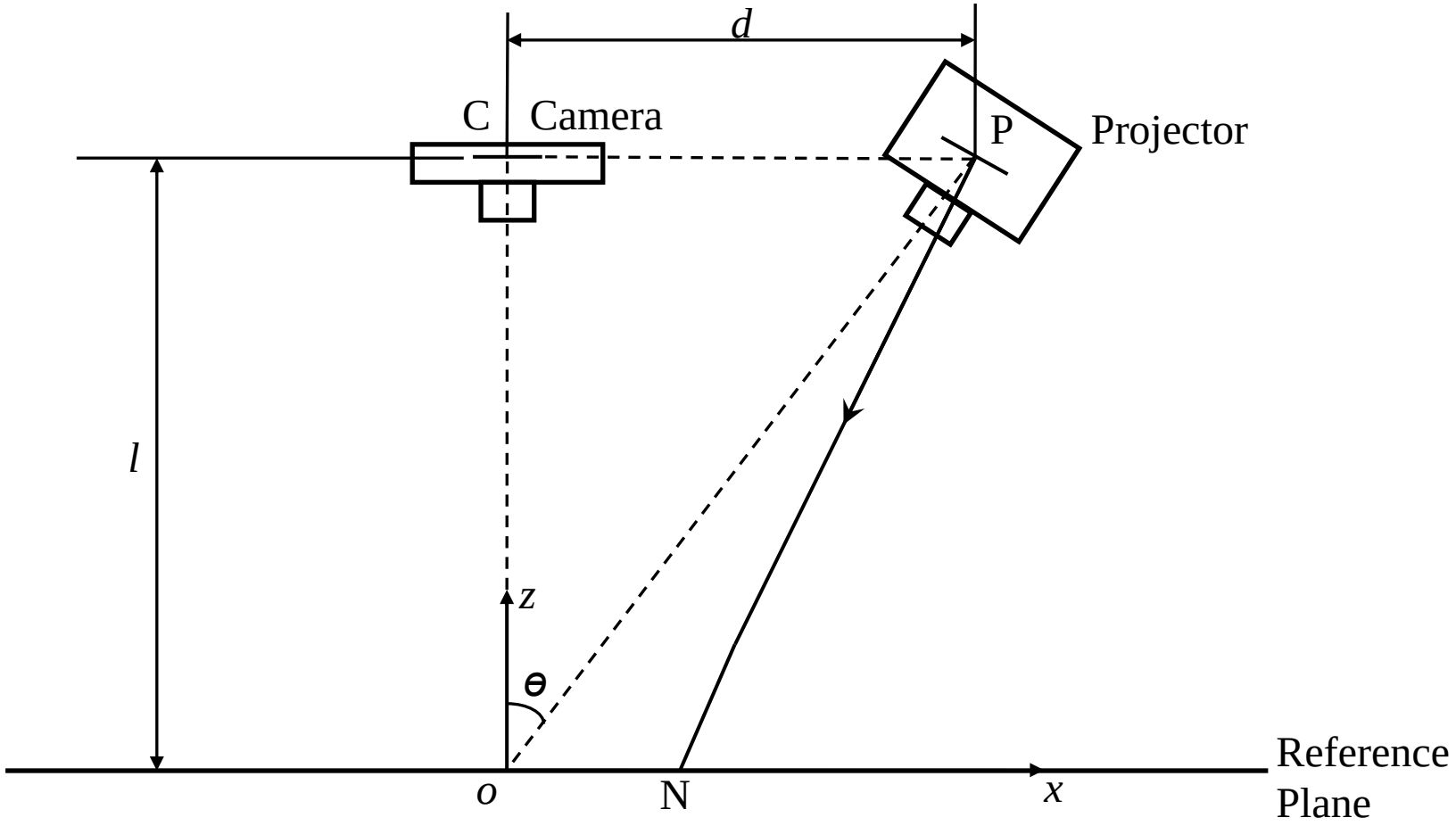


Digital Fringe Projection System[{4}]

