Astigmatic Method and Applications

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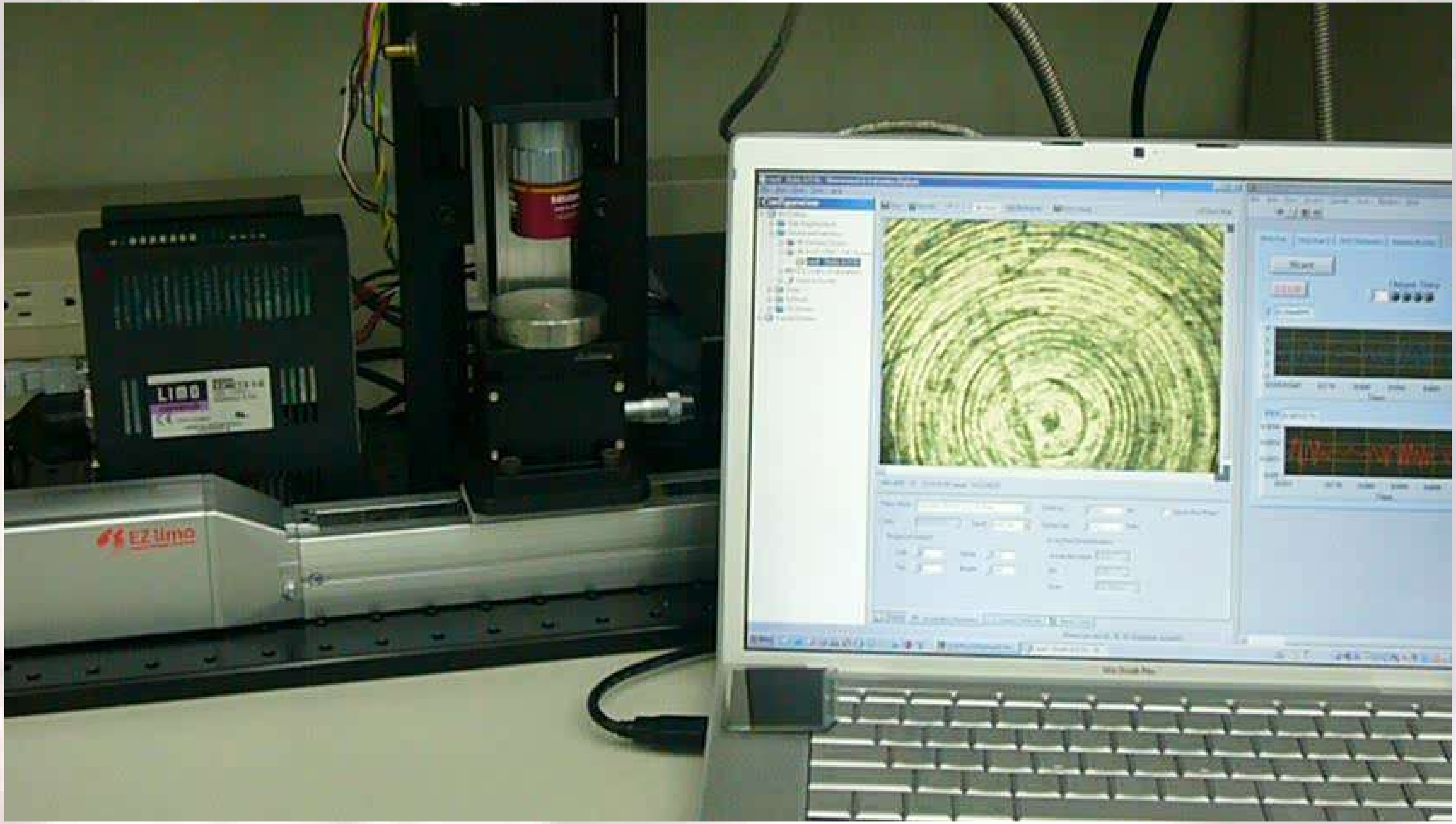
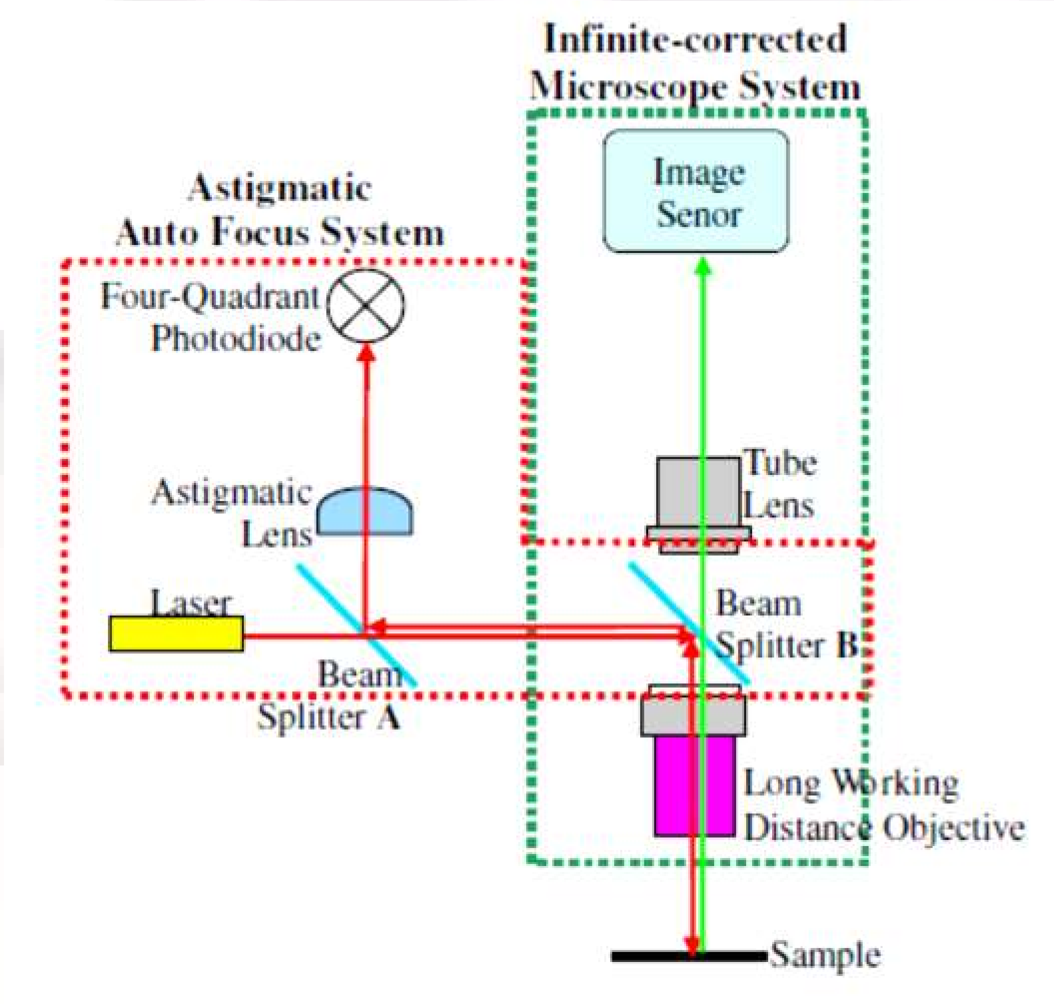
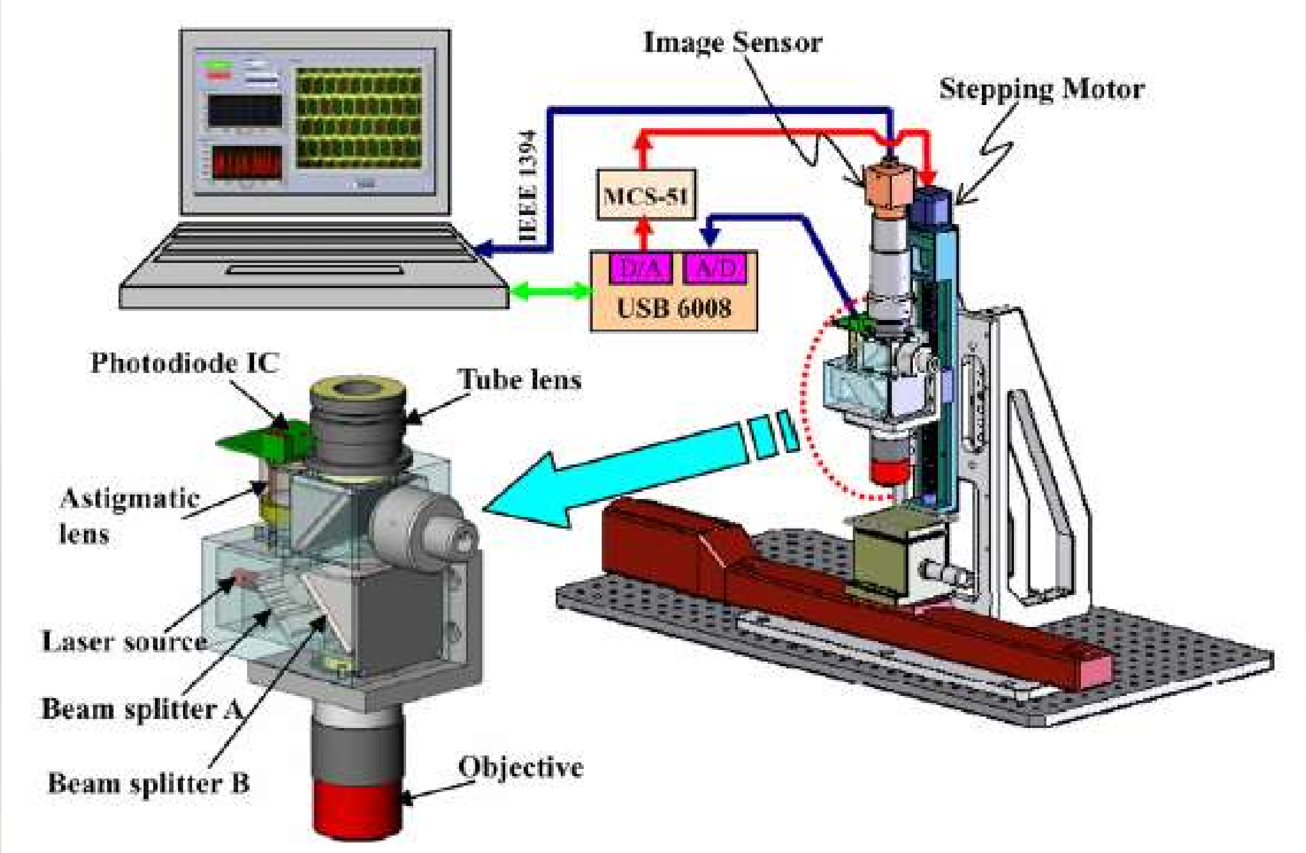


