“Stopping Down” Annular Apertures

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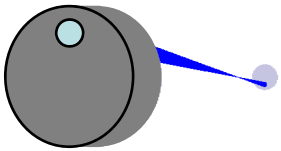
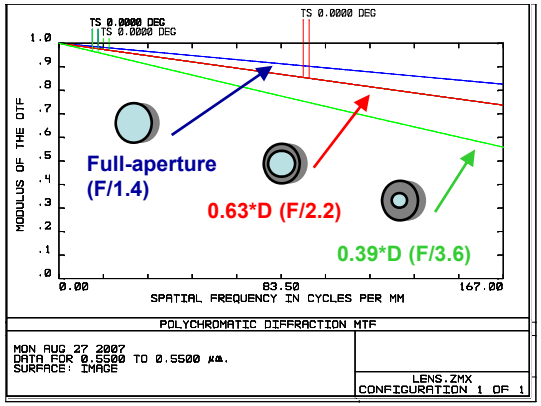
Refractive lens
(35mm, F/1.4)

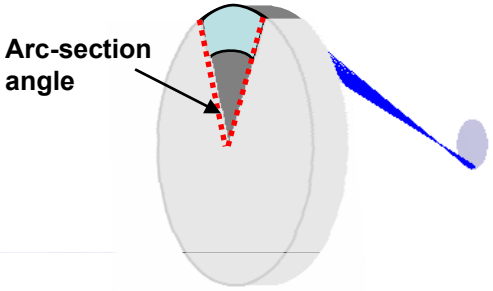


Off-axis aperture mask
On-axis aperture mask
(same diffraction results)

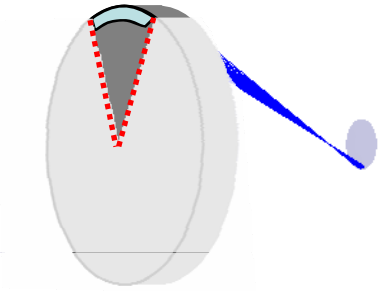
MTF



70% obscured
(D = 60mm, F = 35 mm)

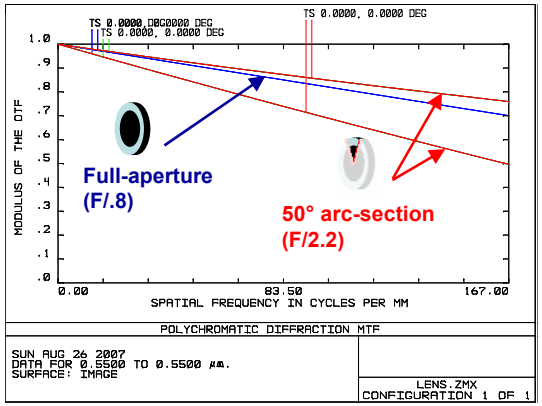


90% obscured
(D = 60mm, F = 35 mm)

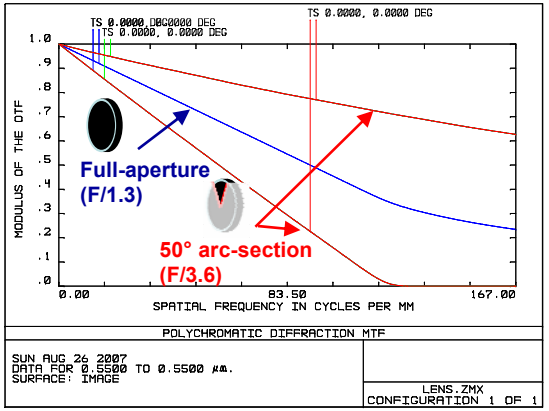


“Arc-section” aperture mask

MTF



MTF



Arc-Sectioning: increased depth of field, reduced volume

- 1D loss of resolution w/ very large obscuration

Arc-Sectioned Eight-Reflection Lens

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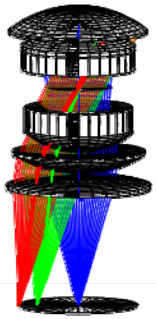
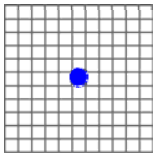
Geometrical Depth of Field

40 mm, F/1.9 lens
(for reference)

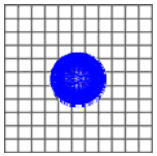


Spot at Best focus

Blur at 4% defocus @ 2.5 m



NA=0.26

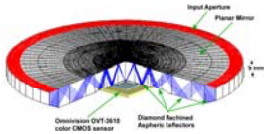


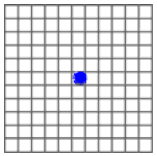
5µm

R_{RMS} 1.5 µm

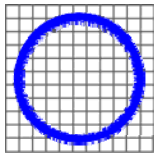
R_{RMS} 7.5 µm

Phase 1 8-Reflection Lens





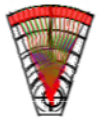
NA=0.7

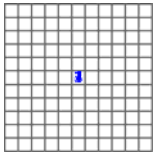


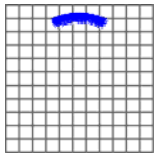
R_{RMS} 0.5 µm

R_{RMS} 20.7 µm (unacceptable)