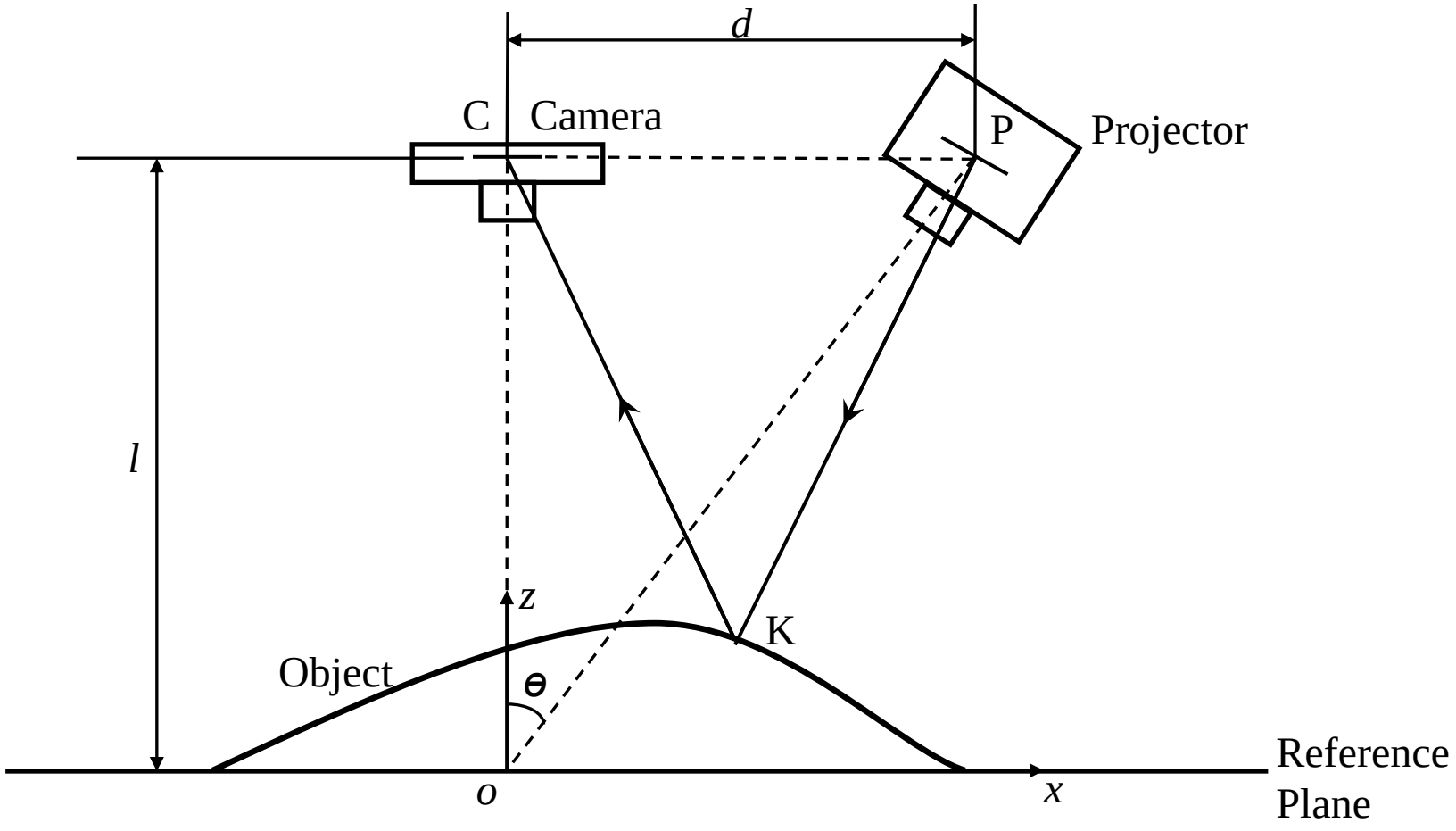
Principle: Setup



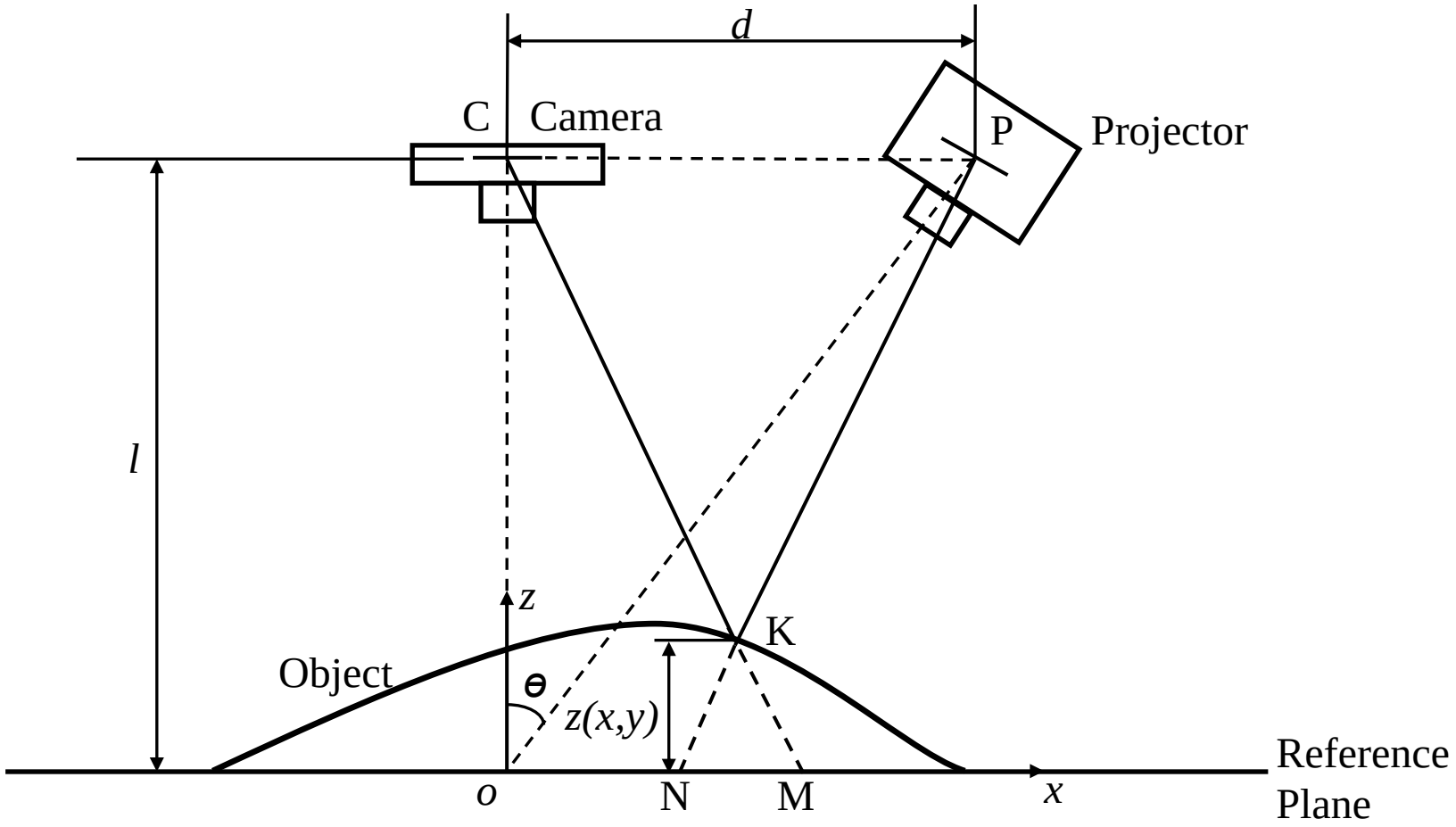
Principle: Triangulation



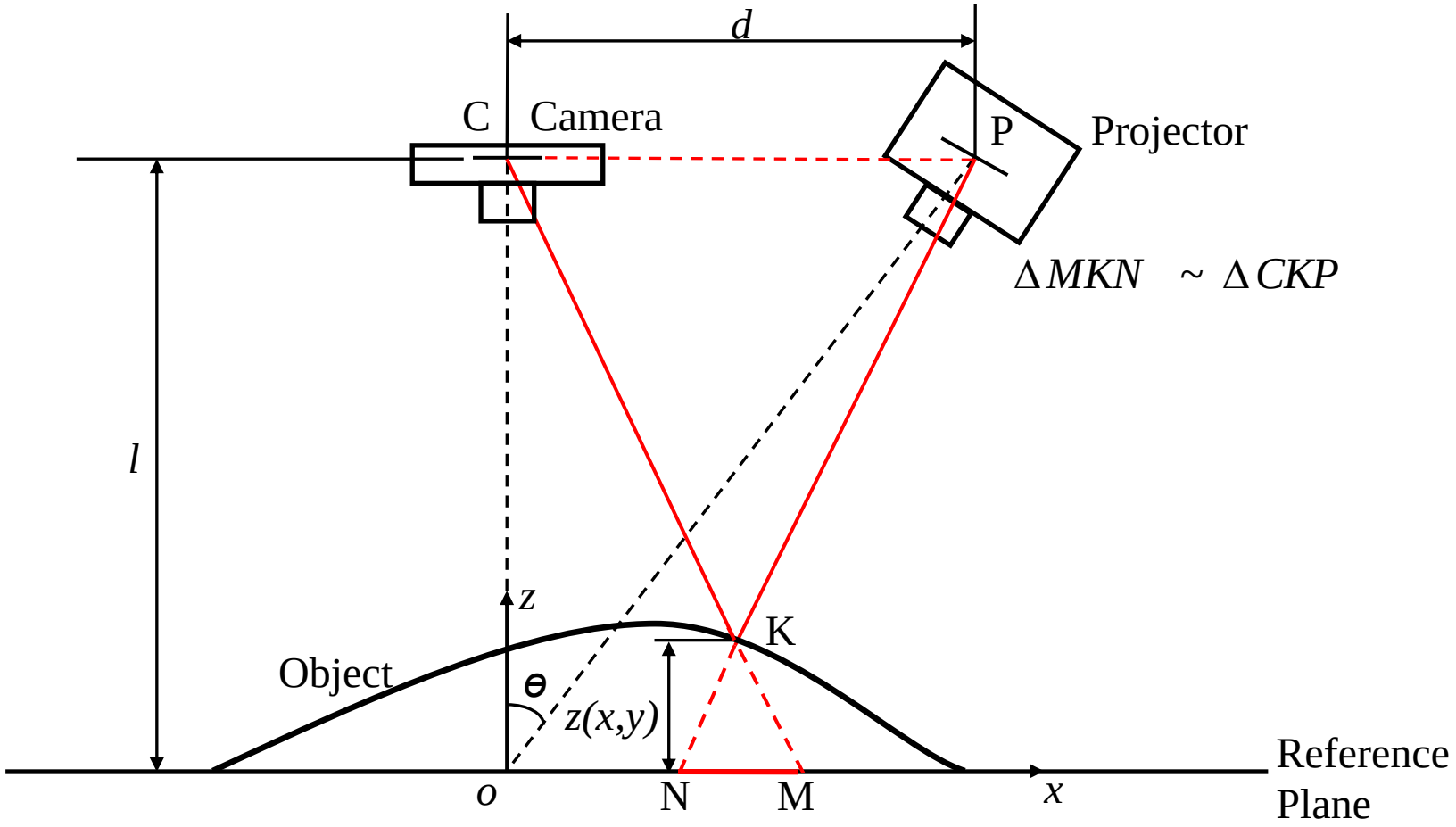
Principle: Triangulation



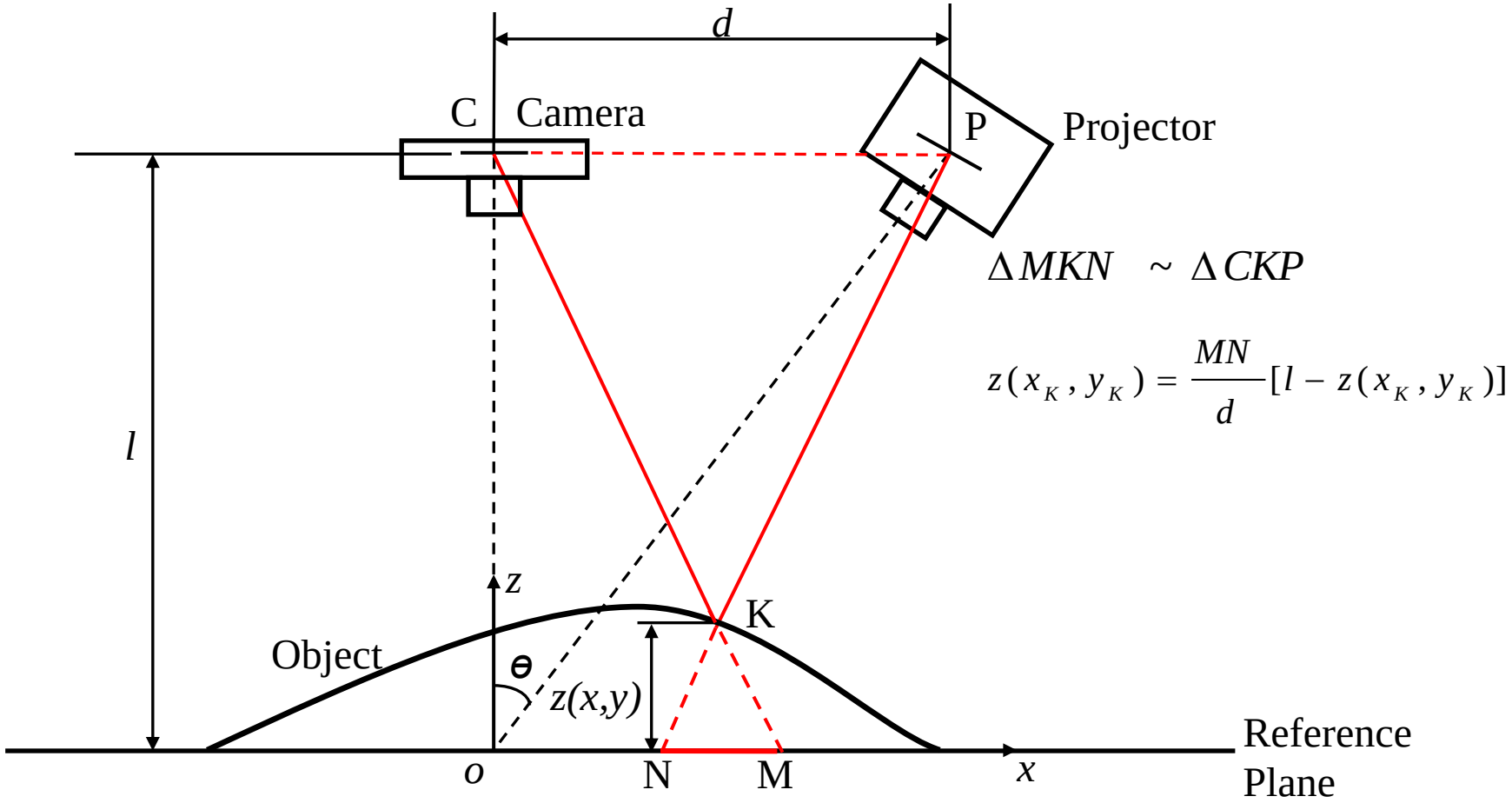
Principle: Triangulation



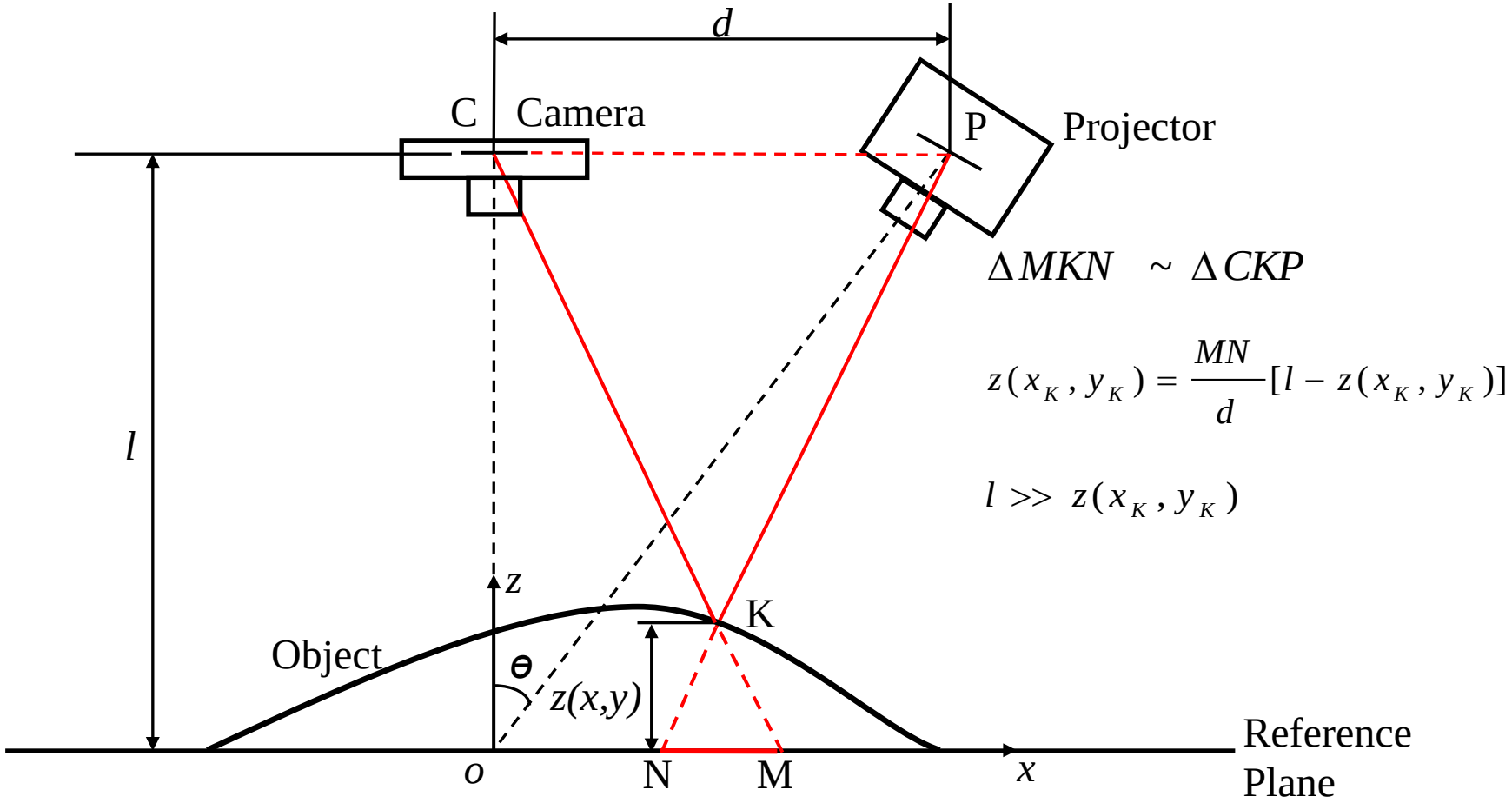
Principle: Triangulation



Principle: Triangulation



Principle: Triangulation

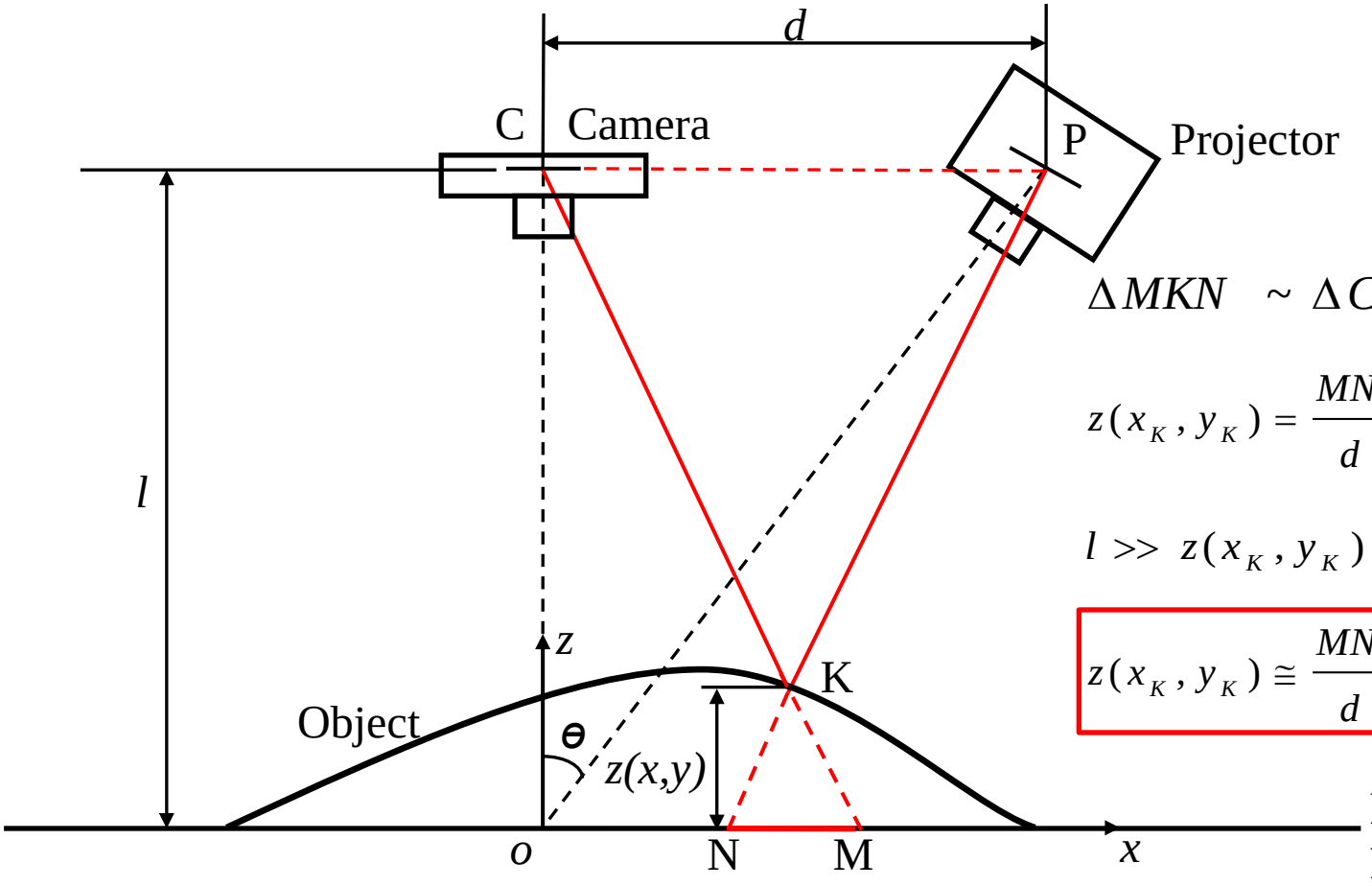


$$\Delta MKN \sim \Delta CKP$$

$$z(x_K, y_K) = \frac{MN}{d}[l - z(x_K, y_K)]$$

$$l >> z(x_K, y_K)$$

Principle: Triangulation



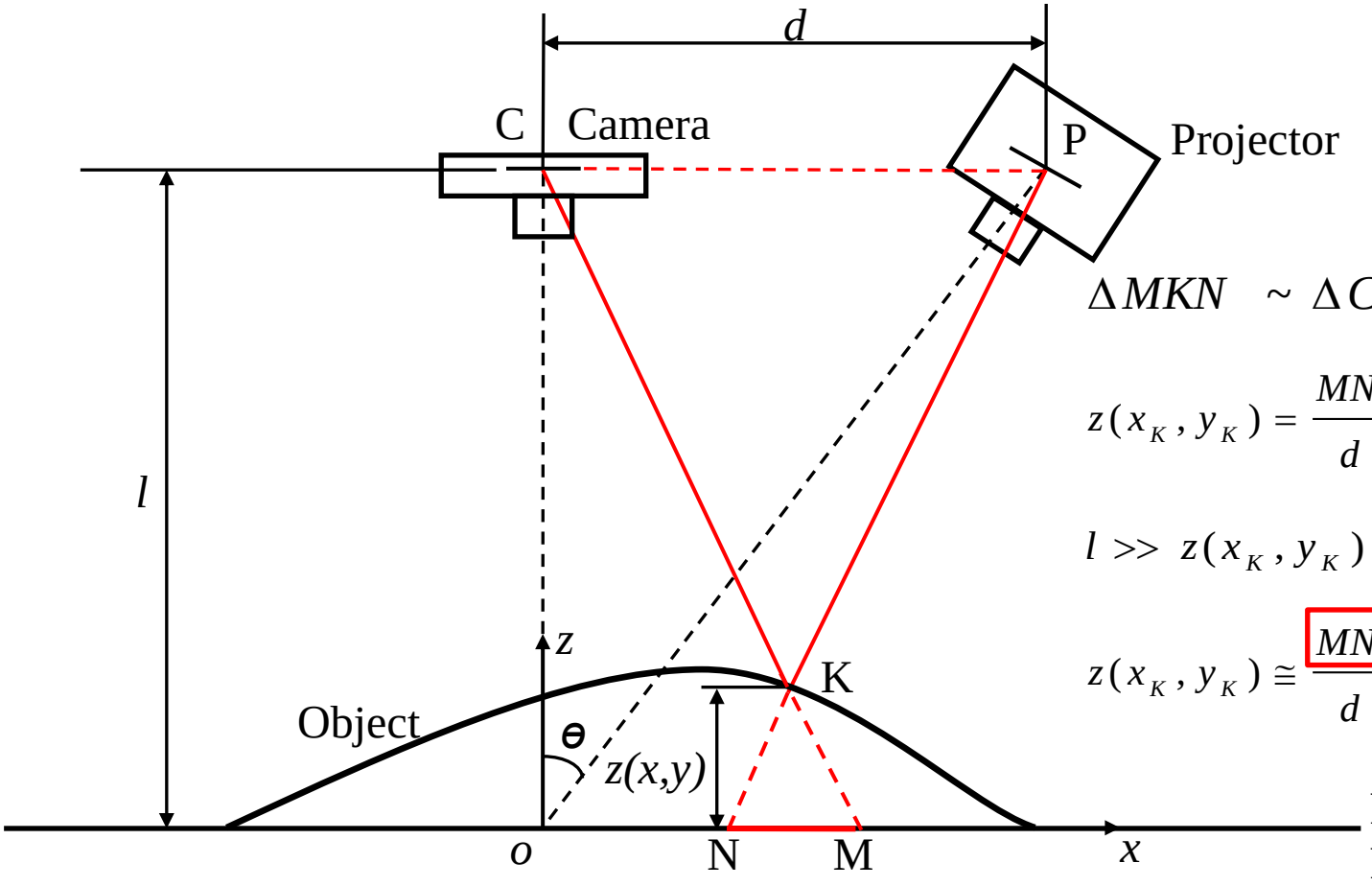
$$\Delta MKN \sim \Delta CKP$$

$$z(x_K, y_K) = \frac{MN}{d}[l - z(x_K, y_K)]$$

$$l >> z(x_K, y_K)$$

$$z(x_K, y_K) \cong \frac{MN}{d} l$$

Principle: Triangulation



$$\Delta MKN \sim \Delta CKP$$

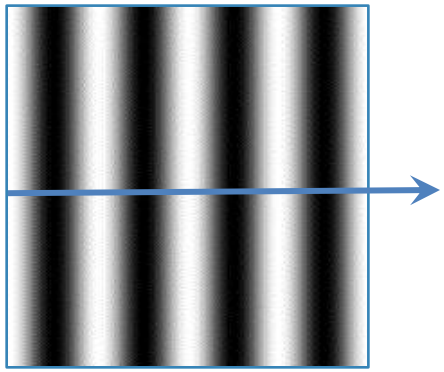
$$z(x_K, y_K) = \frac{MN}{d}[l - z(x_K, y_K)]$$

$$l >> z(x_K, y_K)$$

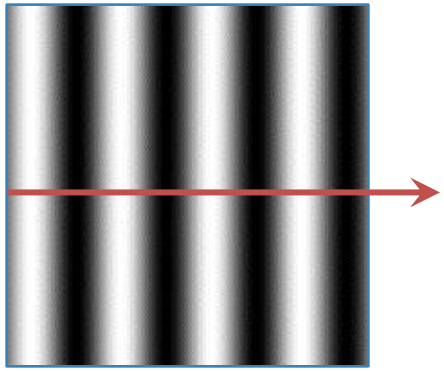
$$z(x_K, y_K) \cong \frac{MN}{d} l$$

Principle: Phase to Length

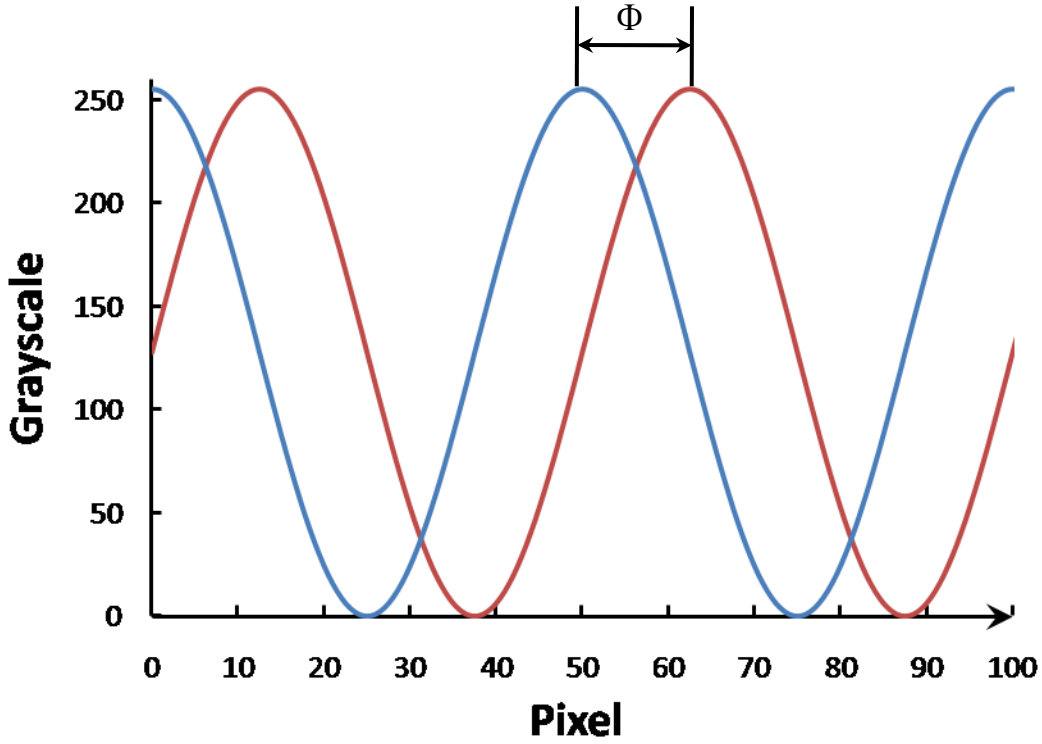
MN is determined by phase difference.