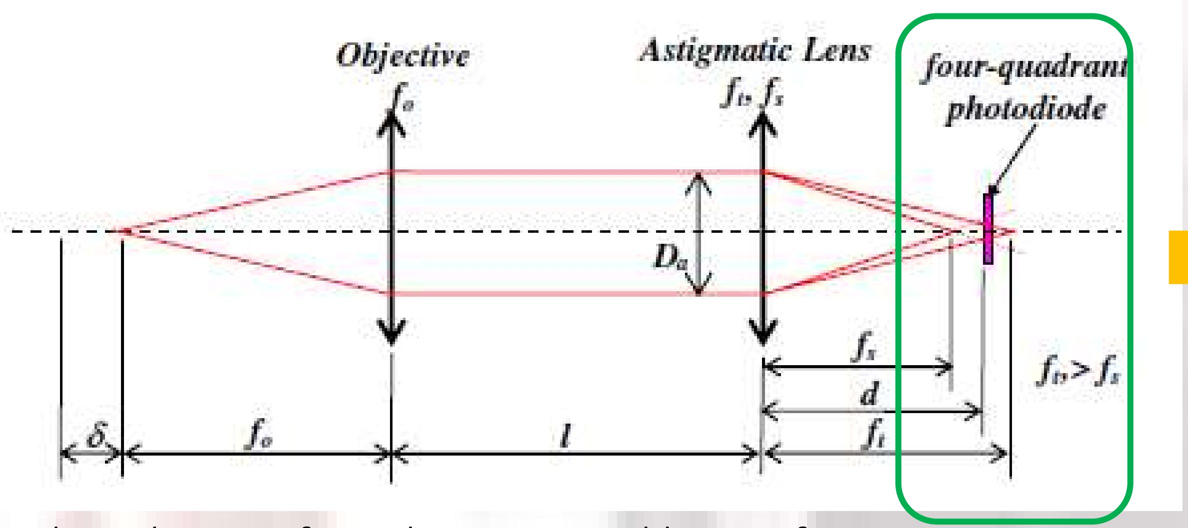
Optical Layout





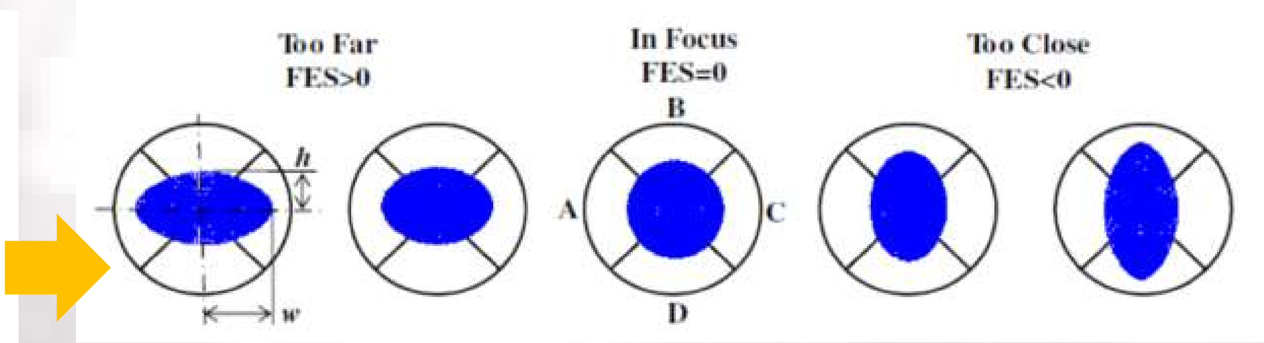
Microscopy with Astigmatic optical system enables autofocusing

Modeling based on Geometrical Optics
(No Gaussian Beam Considered)



The scheme of equilivent optical layout for an astigmatic automatic focus system

f_0: objective's focal length,
l: distance between the objective & the astigmatic lens,
f_t : tangential focal length of the astigmatic lens,
f_s : sagittal focal length of the astigmatic lens ($f_t > f_s$),
D_a: the diameter of the collimated laser beam
d: the distance between the astigmatic lens and the four quadrant photodiode.