$$I_1(x, y) = 128 + 128 \cos(2\pi f_0 x)$$

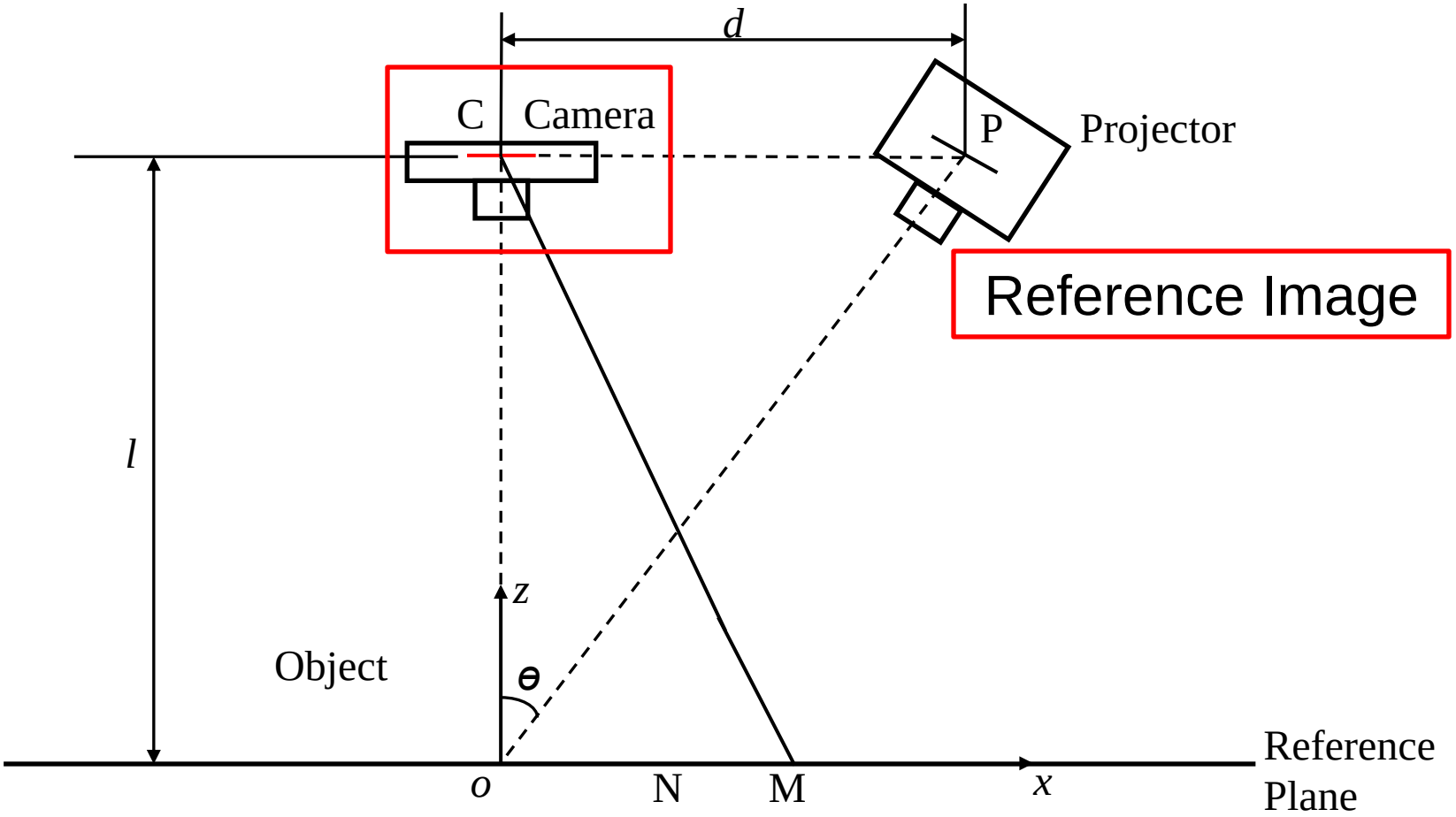


$$I_2(x, y) = 128 + 128 \cos[2\pi f_0 (x - MN)]$$
$$= 128 + 128 \cos[2\pi f_0 x - \Phi]$$