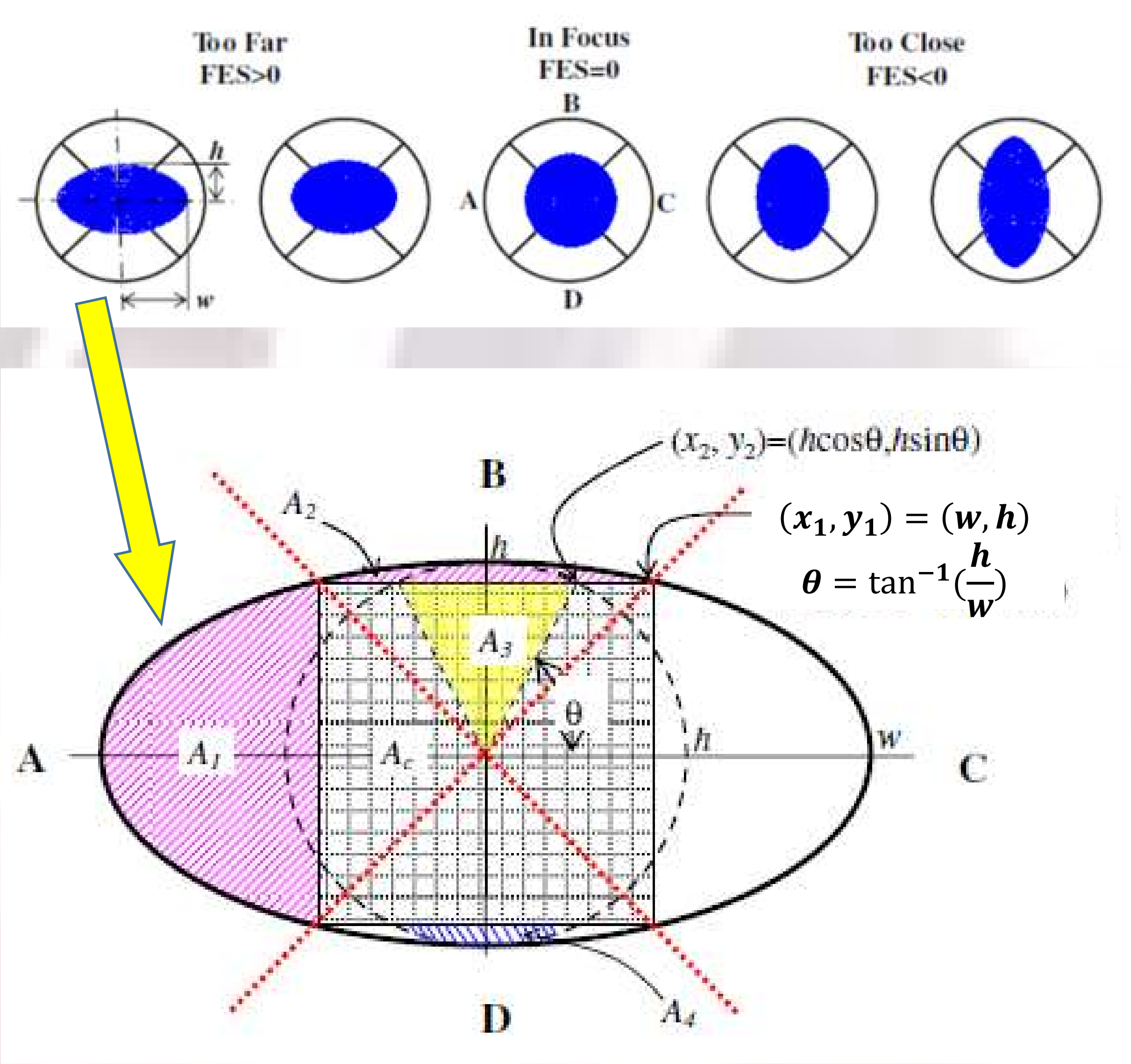


FES(focus error signal) determined by using signal of Quadrant Photodiode

$$\mathrm{FES} = \frac{(\mathrm{Q_A} + \mathrm{Q_C}) - (\mathrm{Q_B} + \mathrm{Q_D})}{\mathrm{Q_A} + \mathrm{Q_B} + \mathrm{Q_C} + \mathrm{Q_D}}$$

$$\mathrm{FES} = \begin{cases} < 0, \text{Too close} \\ = 0, \text{In Focus} \\ > 0, \text{Too Far} \end{cases}$$

Spot Analysis



spot area relationship on the fourquadrant photodiode plane

FES(focus error signal) is defined to be

$$\mathrm{FES} = \frac{(\mathrm{Q_A} + \mathrm{Q_C}) - (\mathrm{Q_B} + \mathrm{Q_D})}{\mathrm{Q_A} + \mathrm{Q_B} + \mathrm{Q_C} + \mathrm{Q_D}}$$

$$\Rightarrow \mathrm{FES} = \frac{\boxed{2(A_1 - A_2)}}{\boxed{\pi w h}}$$

Area difference

Area of Ellipse

$$\Rightarrow \mathrm{FES} = \frac{4}{\pi}\tan^{-1}\frac{h}{w} - 1$$

$Case\ 1.\ h = 0 \Rightarrow \mathrm{FES} = -1$

$\Rightarrow$ Ellipse become a horizontal line

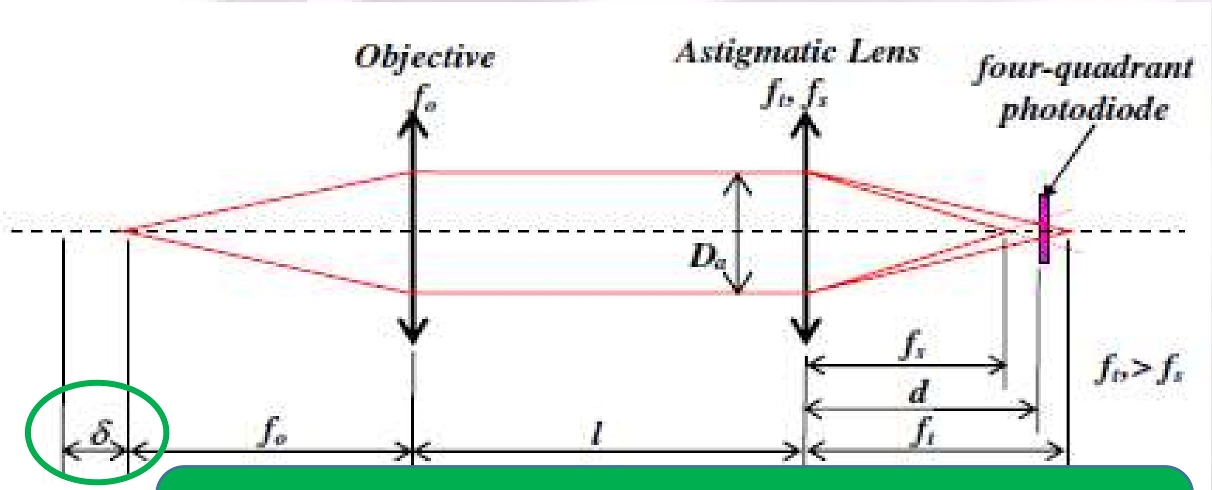
$Case\ 2.\ w = 0 \Rightarrow \mathrm{FES} = 1,$

$\Rightarrow$ Ellipse become a vertical line

$Case\ 3.\ h = w \Rightarrow \mathrm{FES} = 0$

$\Rightarrow$ Ellipse become a circe

Geometrical Optics Modeling



The sample defocus distance Δz is half of the point light source distance δ

To form a circular spot on the four-quadrant photodiode with a point light source located at the objective's focal point (δ = 0), the position of the photodiode is defined to be

$$d = \frac{2 f_t f_s}{f_t + f_s}$$

Mapping Light Source to imaging Plan

$$S_s = \frac{f_s(l - f_o)\delta - f_o^2 f_s}{(l - f_o - f_s)\delta - f_o^2}$$

$$S_t = \frac{f_t(l - f_o)\delta - f_o^2 f_t}{(l - f_o - f_t)\delta - f_o^2}$$

$$\Longrightarrow$$

$$w = \left|\frac{S_s - d}{S_s}\right| \frac{D_a}{2}$$

$$h = \left|\frac{S_t - d}{S_t}\right| \frac{D_a}{2}$$

Considering $S_t = S_s = d$

$$\Longrightarrow \delta_t = \frac{f_0^2(f_t - f_s)}{(1 - f_0)(f_t - f_s) + 2 f_t f_s} = \frac{f_0^2}{(1 - f_0) + e}$$