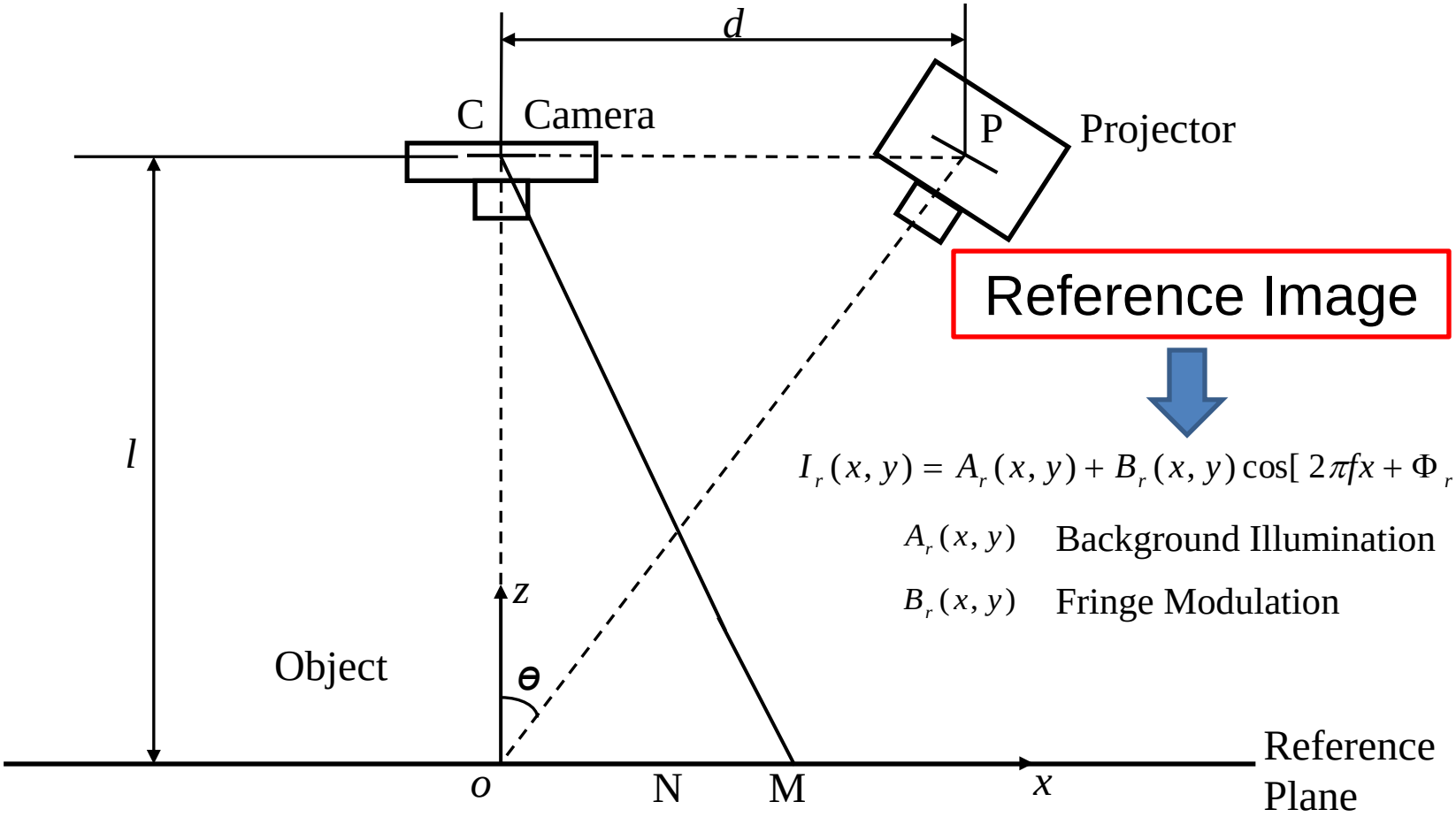


$$MN = \frac{1}{2\pi f_0}\Phi$$

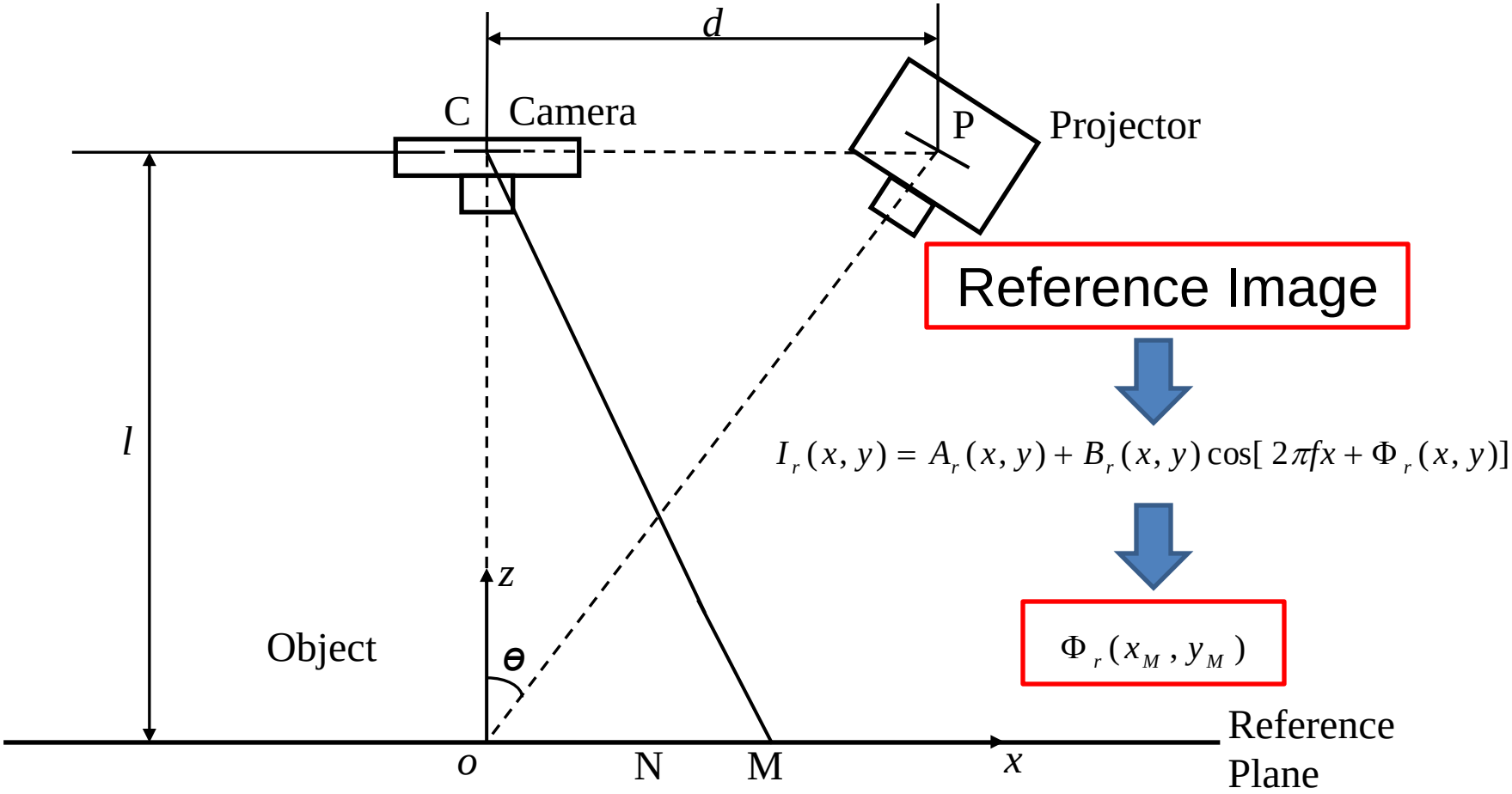
Principle: Phase to Length



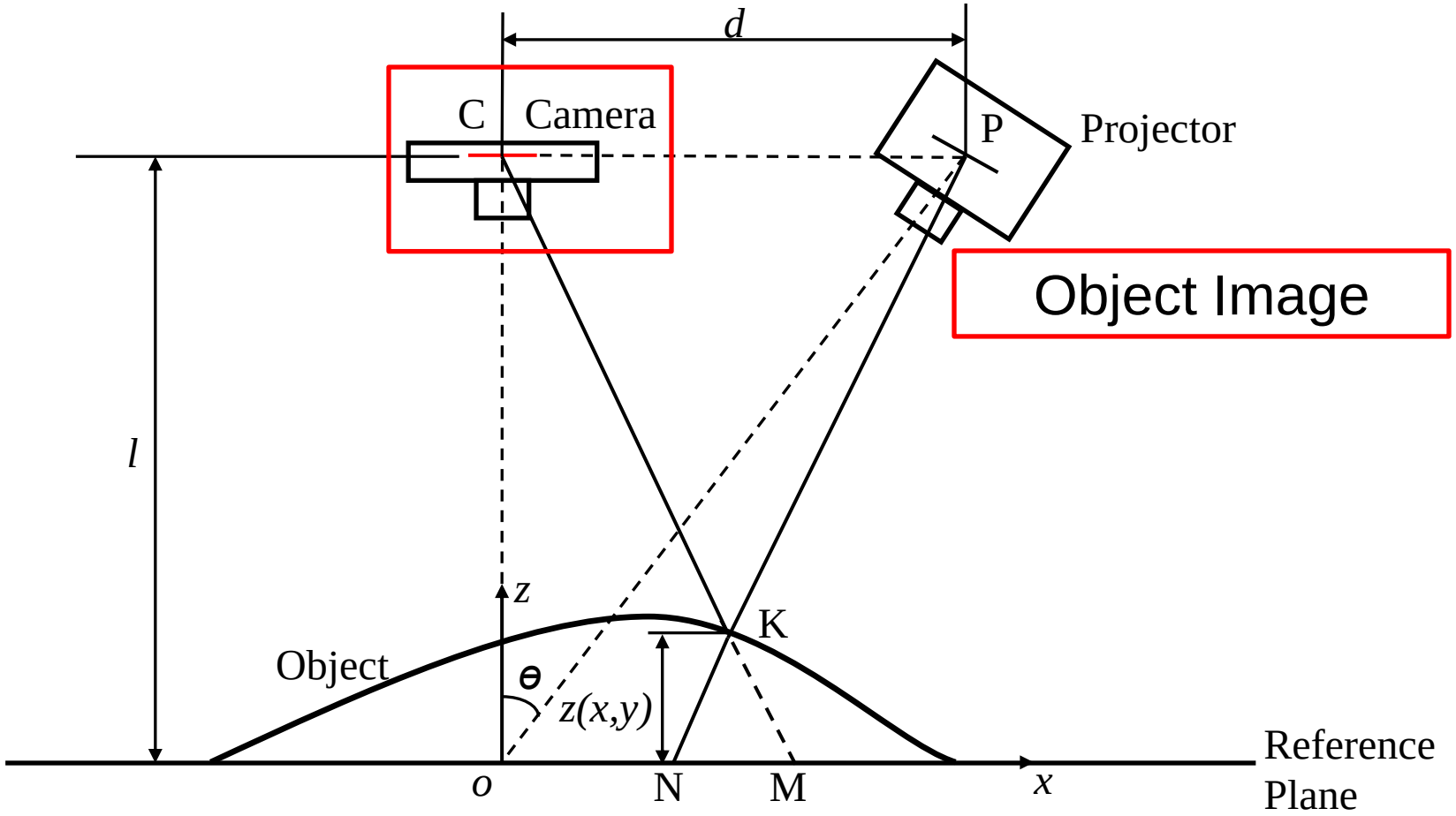
Principle: Phase to Length



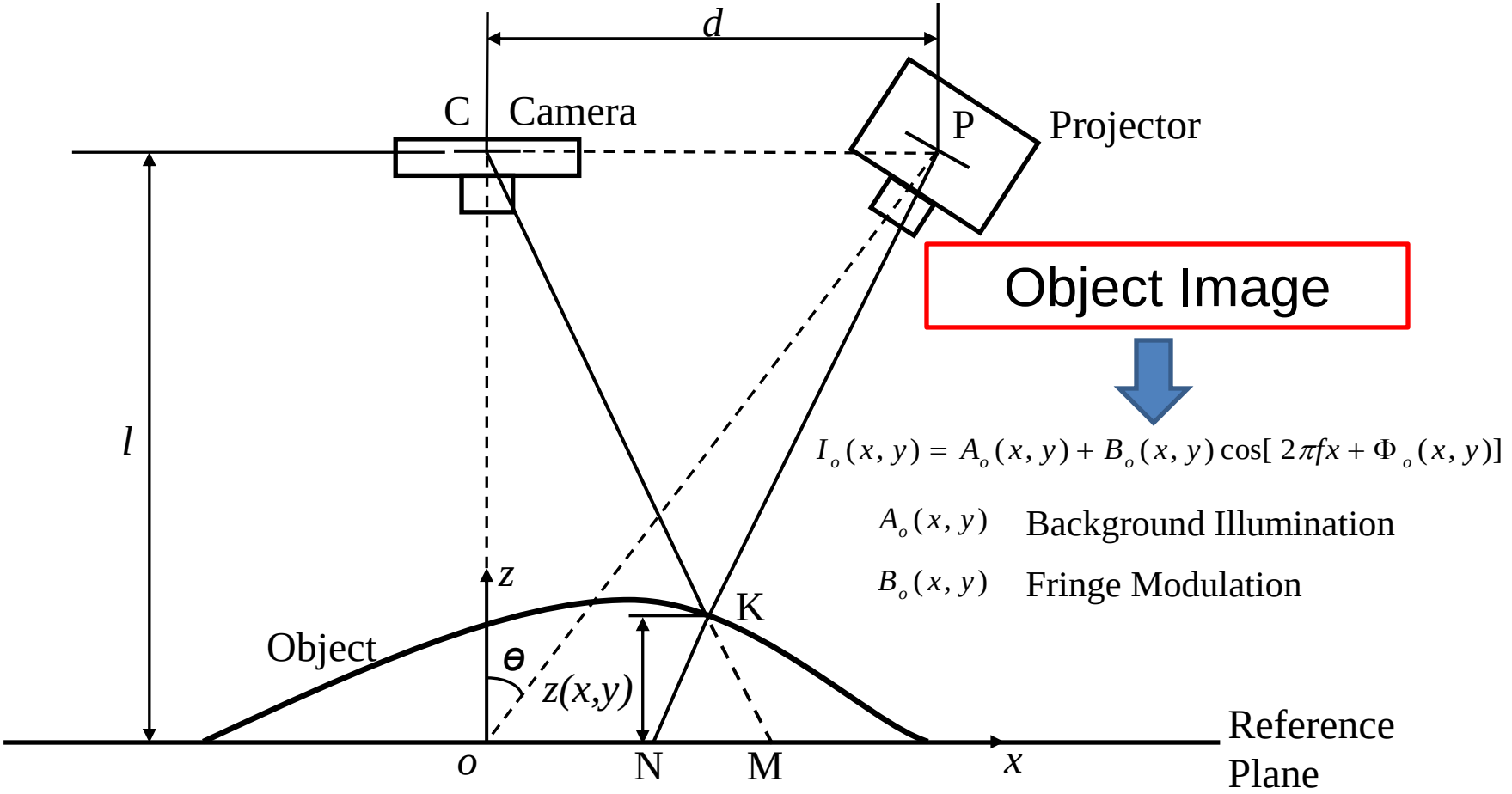
Principle: Phase to Length



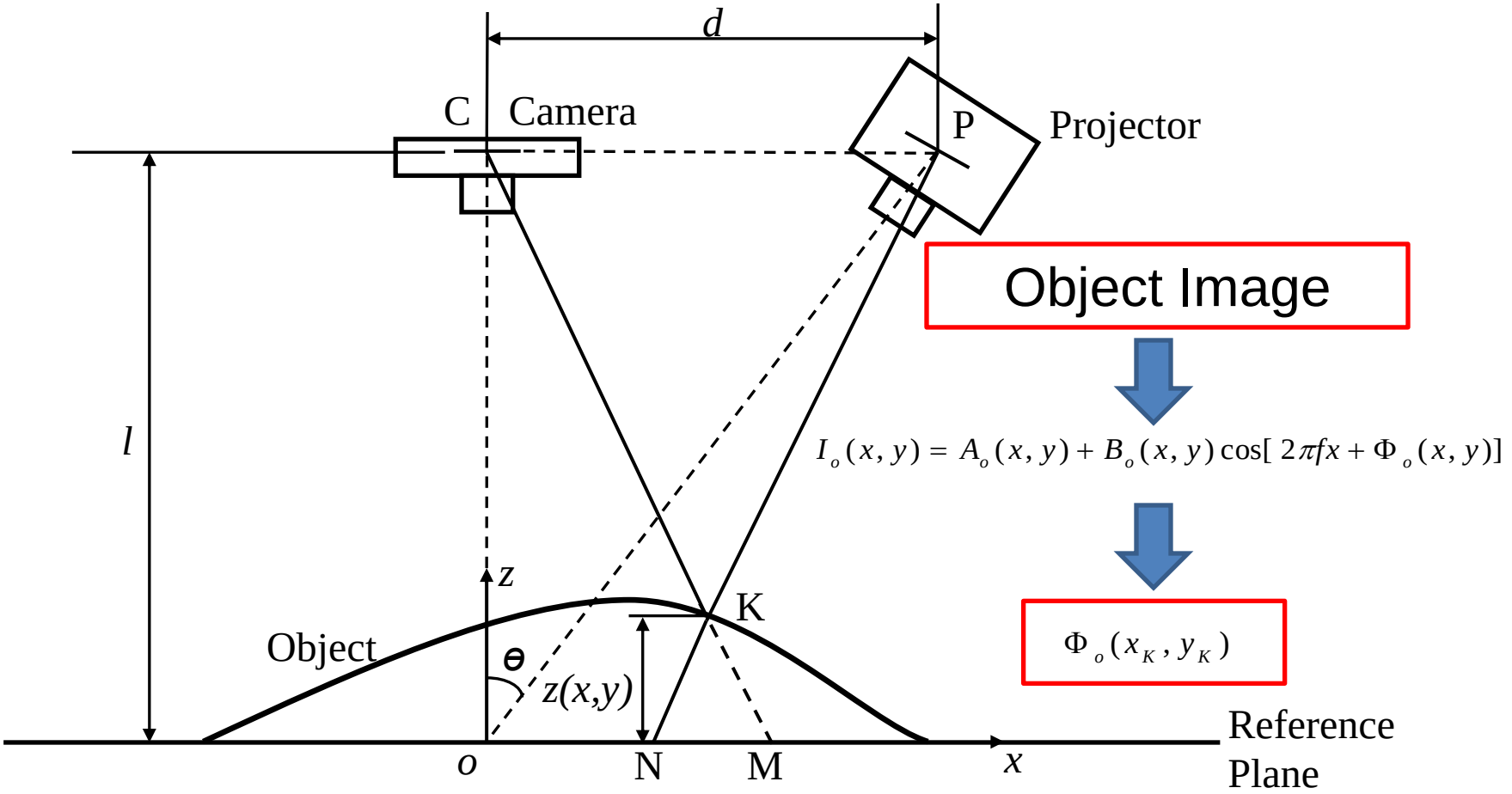
Principle: Phase to Length



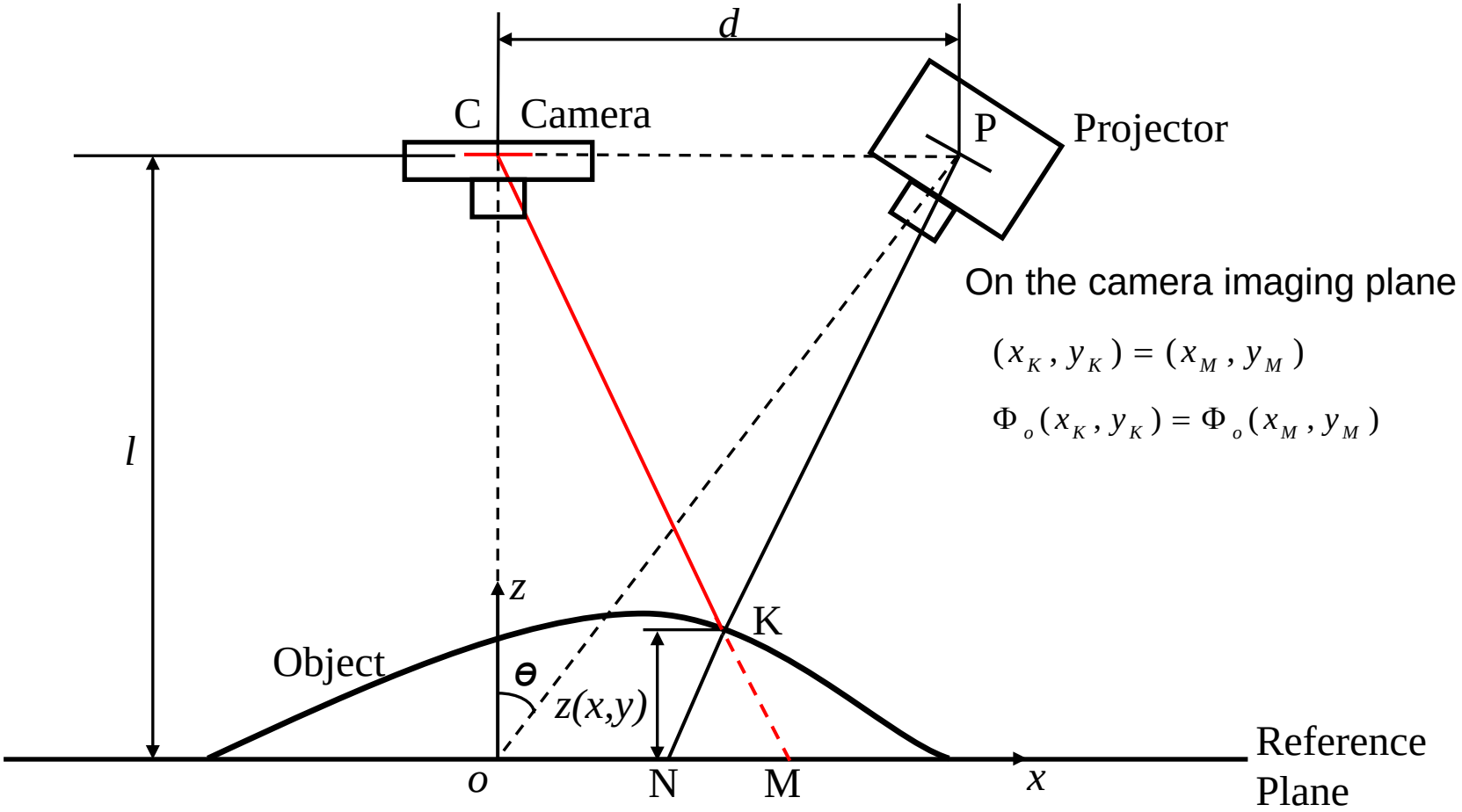
Principle: Phase to Length



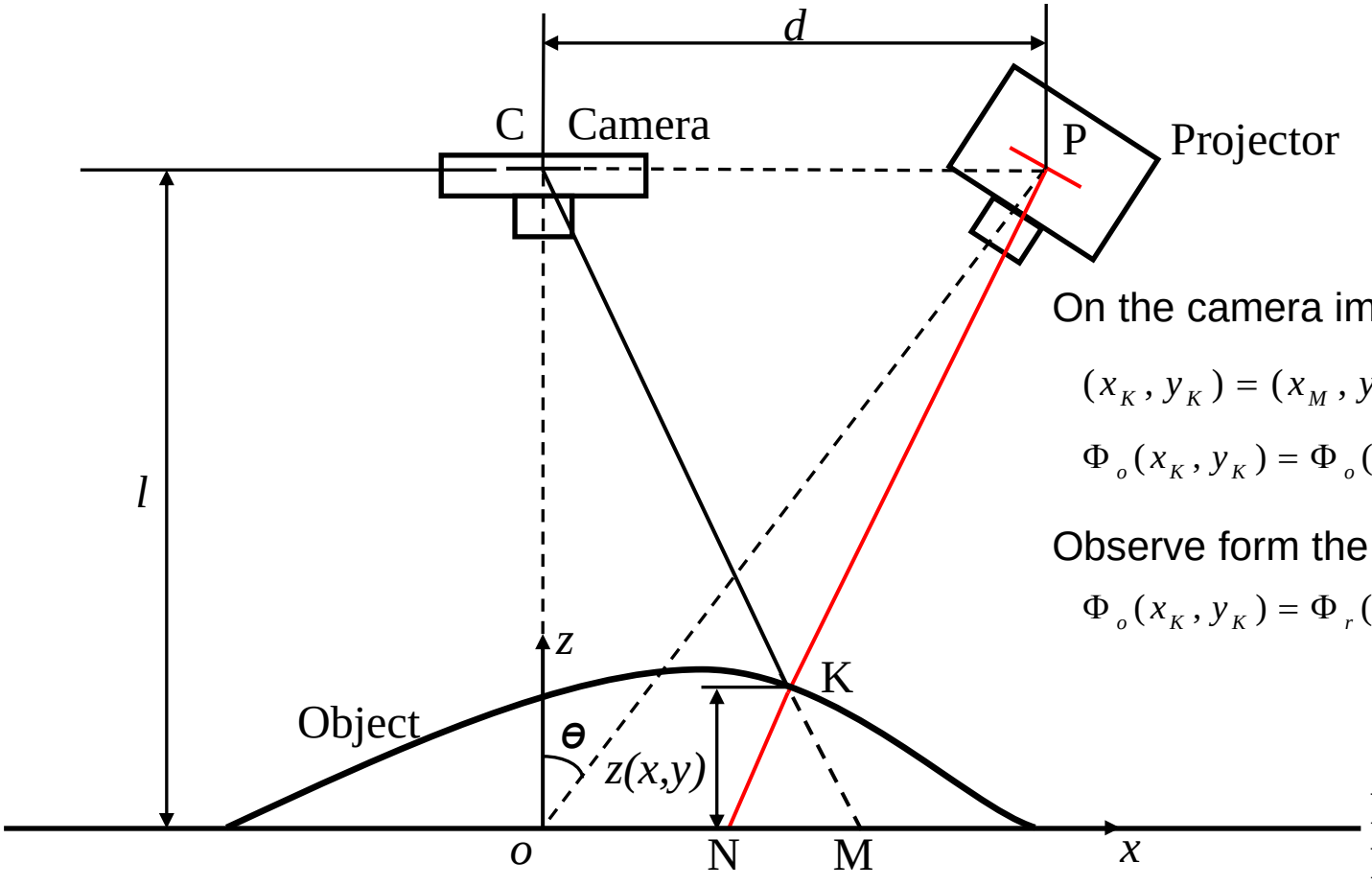
Principle: Phase to Length



Principle: Phase to Length



Principle: Phase to Length



On the camera imaging plane

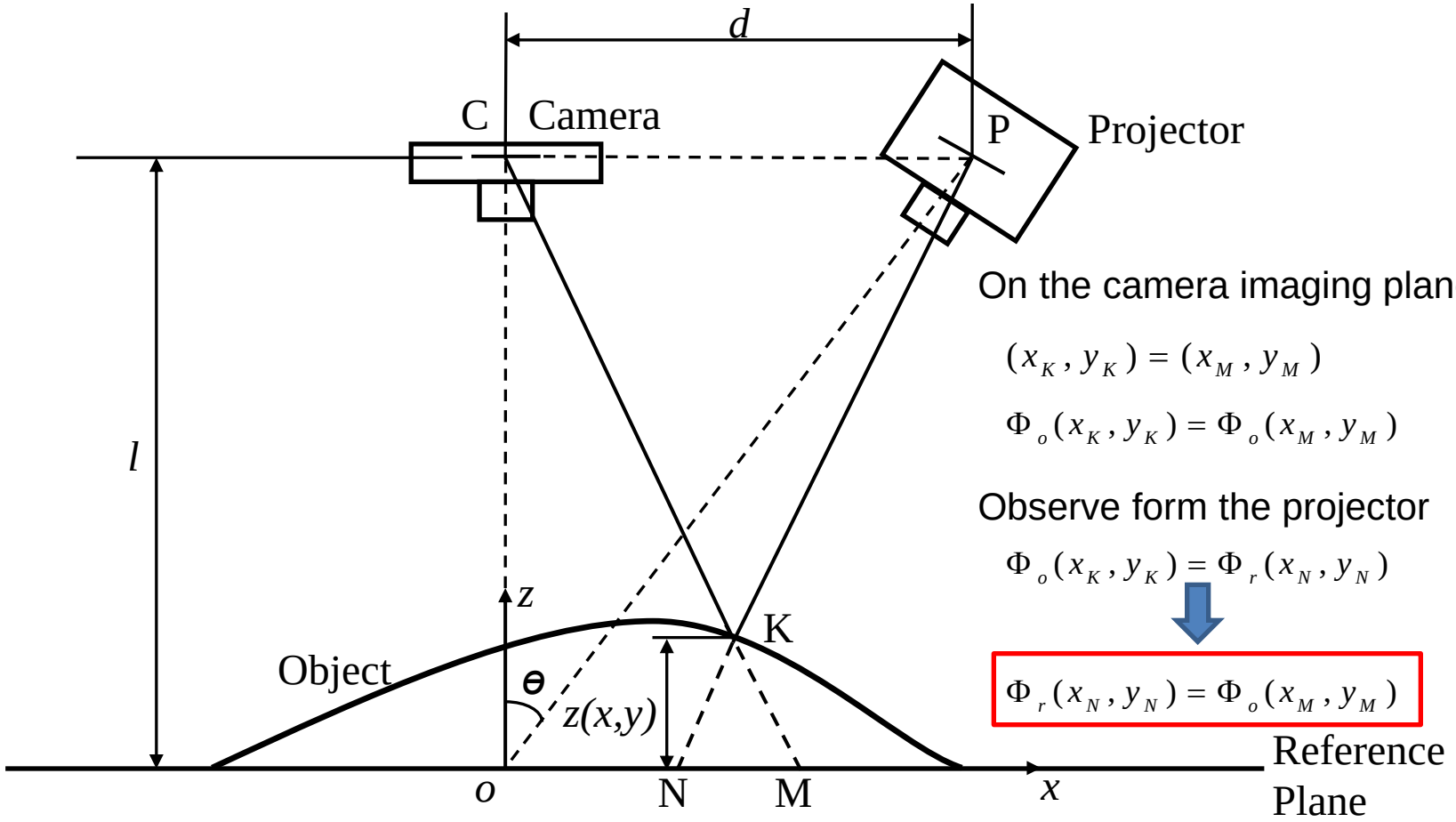
$$(x_K, y_K) = (x_M, y_M)$$

$$\Phi_o(x_K, y_K) = \Phi_o(x_M, y_M)$$

Observe form the projector

$$\Phi_o(x_K, y_K) = \Phi_r(x_N, y_N)$$

Principle: Phase to Length



On the camera imaging plane

$$(x_K, y_K) = (x_M, y_M)$$

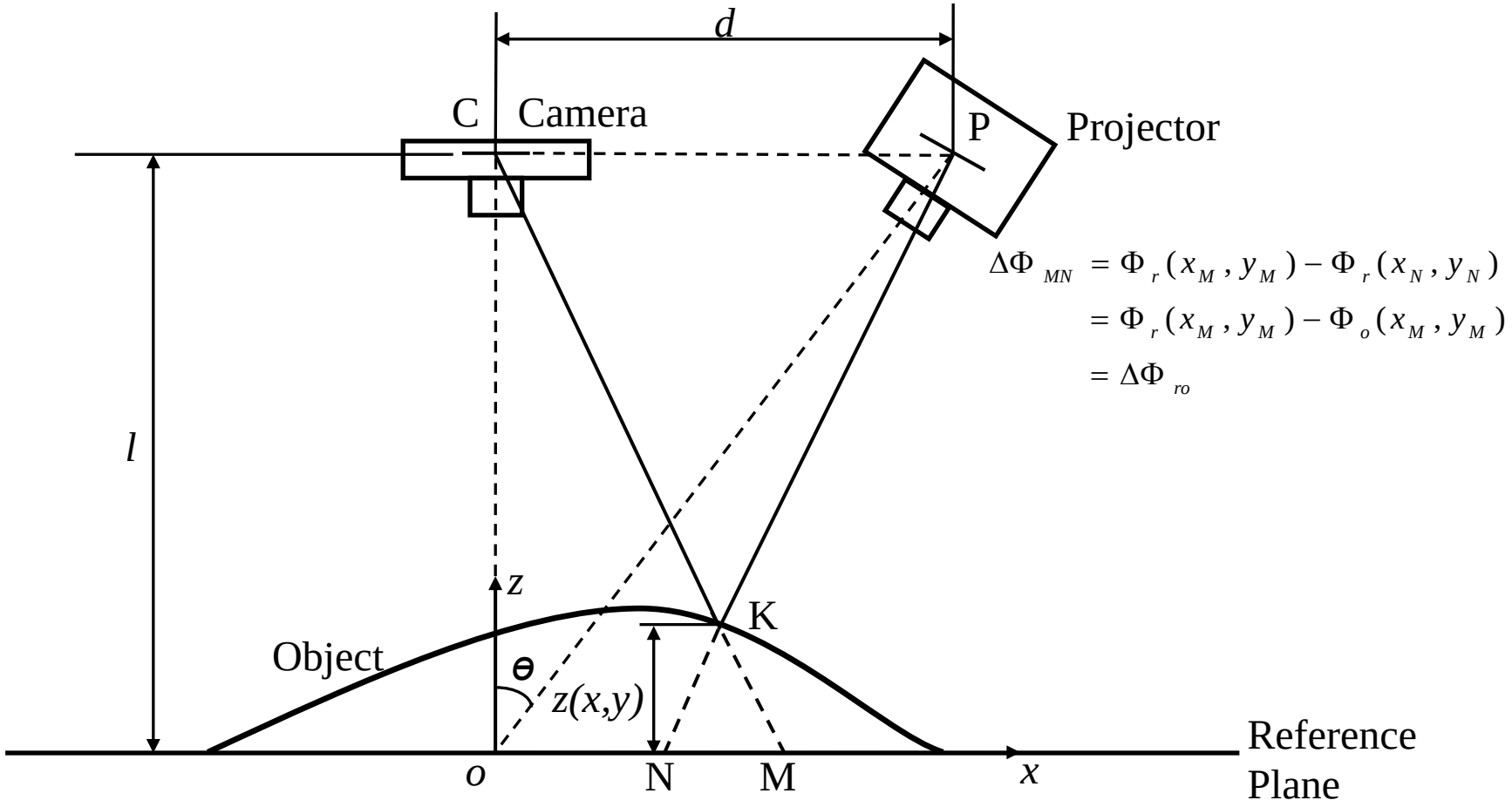
$$\Phi_o(x_K, y_K) = \Phi_o(x_M, y_M)$$

Observe form the projector

$$\Phi_o(x_K, y_K) = \Phi_r(x_N, y_N)$$

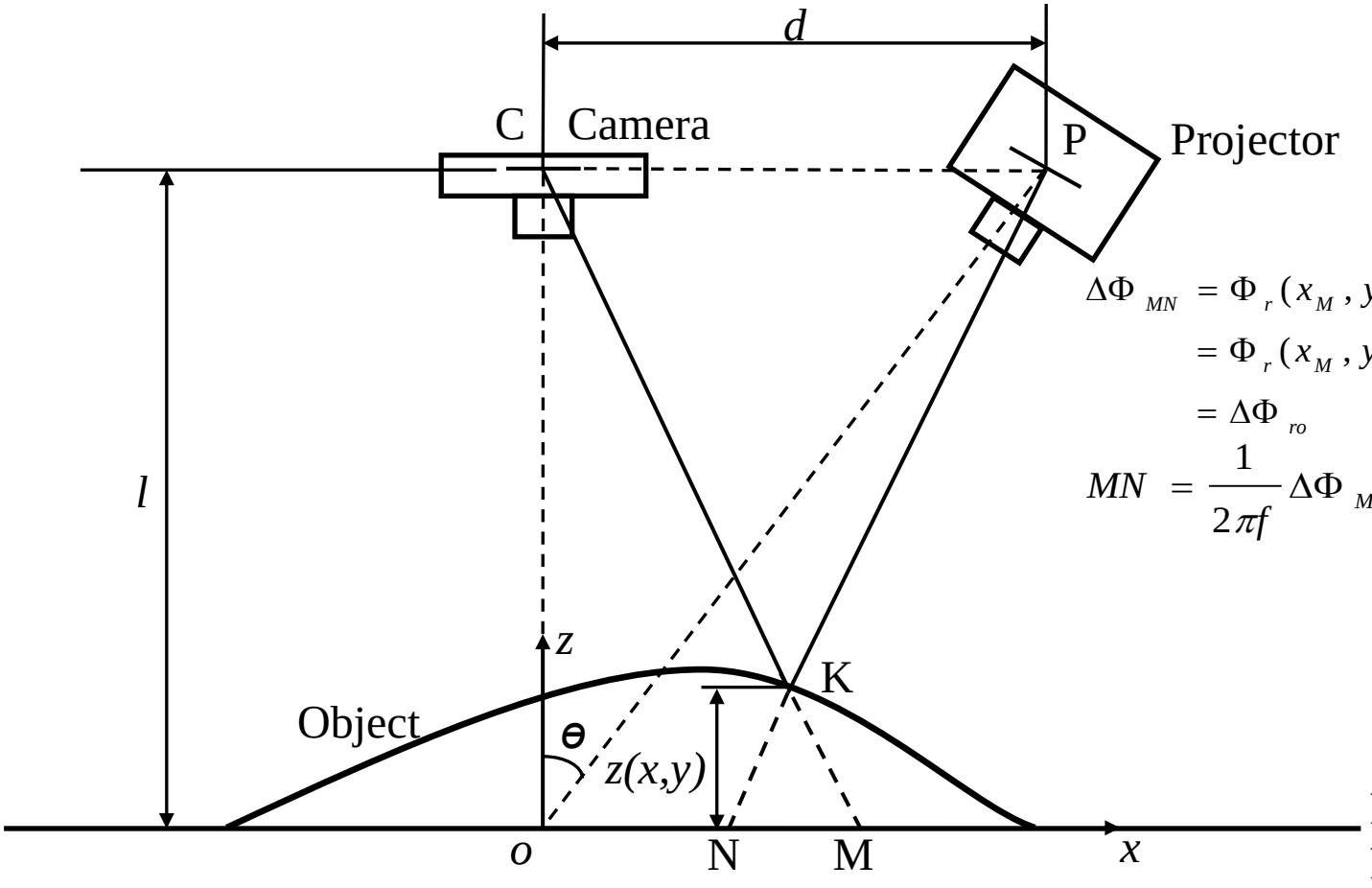
$$\Phi_r(x_N, y_N) = \Phi_o(x_M, y_M)$$