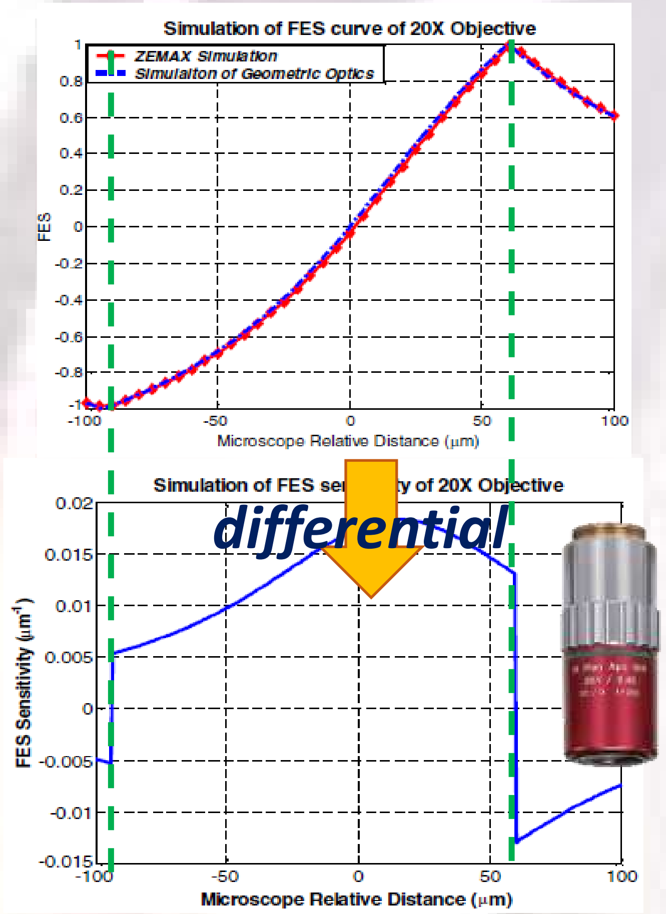
$$\delta_s = \frac{f_0^2(f_t - f_s)}{(1 - f_0)(f_t - f_s) - 2 f_t f_s} = \frac{f_0^2}{(1 - f_0) - e}$$

Where

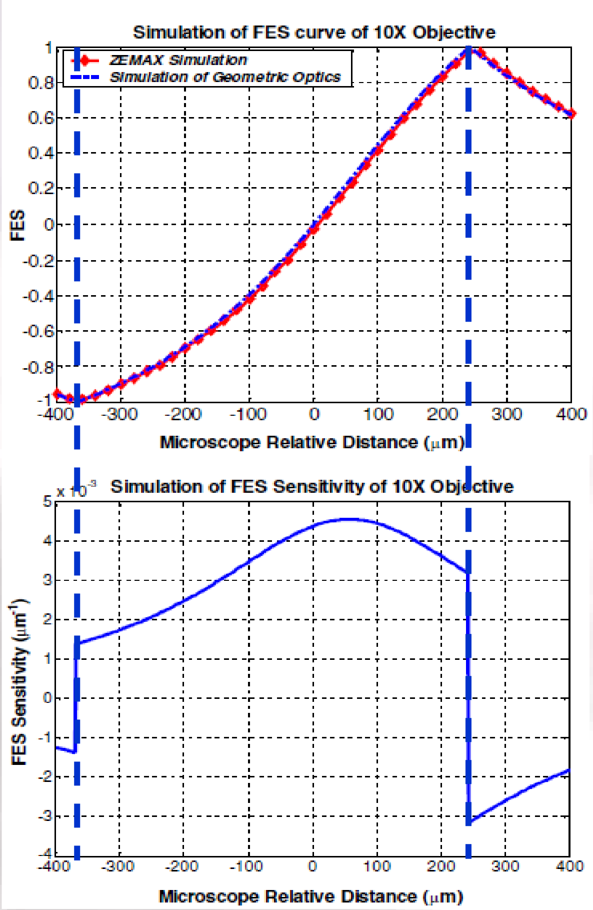
$$e = \frac{2 f_t f_s}{f_t - f_s}$$

$$f_t = \frac{ed}{e - d};\; f_s = \frac{ed}{e + d}$$

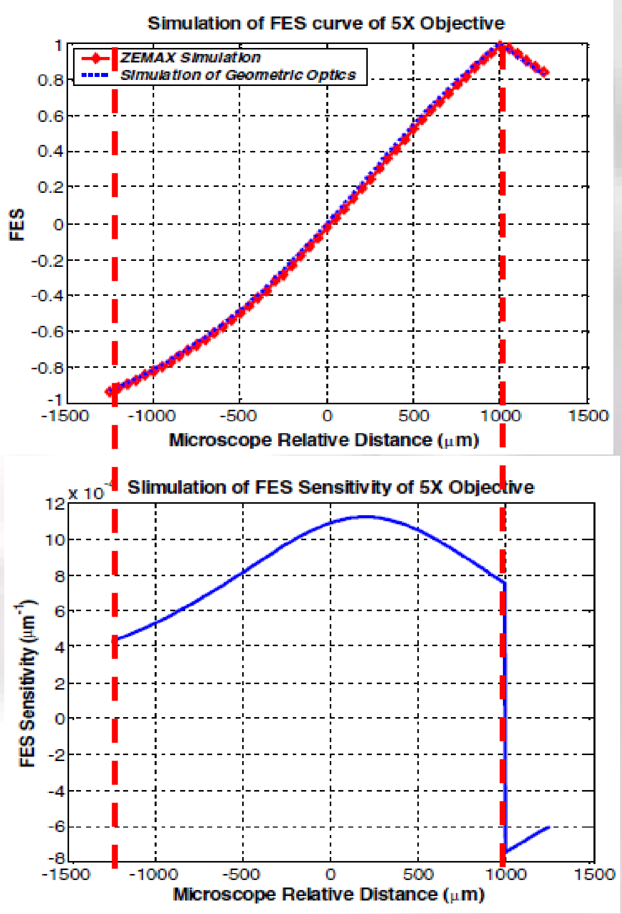
Simulation of FES



Mitutoyo,MPlan Apo NIR 20X
NA=0.4, WD=20.0 mm
Wavelength range 480, 1800 nm



10X

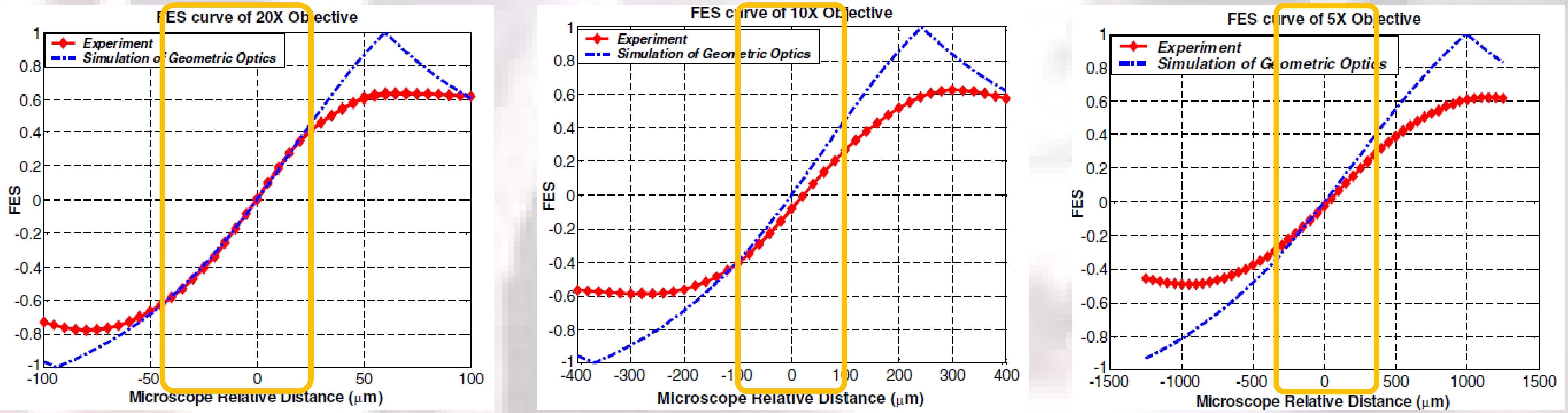


5X

Objective Lens: Magnificent

Possible Working Range

Astigmatic Lens Method for Autofocusing System



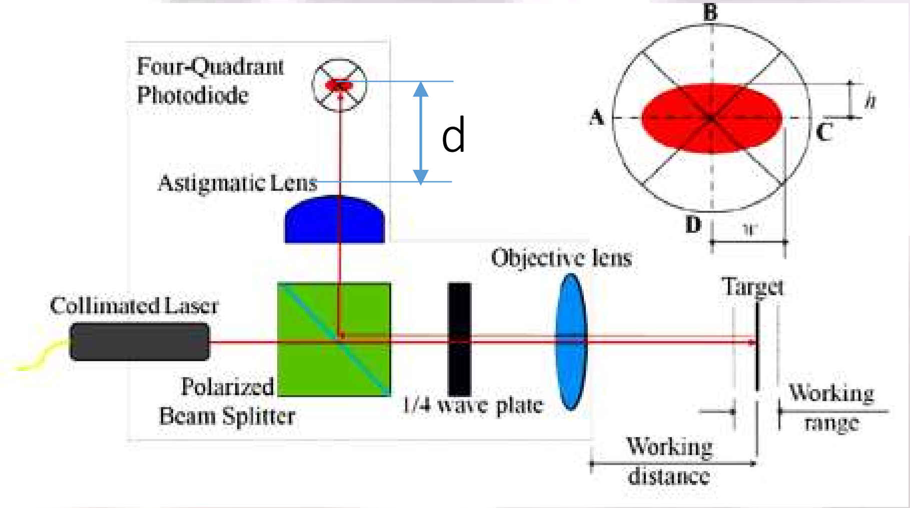
Microscope objective	FES sensitivity at focus position	FES at focus position	Depth of focus	Focusing window
20×	$18.40 \times 10^{-3}\ \mu m^{-1}$	0.004	1.7 μm	0.004 ± 0.016
10×	$3.58 \times 10^{-3}\ \mu m^{-1}$	−0.082	4.1 μm	-0.082 ± 0.08
5×	$0.87 \times 10^{-3}\ \mu m^{-1}$	−0.023	14.0 μm	-0.023 ± 0.06

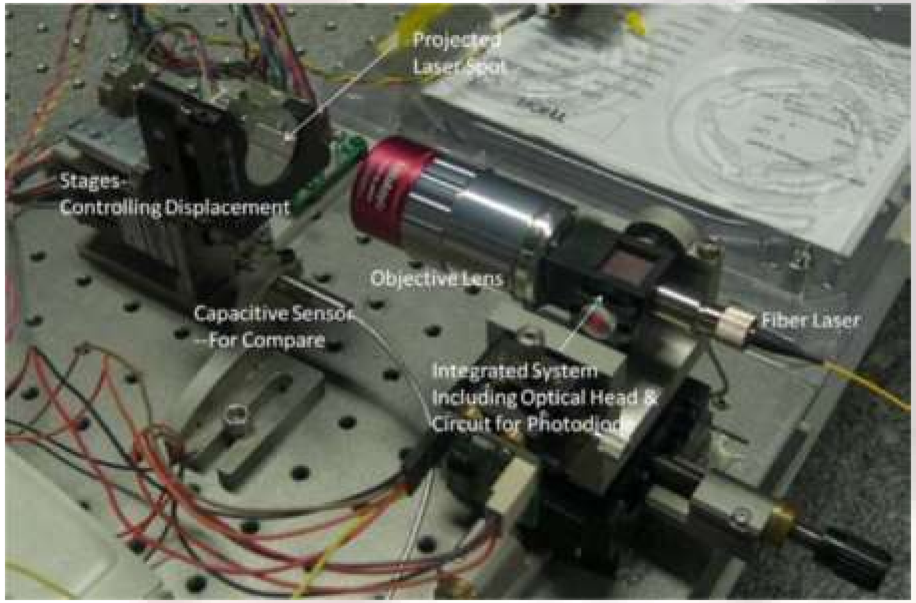
Center of Spot Size Determined by FES

Objective Lens

Laser Spot Size

For Displacement Measurement





Objective Lens:

Mitutoyo, MPlan Apo NIR 5X

Focal Length: 40 mm

WD: 35 mm

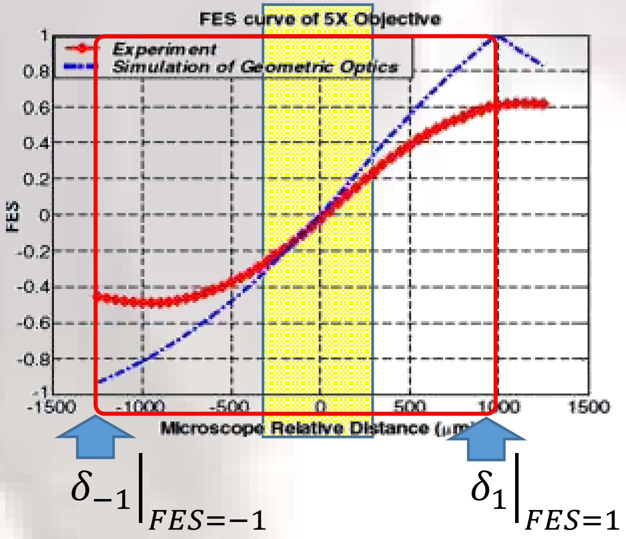
d = 50 mm

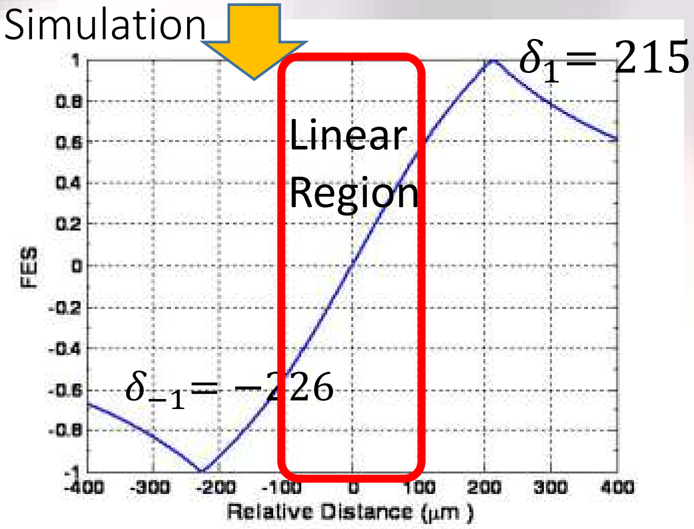
Define $\delta_i = \delta @\mathrm{FES} = i,\ \mathrm{FES} \in [-1,1]$

Working Range: $200\mu m$ (FES-δ curve is Linear)

$\Longrightarrow \delta_1 = 215\mu m$ for design

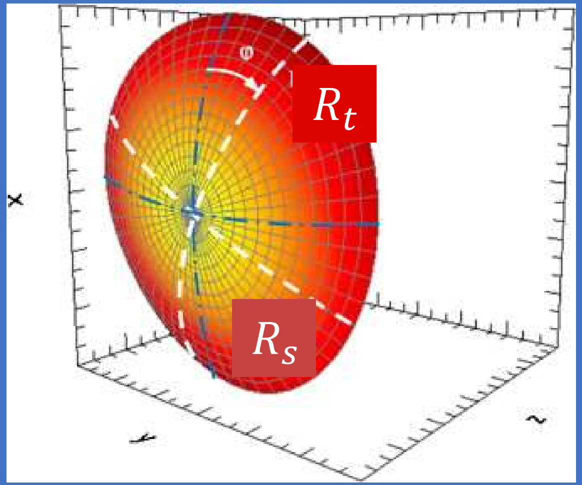
$\Longrightarrow (f_s, f_t) = (49.321\ \mathrm{mm}, 50.699\ mm)$