Principle: Phase to Length



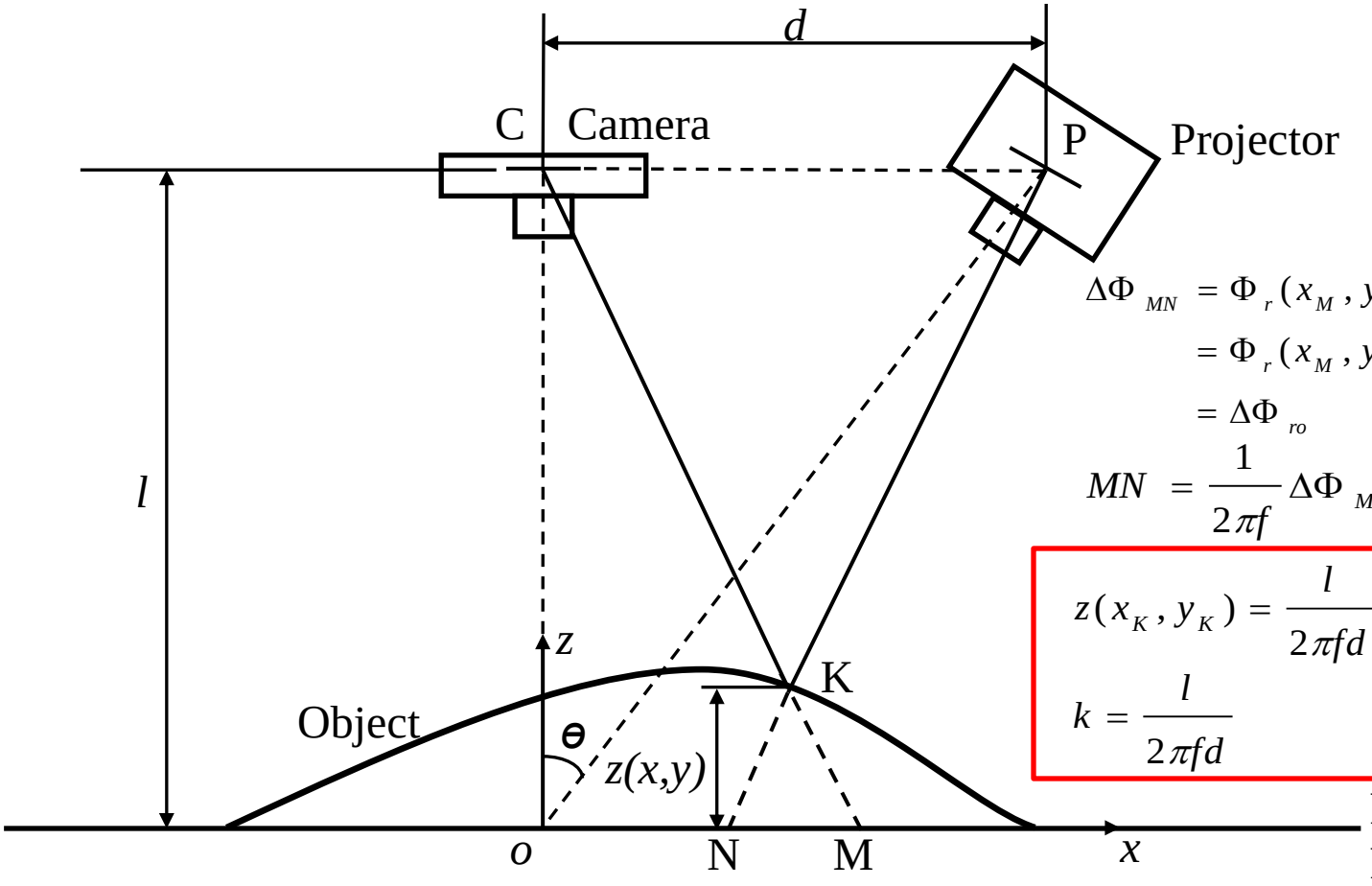
$$\Delta\Phi_{MN} = \Phi_r(x_M, y_M) - \Phi_r(x_N, y_N)$$
$$= \Phi_r(x_M, y_M) - \Phi_o(x_M, y_M)$$
$$= \Delta\Phi_{ro}$$

Principle: Phase to Length



$$\Delta\Phi_{MN} = \Phi_r(x_M, y_M) - \Phi_r(x_N, y_N)$$
$$= \Phi_r(x_M, y_M) - \Phi_o(x_M, y_M)$$
$$= \Delta\Phi_{ro}$$
$$MN = \frac{1}{2\pi f}\Delta\Phi_{MN}$$

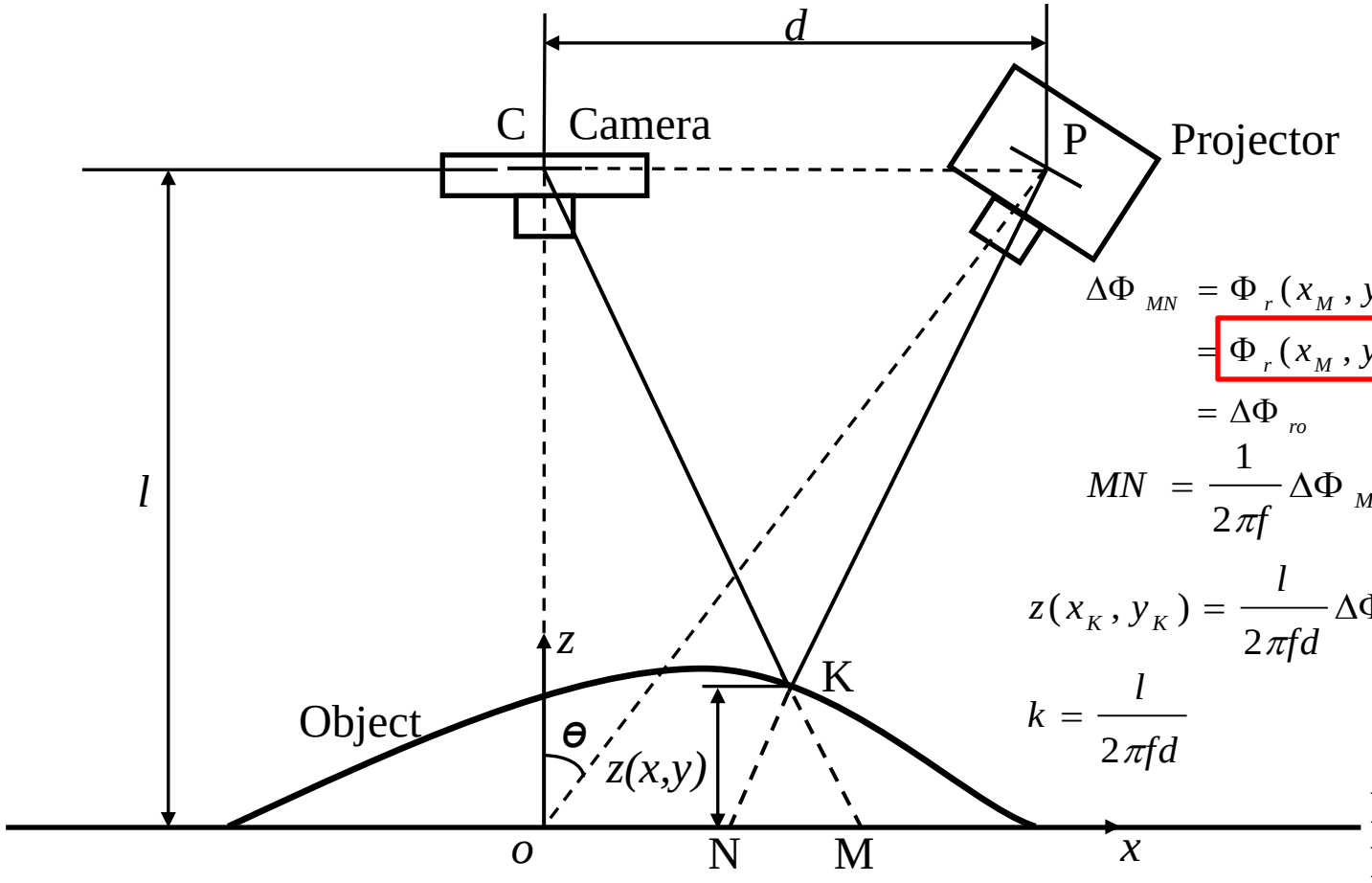
Principle: Phase to Length



$$\Delta\Phi_{MN} = \Phi_r(x_M, y_M) - \Phi_r(x_N, y_N)$$
$$= \Phi_r(x_M, y_M) - \Phi_o(x_M, y_M)$$
$$= \Delta\Phi_{ro}$$
$$MN = \frac{1}{2\pi f}\Delta\Phi_{MN}$$

$$z(x_K, y_K) = \frac{l}{2\pi f d}\Delta\Phi_{ro} = k\Delta\Phi_{ro}$$
$$k = \frac{l}{2\pi f d}$$

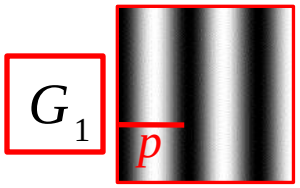
Principle: Phase to Length



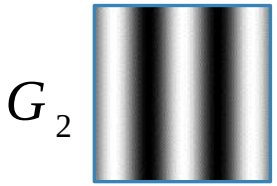
$$\Delta\Phi_{MN} = \Phi_r(x_M, y_M) - \Phi_r(x_N, y_N)$$
$$= \Phi_r(x_M, y_M) - \Phi_o(x_M, y_M)$$
$$= \Delta\Phi_{ro}$$
$$MN = \frac{1}{2\pi f}\Delta\Phi_{MN}$$
$$z(x_K, y_K) = \frac{l}{2\pi f d}\Delta\Phi_{ro} = k\Delta\Phi_{ro}$$
$$k = \frac{l}{2\pi f d}$$

Principle: Phase Extraction by Physical Shifting

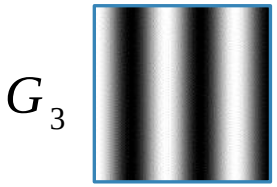
Five-step Phase Calculation Algorithm[{6},{7},{8}]



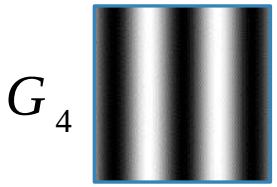
$$G_1(i,j) = G_3(i - \frac{p}{2}, j)$$



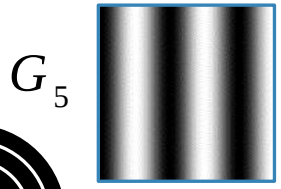
$$G_2(i,j) = G_3(i - \frac{p}{4}, j)$$



$$G_3(i,j) = 128 + 128\cos(2\pi f_0 i)$$

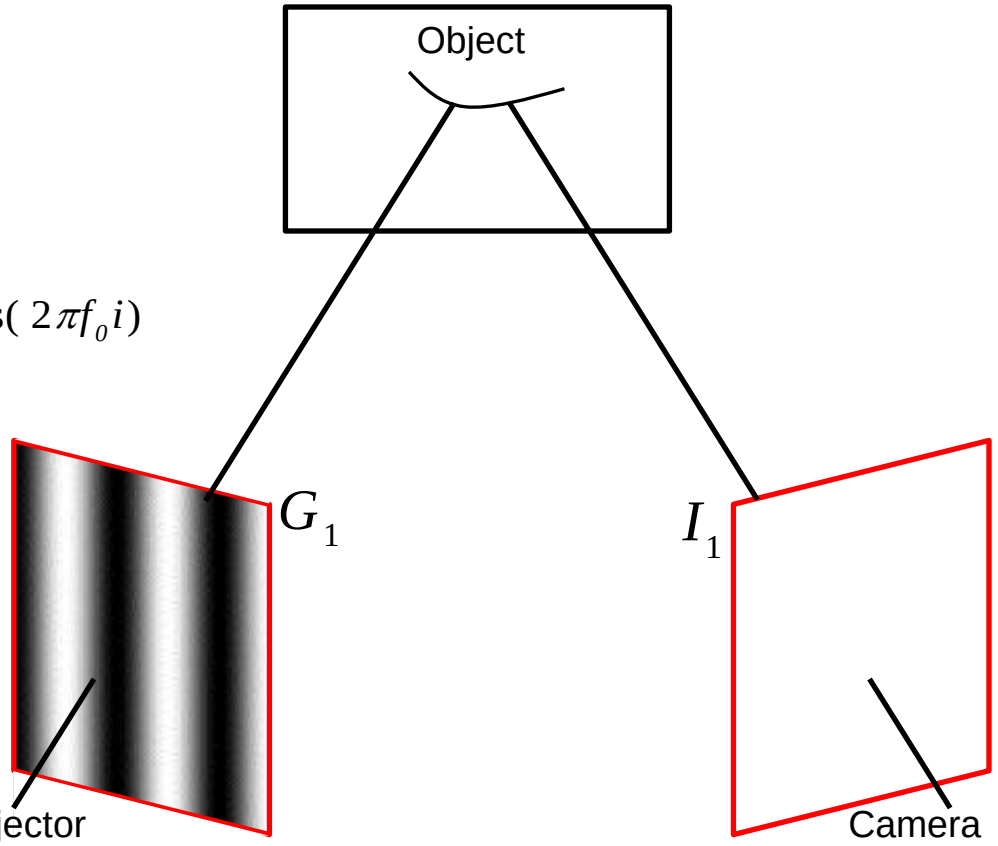


$$G_4(i,j) = G_3(i + \frac{p}{4}, j)$$



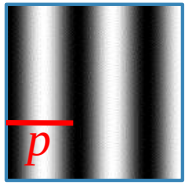
$$G_5(i,j) = G_3(i + \frac{p}{2}, j)$$

$$I_1 = A(x,y) + B(x,y)\cos[2\pi fx + \Phi(x,y) - \pi]$$

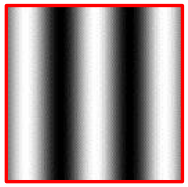


Principle: Phase Extraction by Physical Shifting

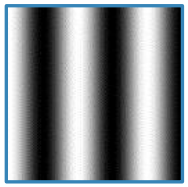
Five-step Phase Calculation Algorithm[{6},{7},{8}]

G_1 

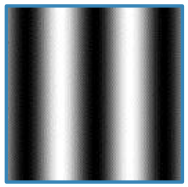
$$G_1(i, j) = G_3(i - \frac{p}{2}, j)$$

G_2 

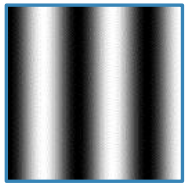
$$G_2(i, j) = G_3(i - \frac{p}{4}, j)$$

G_3 

$$G_3(i, j) = 128 + 128 \cos(2\pi f_0 i)$$

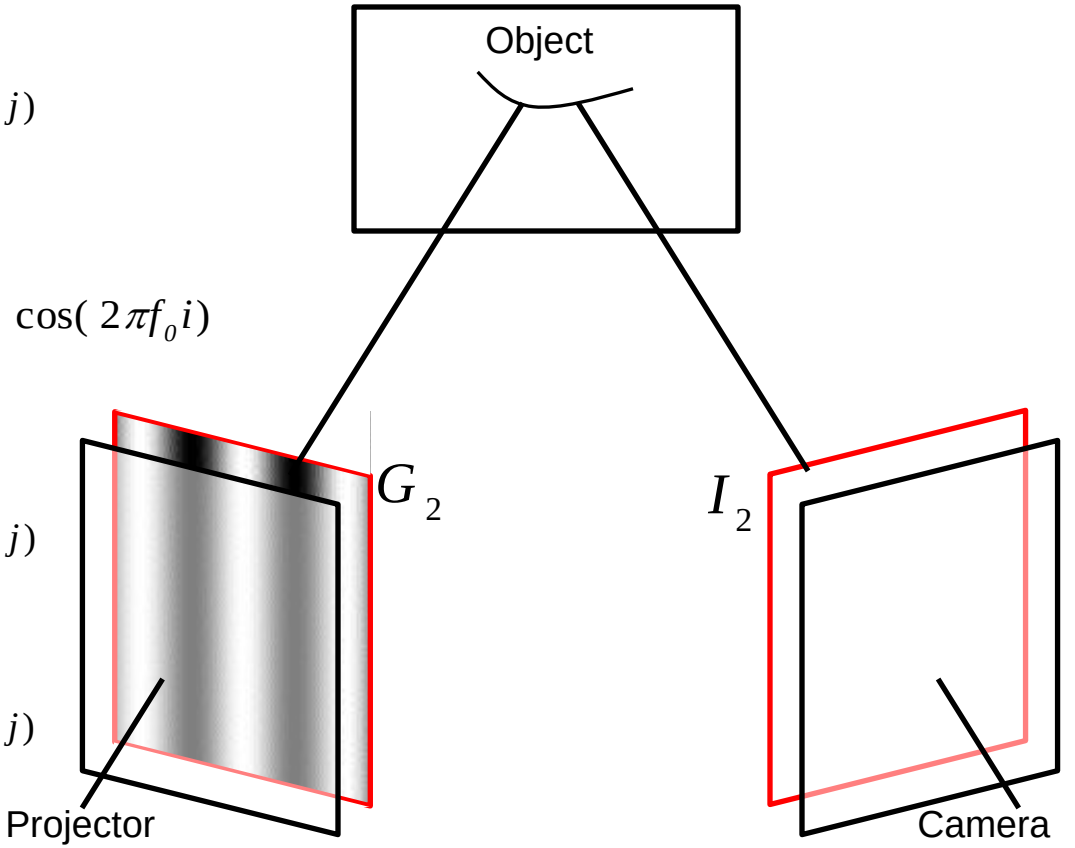
G_4 

$$G_4(i, j) = G_3(i + \frac{p}{4}, j)$$

G_5 

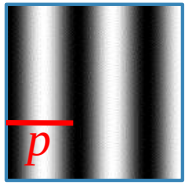
$$G_5(i, j) = G_3(i + \frac{p}{2}, j)$$

$$I_2 = A(x, y) + B(x, y) \cos[2\pi f x + \Phi(x, y) - \frac{\pi}{2}]$$



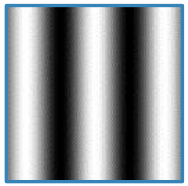
Principle: Phase Extraction by Physical Shifting

Five-step Phase Calculation Algorithm[{6},{7},{8}]



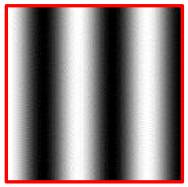
G_1

$$G_1(i, j) = G_3(i - \frac{p}{2}, j)$$



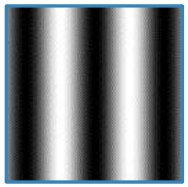
G_2

$$G_2(i, j) = G_3(i - \frac{p}{4}, j)$$



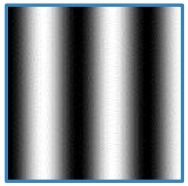
G_3

$$G_3(i, j) = 128 + 128\ \cos(2\pi f_0 i)$$



G_4

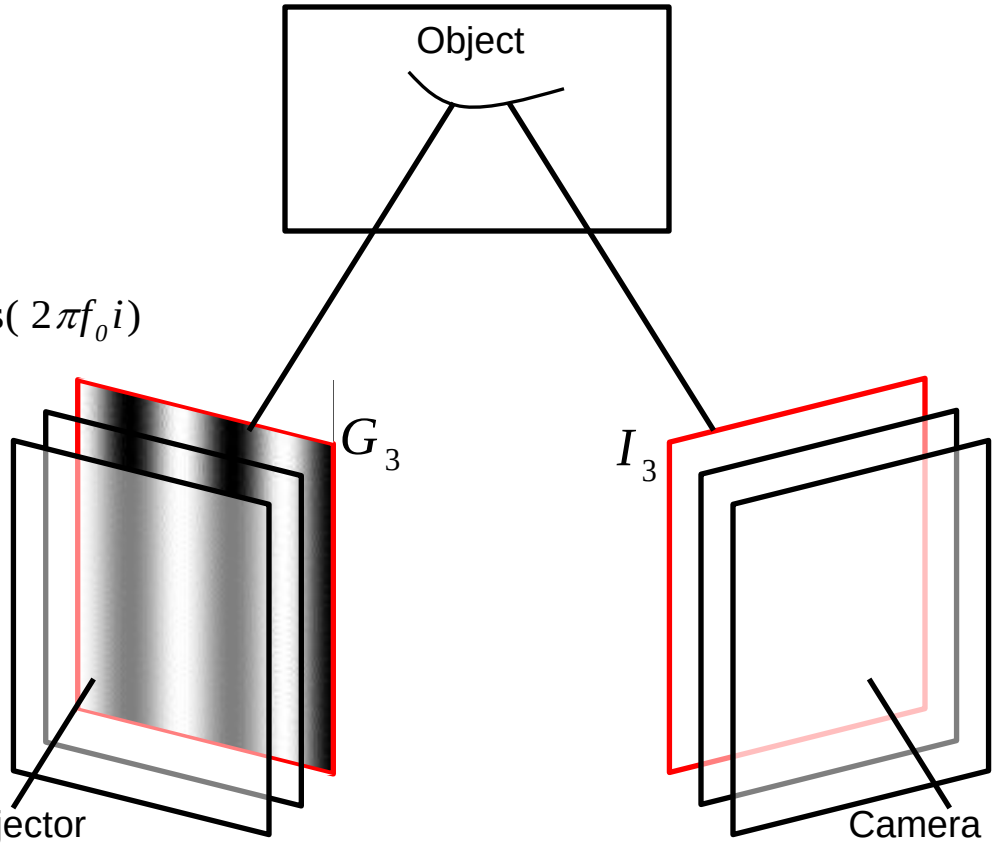
$$G_4(i, j) = G_3(i + \frac{p}{4}, j)$$



G_5

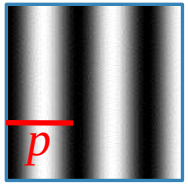
$$G_5(i, j) = G_3(i + \frac{p}{2}, j)$$

$$I_3 = A(x, y) + B(x, y)\cos[2\pi fx + \Phi(x, y)]$$

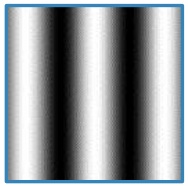


Principle: Phase Extraction by Physical Shifting

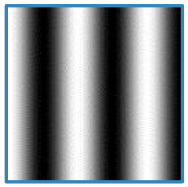
Five-step Phase Calculation Algorithm[{6},{7},{8}]

G_1 

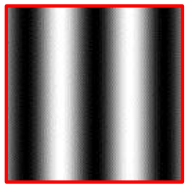
$$G_1(i, j) = G_3(i - \frac{p}{2}, j)$$

G_2 

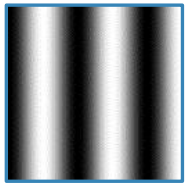
$$G_2(i, j) = G_3(i - \frac{p}{4}, j)$$

G_3 

$$G_3(i, j) = 128 + 128\cos(2\pi f_0 i)$$

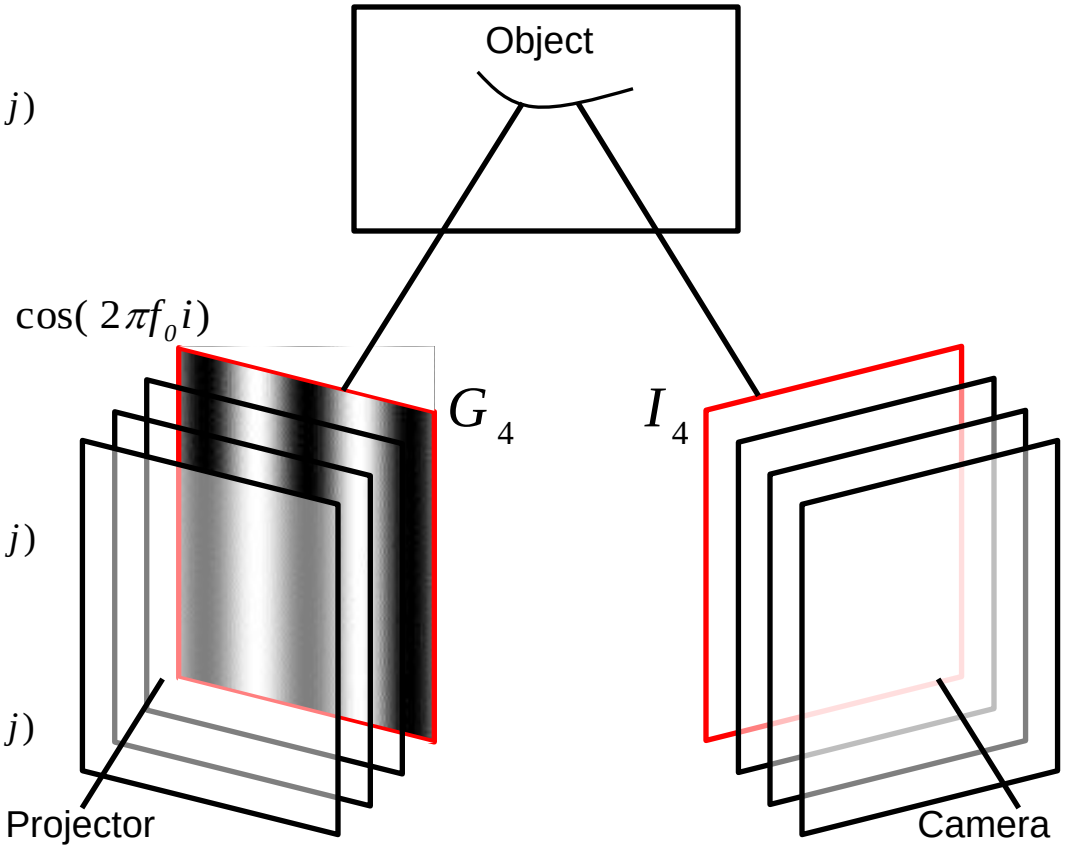
G_4 

$$G_4(i, j) = G_3(i + \frac{p}{4}, j)$$

G_5 

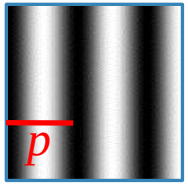
$$G_5(i, j) = G_3(i + \frac{p}{2}, j)$$

$$I_4 = A(x, y) + B(x, y)\cos[2\pi fx + \Phi(x, y) - \frac{\pi}{2}]$$

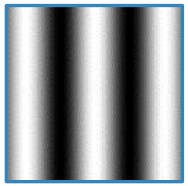


Principle: Phase Extraction by Physical Shifting

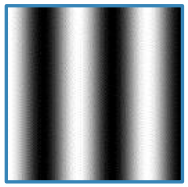
Five-step Phase Calculation Algorithm[{6},{7},{8}]