System Development

Bi-conic Lens



Methodical Model for Optical Surface

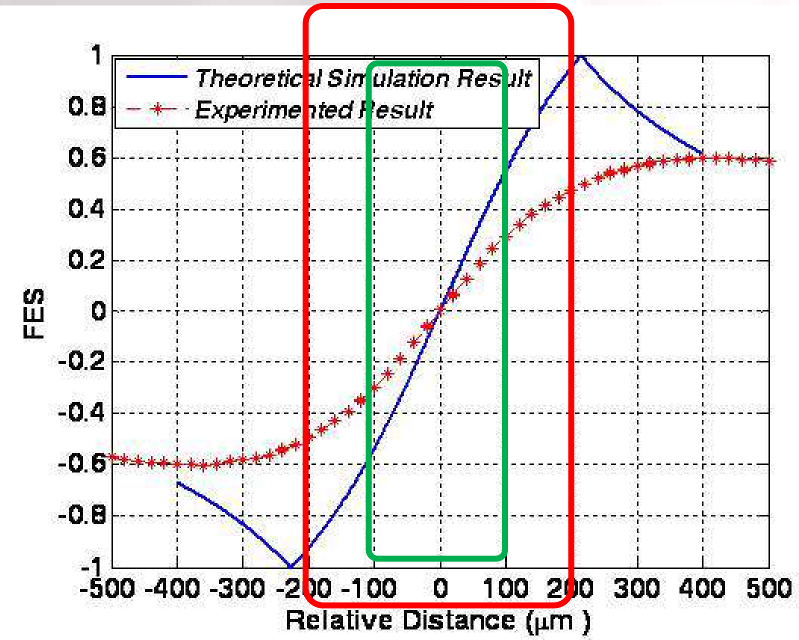
$$z = \frac{x^2/R_s + y^2/R_t}{1+\sqrt{1-(x/R_s)^2-(y/R_t)^2}}$$

Design Analysis Results

$(f_s, f_t) = (49.321\ \mathrm{mm}, 50.699\ mm)$

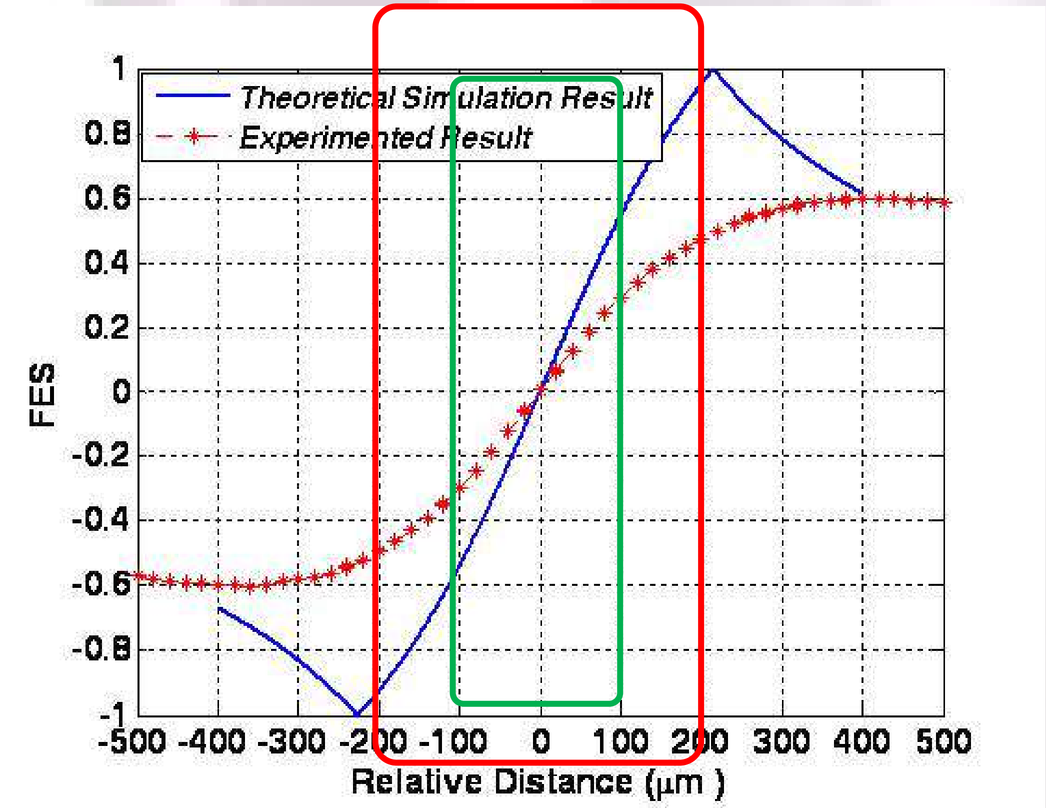
By using PMMA, n=1.49

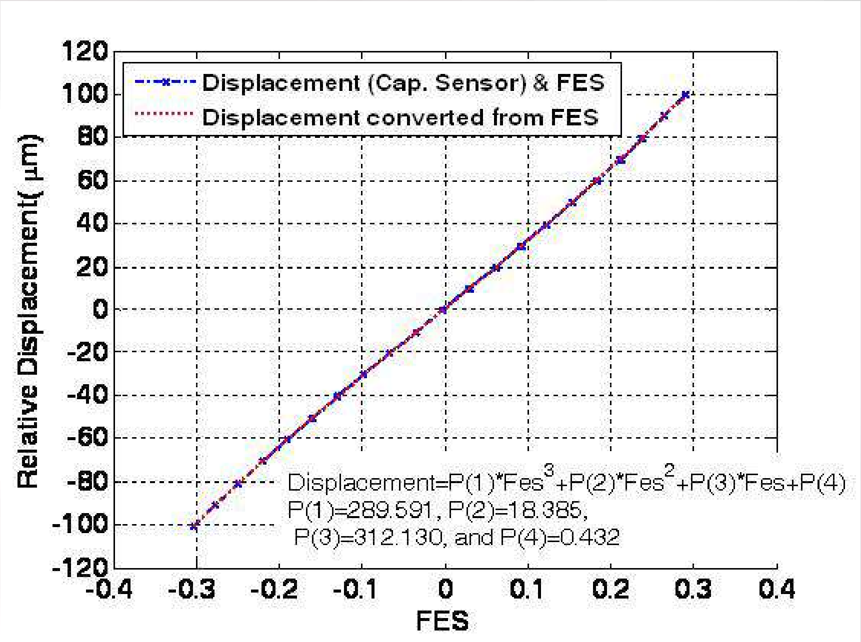
$\Longrightarrow R_s = 24.167\ mm;\ R_t = 24.842\ mm$