G_1 

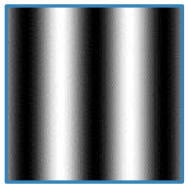
$$G_1(i, j) = G_3(i - \frac{p}{2}, j)$$

G_2 

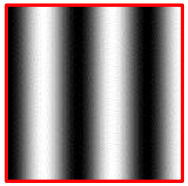
$$G_2(i, j) = G_3(i - \frac{p}{4}, j)$$

G_3 

$$G_3(i, j) = 128 + 128\ \cos(2\pi f_0 i)$$

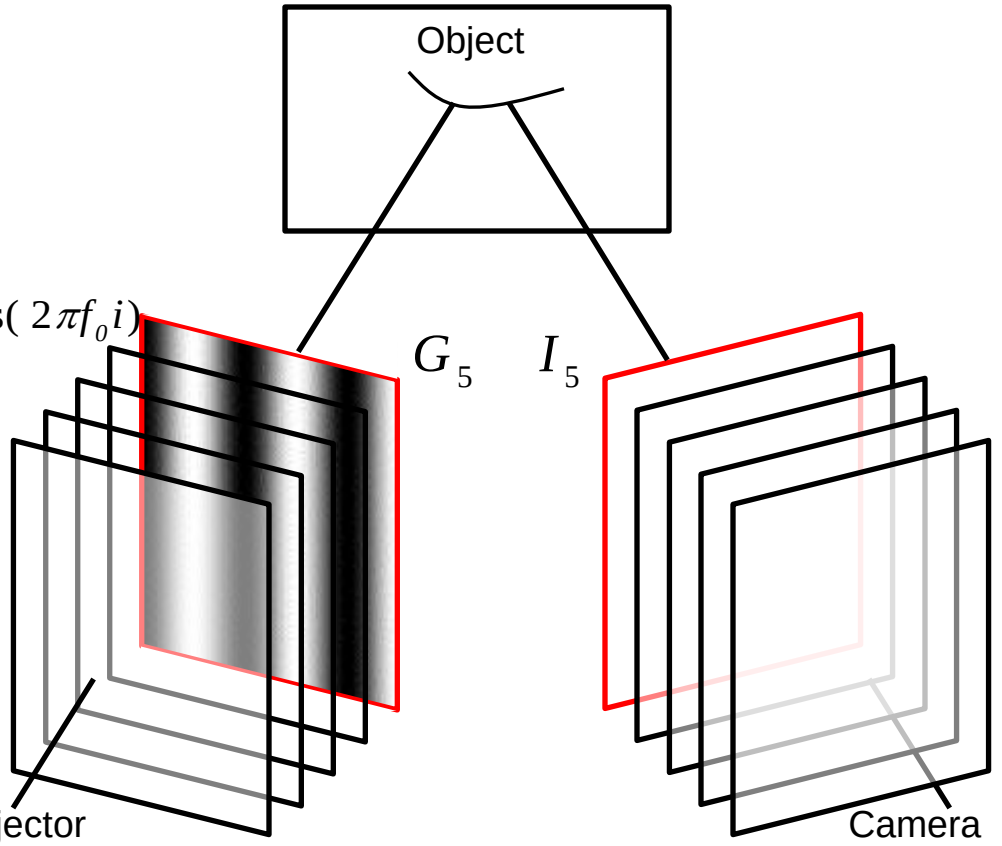
G_4 

$$G_4(i, j) = G_3(i + \frac{p}{4}, j)$$

G_5 

$$G_5(i, j) = G_3(i + \frac{p}{2}, j)$$

$$I_5 = A(x, y) + B(x, y)\cos[\,2\pi fx + \Phi(x, y) + \pi\,]$$



Principle: Phase Extraction by Physical Shifting

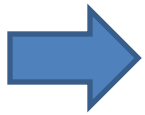
$$I_1 = A(x,y) + B(x,y)\cos[\,2\pi fx + \Phi(x,y) - \pi\,]$$

$$I_2 = A(x,y) + B(x,y)\cos[\,2\pi fx + \Phi(x,y) - \frac{\pi}{2}]$$

$$I_3 = A(x,y) + B(x,y)\cos[\,2\pi fx + \Phi(x,y)]$$

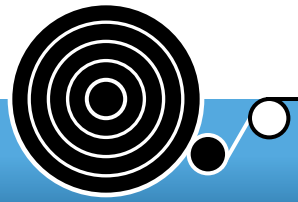
$$I_4 = A(x,y) + B(x,y)\cos[\,2\pi fx + \Phi(x,y) - \frac{\pi}{2}]$$

$$I_5 = A(x,y) + B(x,y)\cos[\,2\pi fx + \Phi(x,y) + \pi\,]$$



$$\frac{2(I_2 - I_4)}{2I_3 - I_5 - I_1} = \tan\,\Phi$$

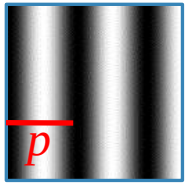
$$\Phi = \arctan(\,\frac{2(I_2 - I_4)}{2I_3 - I_5 - I_1}\,)$$



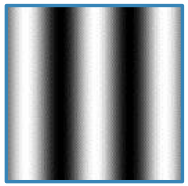
Principle: Phase Extraction by Virtual Shifting

$$I(x,y) = A + B\cos[\,2\pi fx + \Phi(x,y)]$$

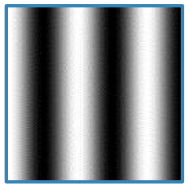
Reference Images



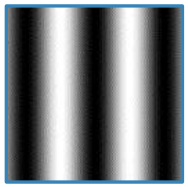
$$I_1 = A + B\cos[\,2\pi fx + \Phi(x,y) - \pi\,] = I(x - \text{int}(\,p/2), y)$$



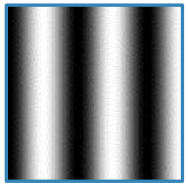
$$I_2 = A + B\cos[\,2\pi fx + \Phi(x,y) - \frac{\pi}{2}] = I(x - \text{int}(\,p/4), y)$$



$$I_3 = I(x,y)$$

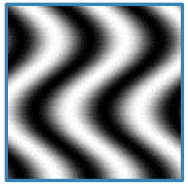


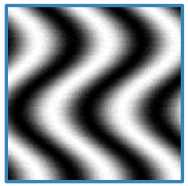
$$I_4 = A + B\cos[\,2\pi fx + \Phi(x,y) + \frac{\pi}{2}] = I(x + \text{int}(\,p/4), y)$$

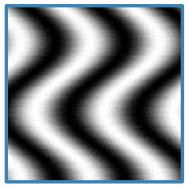


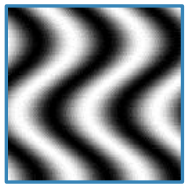
$$I_5 = A + B\cos[\,2\pi fx + \Phi(x,y) + \pi\,] = I(x + \text{int}(\,p/2), y)$$

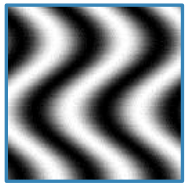
Objects Images











$$\frac{2(I_2 - I_4)}{2I_3 - I_5 - I_1} = \tan\,\Phi$$

$$\Phi = \arctan(\,\frac{2(I_2 - I_4)}{2I_3 - I_5 - I_1}\,)$$

Principle: Phase Unwrapping

$$\Phi = \arctan\left(\frac{2(I_2 - I_4)}{2I_3 - I_5 - I_1}\right)$$

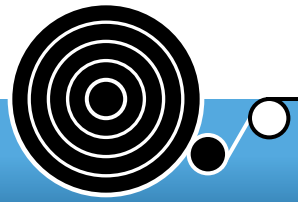
$$\Phi_r = \arctan\left(\frac{2(I_{r2} - I_{r4})}{2I_{r3} - I_{r5} - I_{r1}}\right)$$

$$\Phi_o = \arctan\left(\frac{2(I_{o2} - I_{o4})}{2I_{o3} - I_{o5} - I_{o1}}\right)$$

$$\Phi_r, \Phi_o \in [-\pi, \pi]$$

Discontinuity of 2π

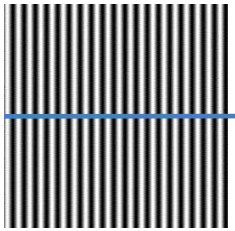
Phase unwrapping is used to detect the jumps in phase value and add proper multiples of 2π to make a continuous phase map.



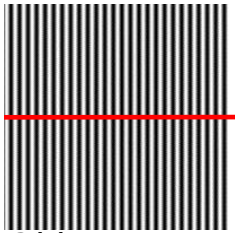
Principle: Phase Unwrapping

Example

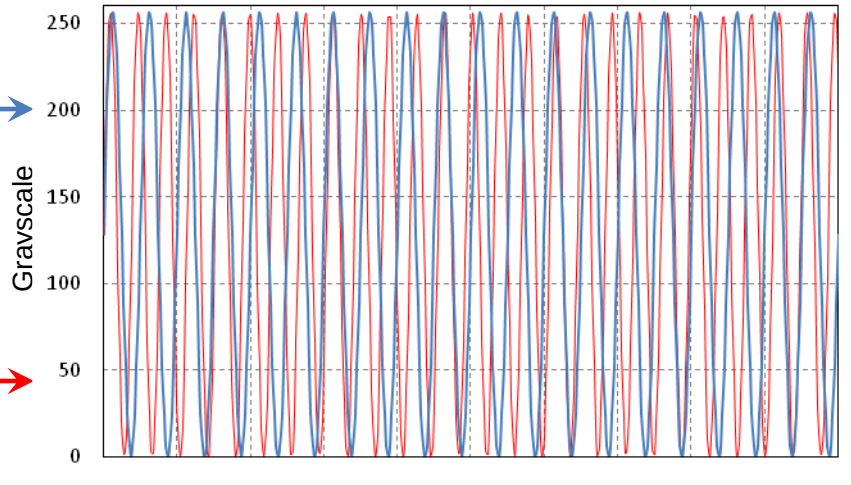
Measurement of a panel with a slope of 0.2 rad



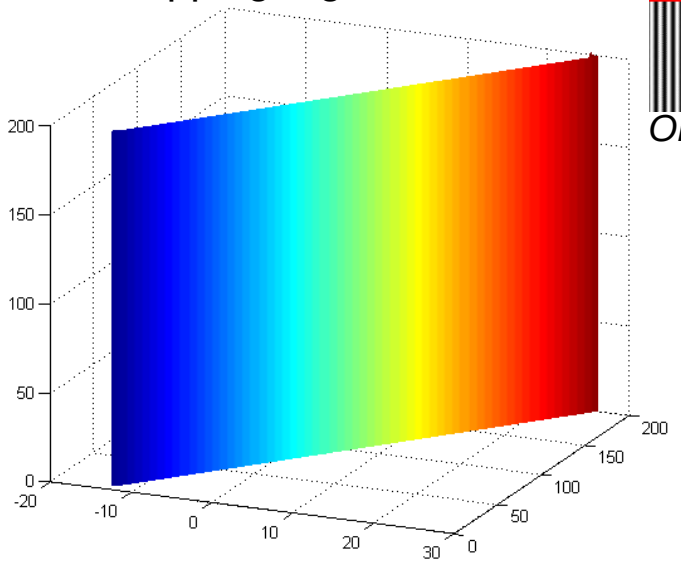
Reference Image



Object Image

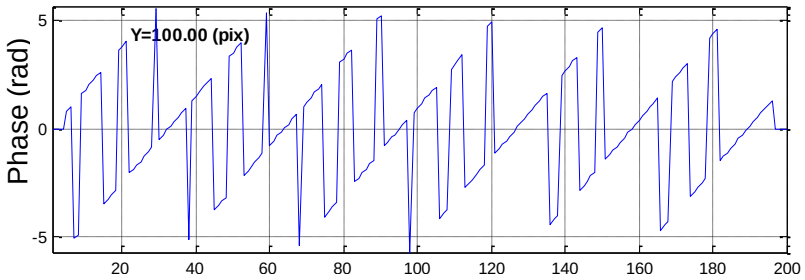


2D Quality-guided Phase Unwrapping Algorithm[{8}, {11}]

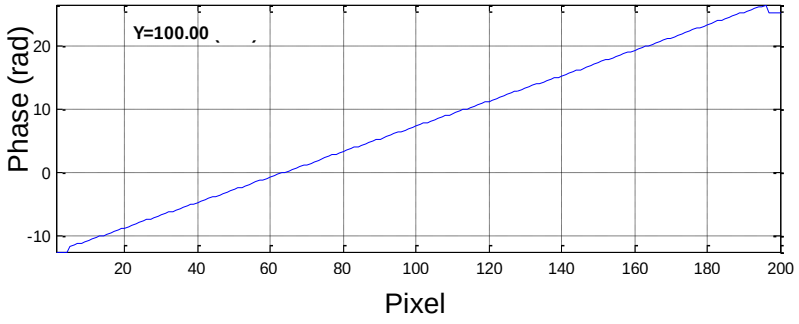


3D Reconstruction of the Panel

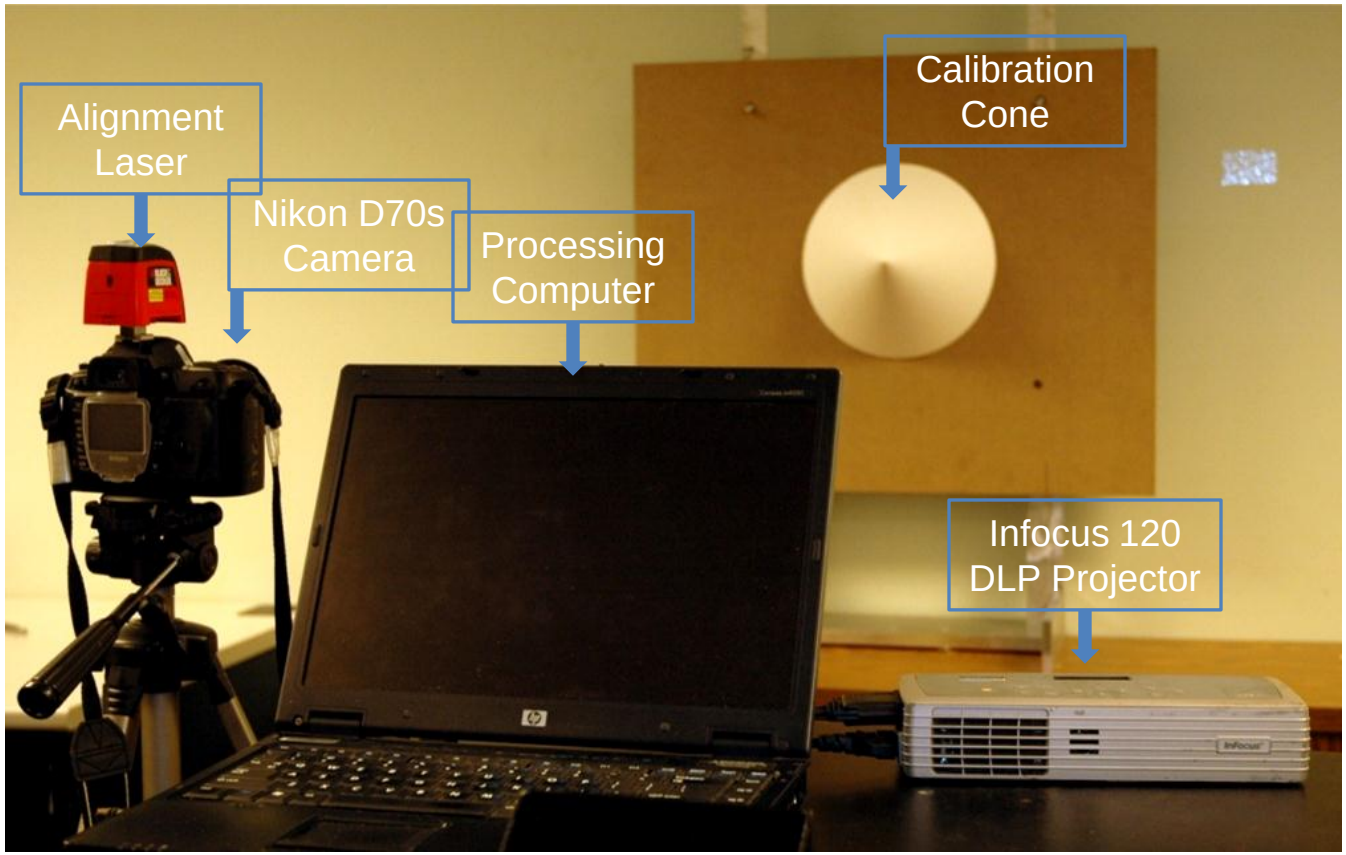
Wrapped Phase Difference



Unwrapped Phase Difference



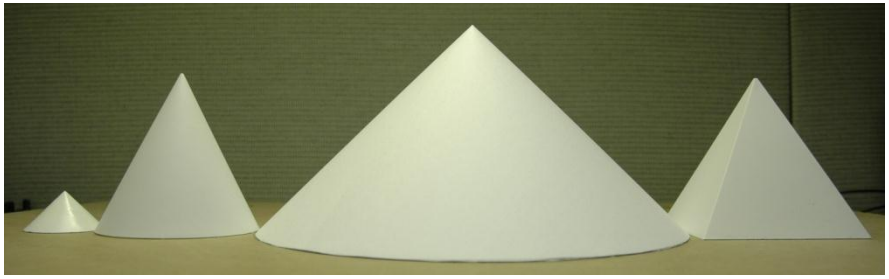
Digital Fringe Projection System Setup

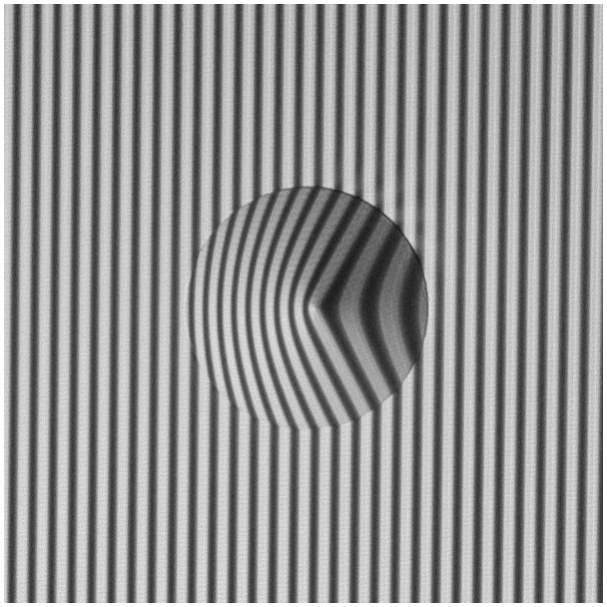


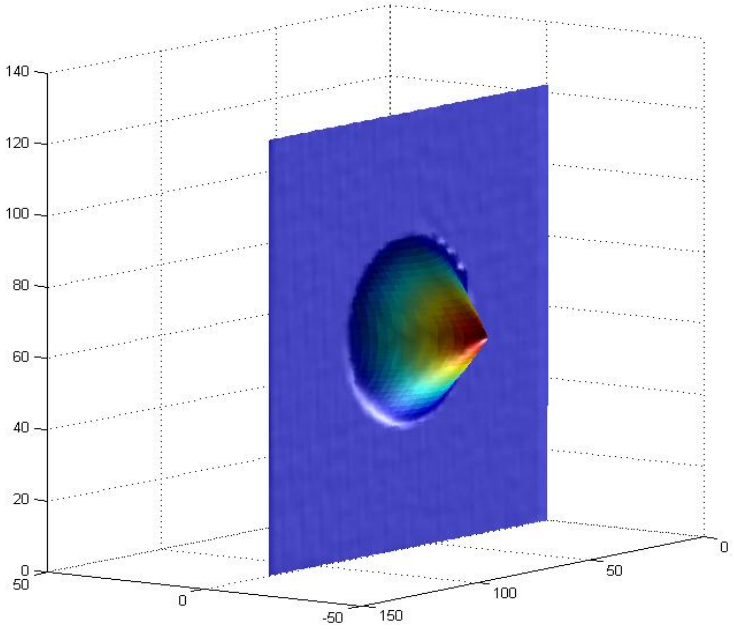
Digital Fringe Projection System: Calibration

$$z(x_K, y_K) = \frac{l}{2\pi f d}\Delta\Phi_{ro} = k\Delta\Phi_{ro}$$

$$k = \frac{l}{2\pi f d}$$



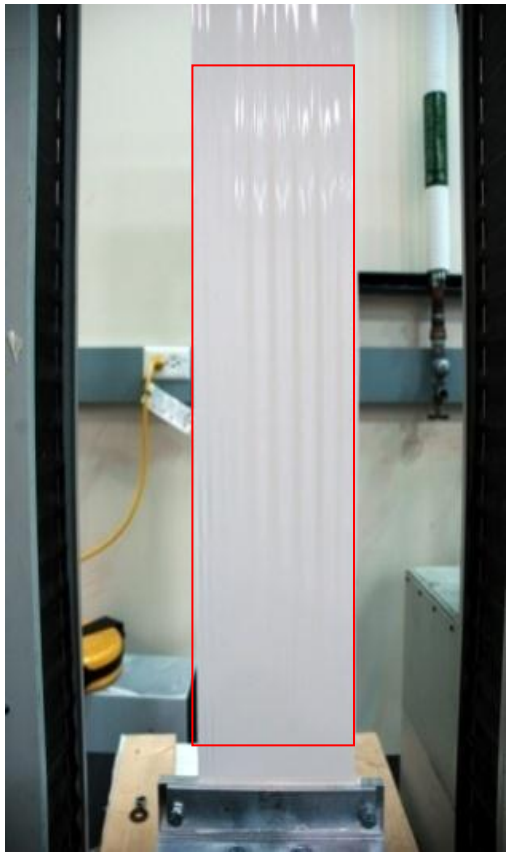




3D Reconstruction of the Cone

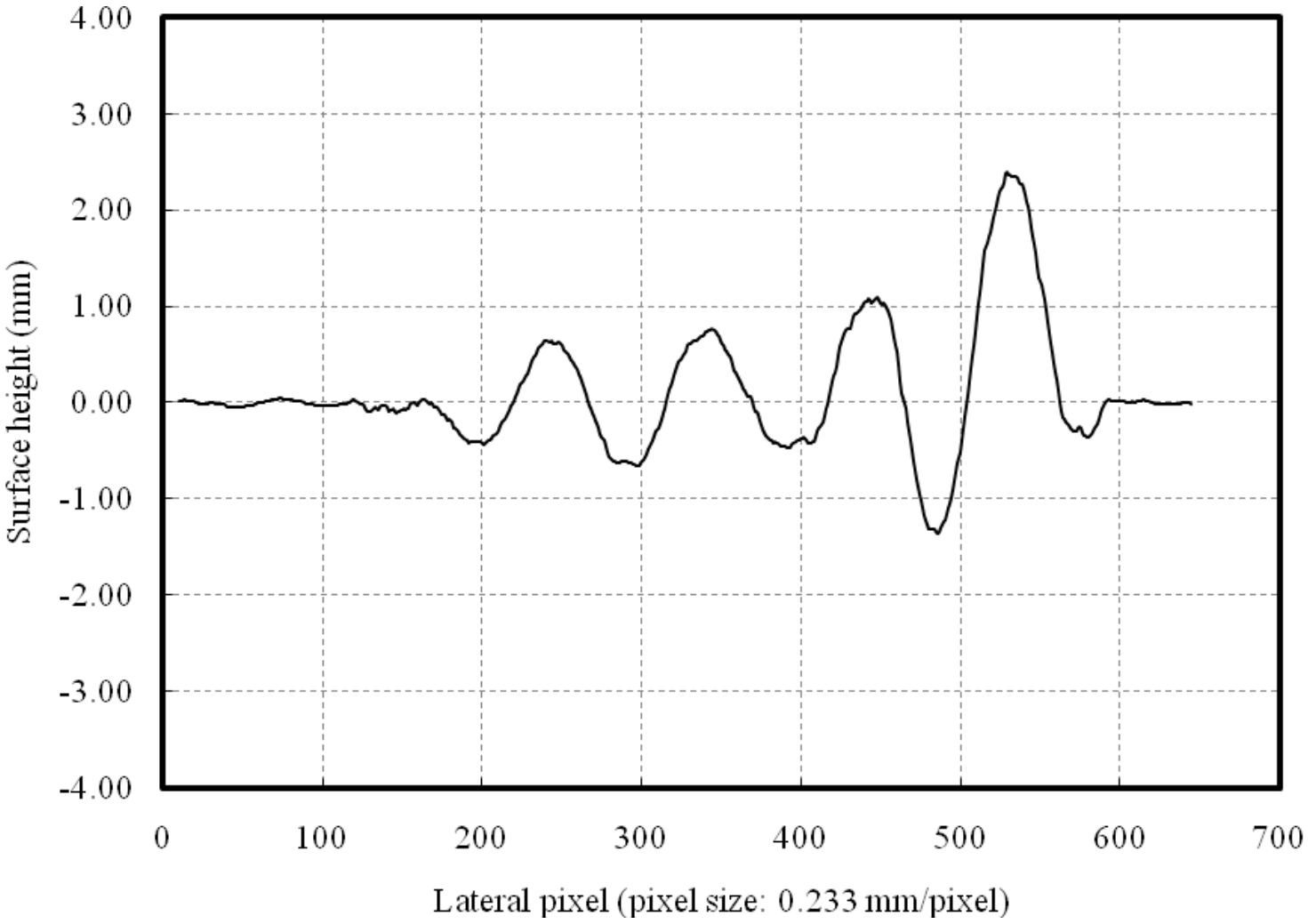
Application: Surface Profile of Wrinkles

- Polyvinyl Fluoride (PVF) Web



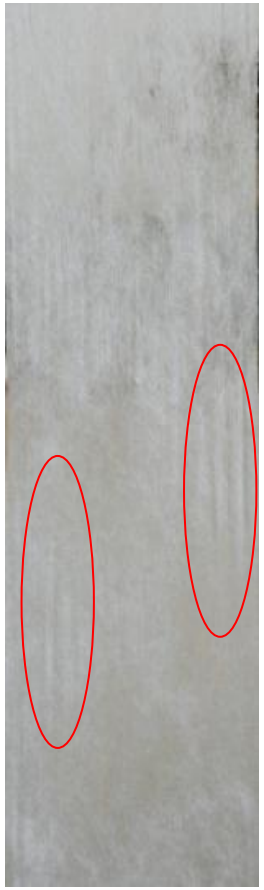
Application: Surface Profile of Wrinkles

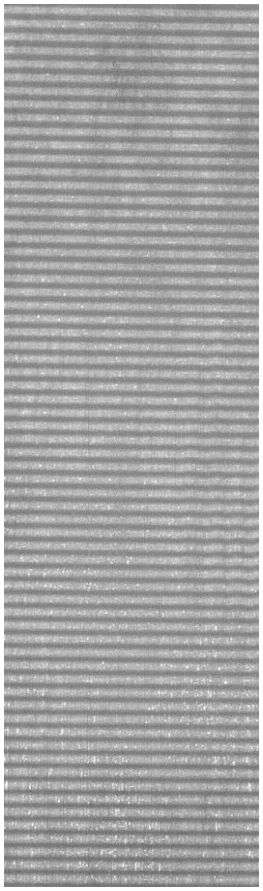
- PVF

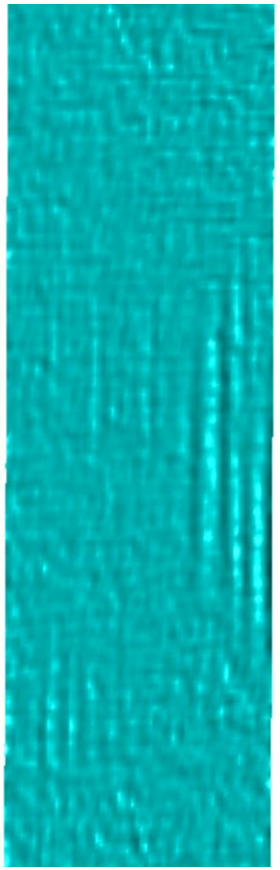


Application: Surface Profile of Wrinkles

- Nonwoven Web



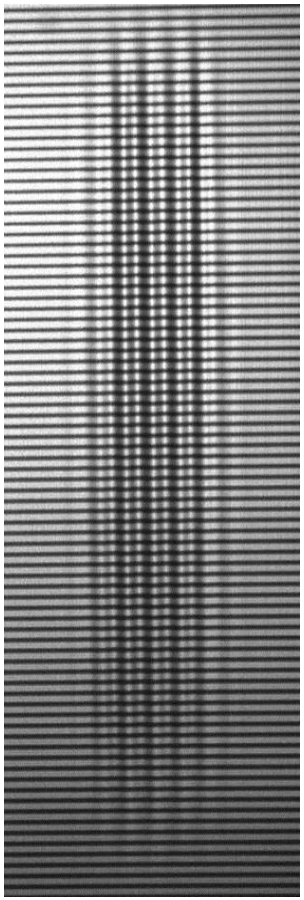
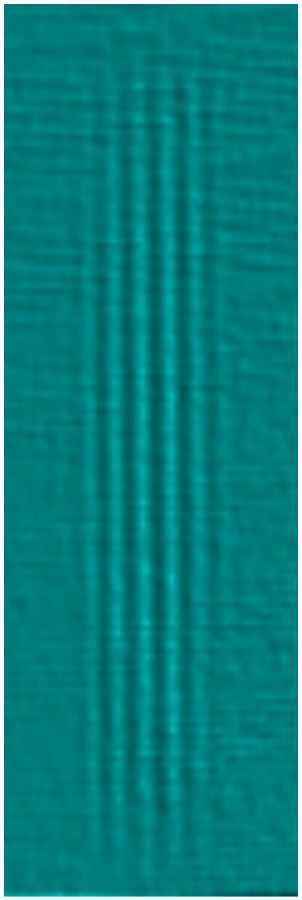




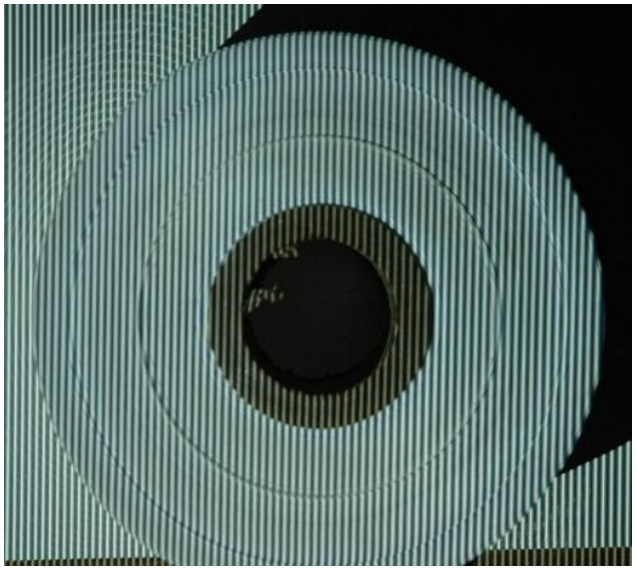
Application: Surface Profile of Wrinkles

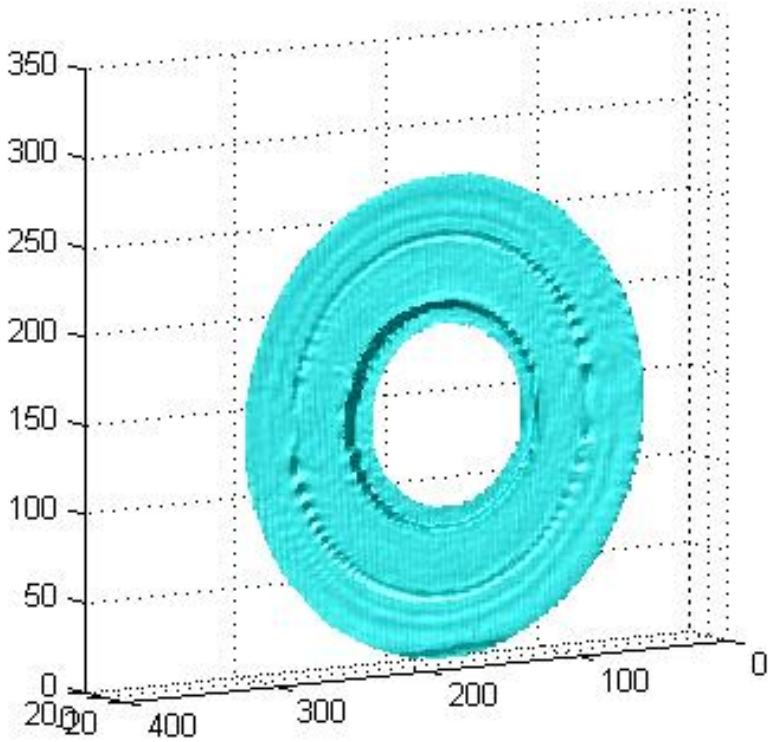
- Polyethylene Web



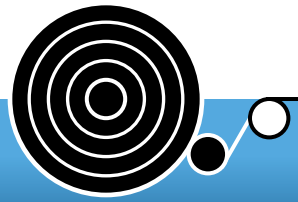



Application: Roll Side Surface





- Concluding Remarks
  - Demonstration of using a simple digital fringe projection system to acquire images of projected fringes.
  - Surface profiling the web wrinkles, roll side surface, and wound roll geometry.
  - Real-time shape measurement
  - Online quality control
  - It has potential to use at microscale to measure edge imperfections, such as burrs
  - For a transparent web, instead of white light source, a laser can be used. The analysis follows the same procedures.



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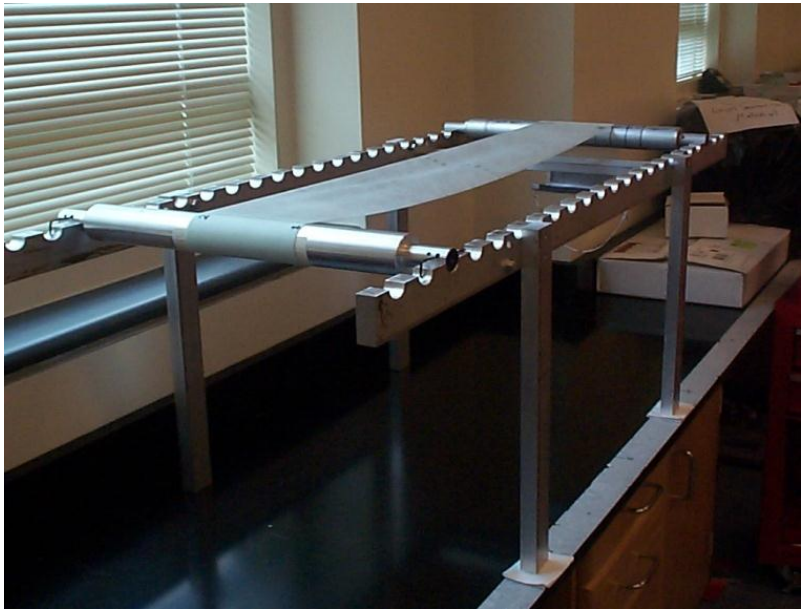
Motivation: Traditional Methods

- Instruments
  - Micrometers, height gages, reflection of laser beams, etc.
- Drawbacks
  - Contact
  - Low efficiency: single sampling at a time



A setup used to measure the surface profile of the baggy lane[4]