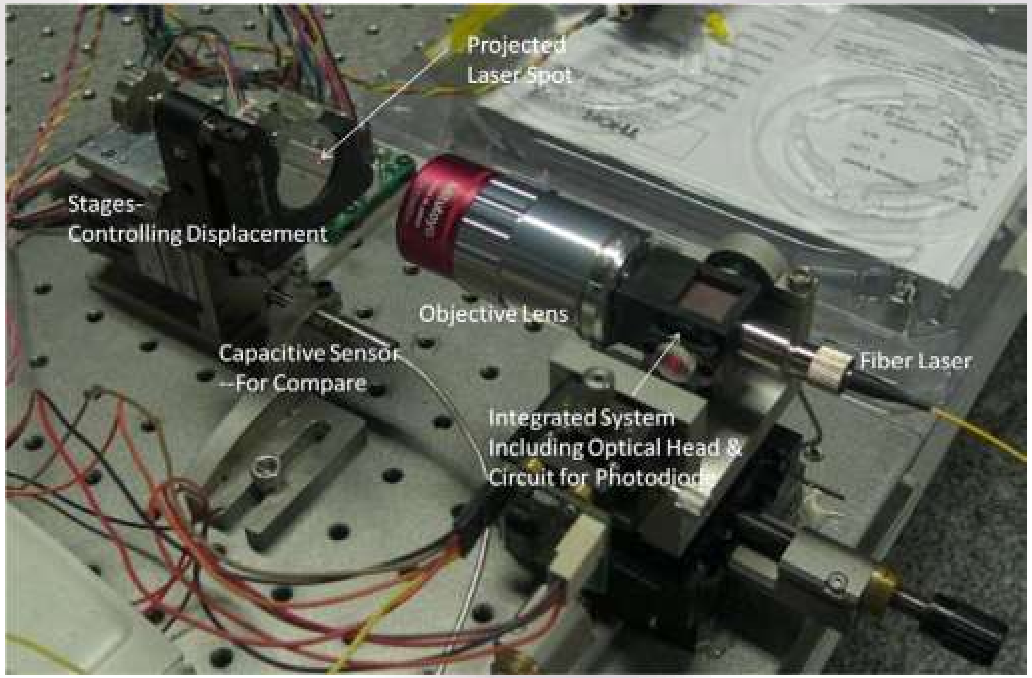


Parameters	Spec.
Displ. Range	$\pm 100\mu m$
Meas. Sensitivity	3.35×10^{-3} $(a.u./\mu m)$
Accuracy	$\leq 0.6\mu m$
Working Range	37.5 mm

Calibration





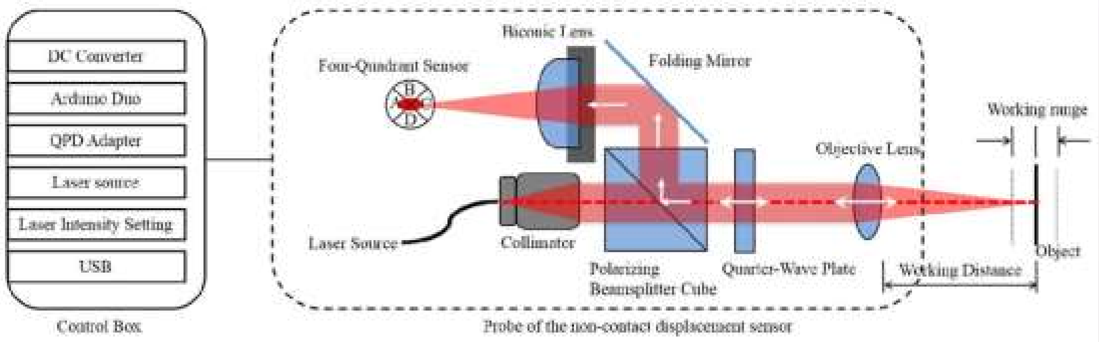


Fitting Displacenent with FES by

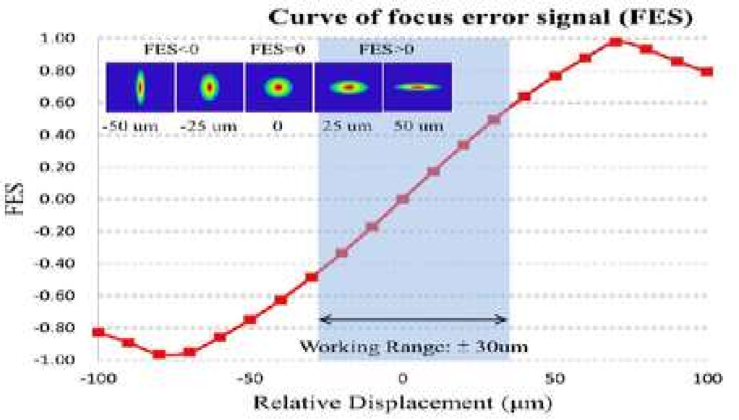
$$Disp = \sum_{i=0}^{3} a_i \times \mathrm{FES}^i$$

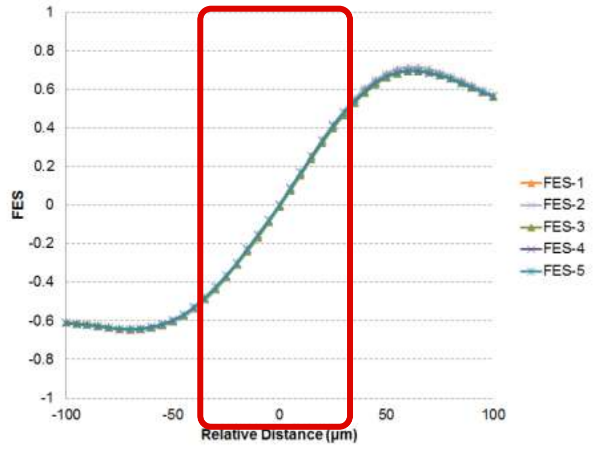
$$\Longrightarrow [a_i] = [0.43, 312.13, 18.39, 289.60]$$

Vibration measurement

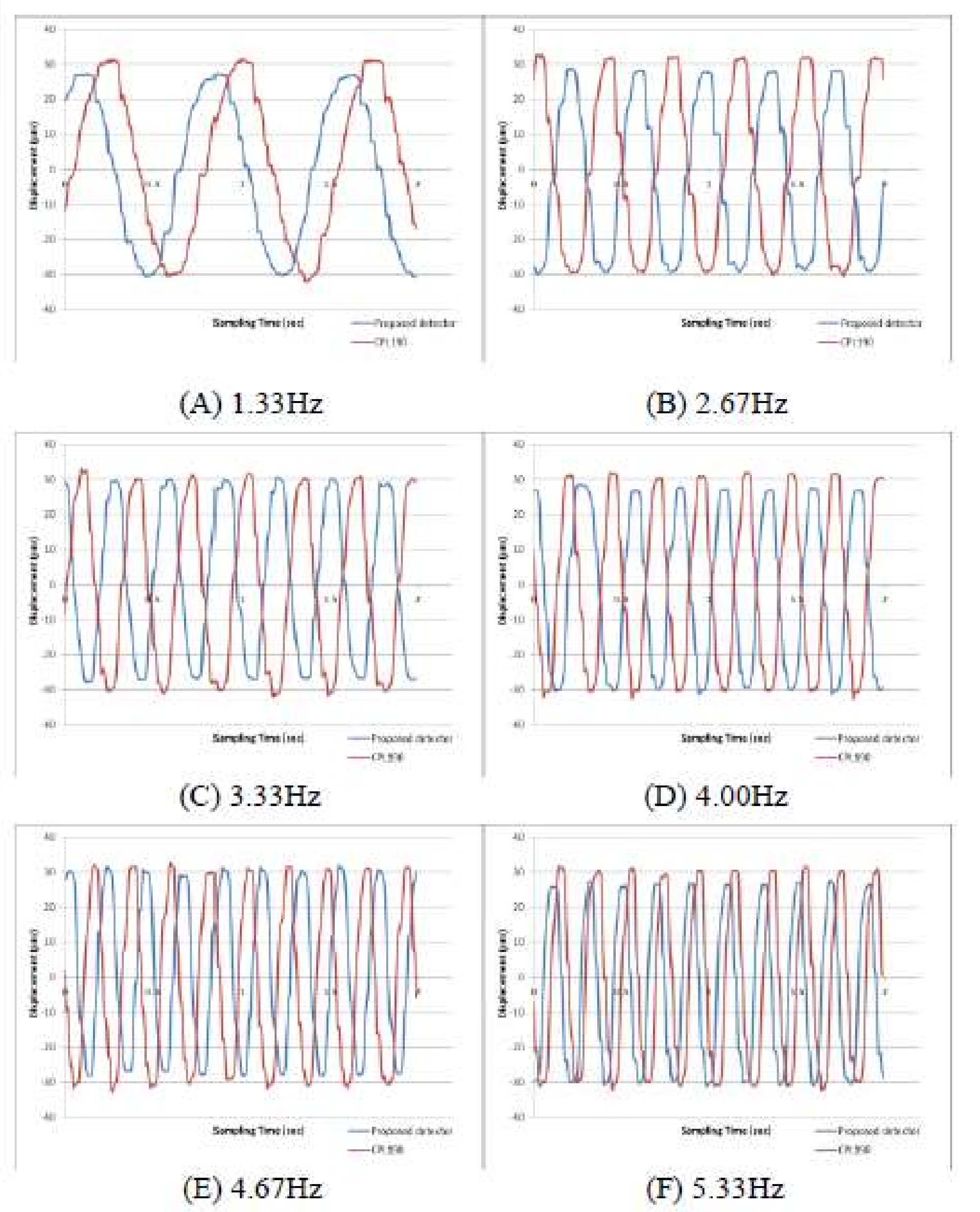


objective lens, f_o=10mm
Diode Laser, 637 nm
$f_t = 53.979$ mm; $f_s = 46.566$ mm
QPD is 49.7 mm away from astigmatic lens



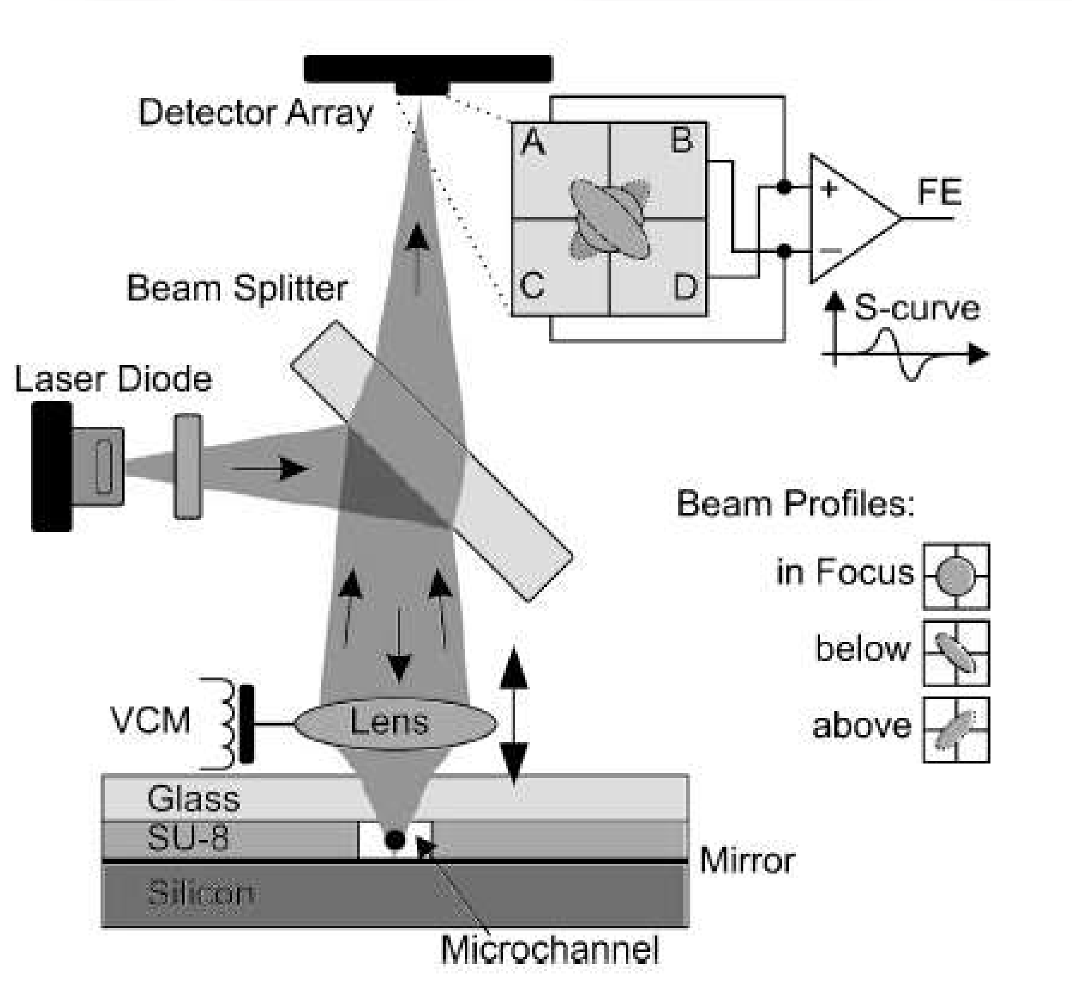


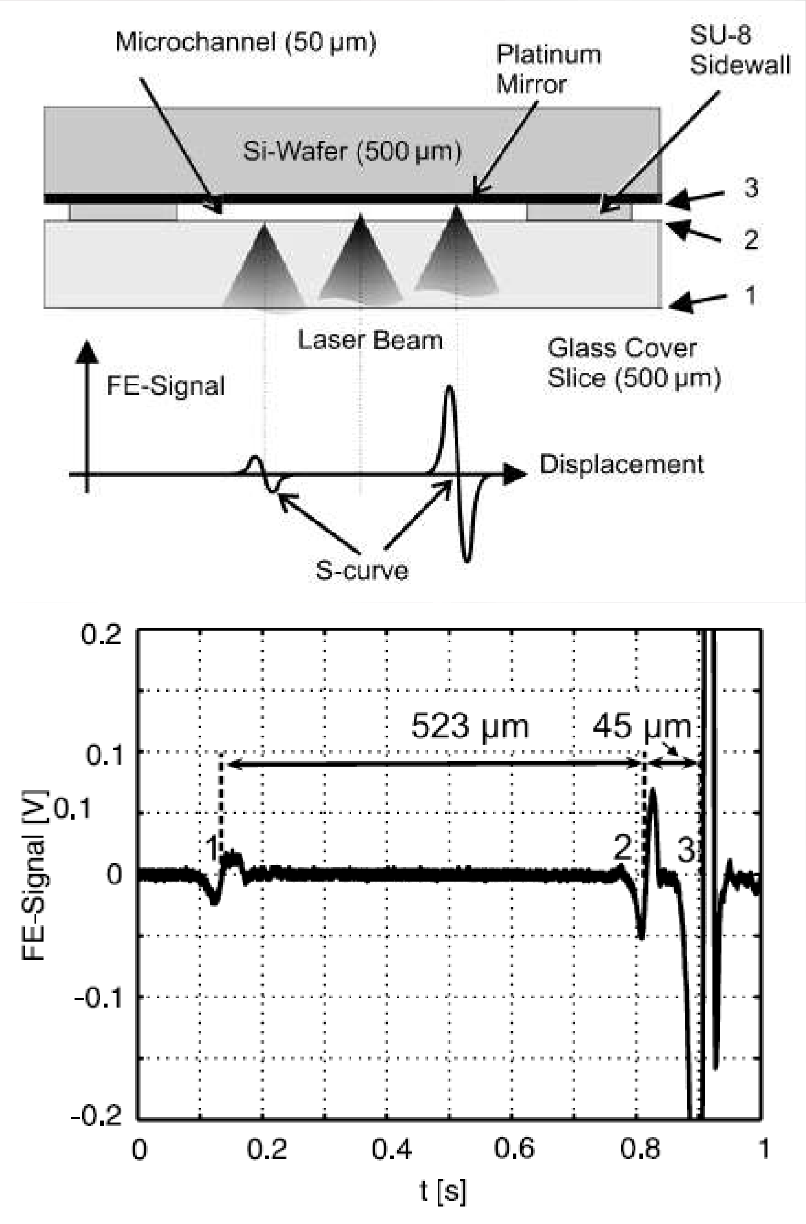
$$\mathrm{FES}(d) = 0.0158d + 0.0152$$



Comparing with Capacitor Displacement Sensor

Application of DVD pickup heads





Scanning Vertically in Constant Velocity

10.1007/s00502-008-0505-4