Arc-Section 8-Reflection Lens







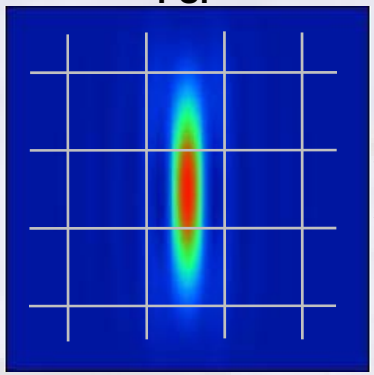
R_{RMS} 0.5 µm

R_{RMS} 5.2 µm

Modeled performance:

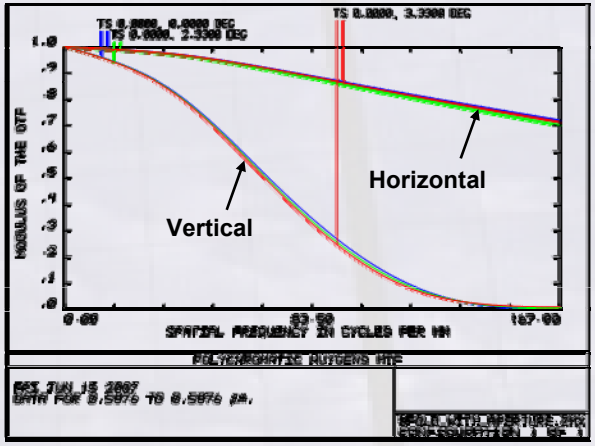
- 38 mm focal length, $F/\#_{eff}$ = 3.76
- asymmetrical PSF and MTF due to diffraction
- Trade light collection and 1D resolution for depth of field and compactness

PSF



3 µm

MTF



Prototype Arc-Sectioned Camera

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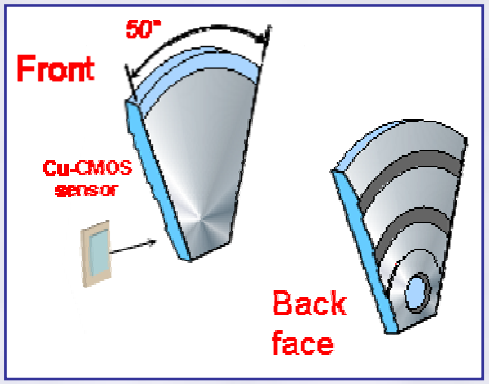
Fabrication:

- Diamond section 50° from round diamond-machined lens
  Aperture is 7.2x smaller than full ring
- Replace metal mirrors w/ dielectric stacks
  Transmission increases from 12% to ~50% (4.2x)



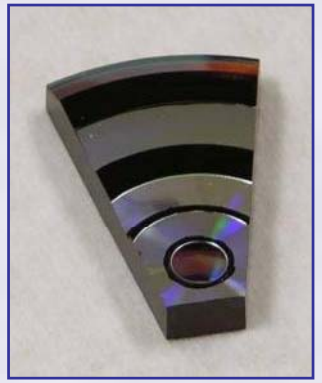
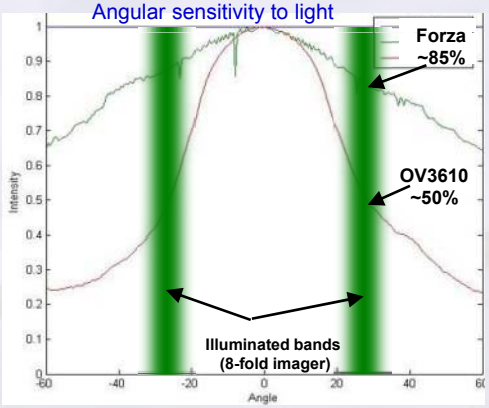
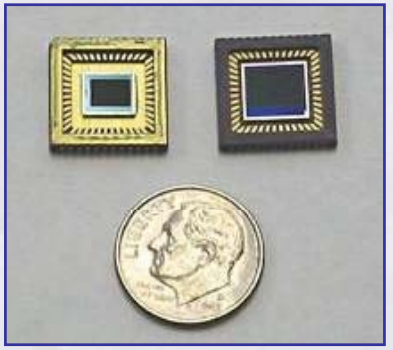


Image sensor:

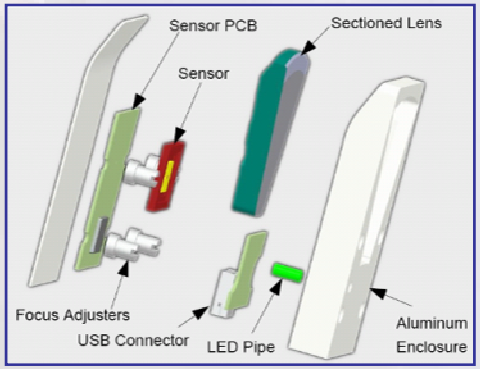
- Forza/Sunplus 2.1Mpix sensor with 3 μm pixels
- IBM Copper-CMOS process: Thinner interconnects & larger sensor area
  → 70% greater energy collection at edge

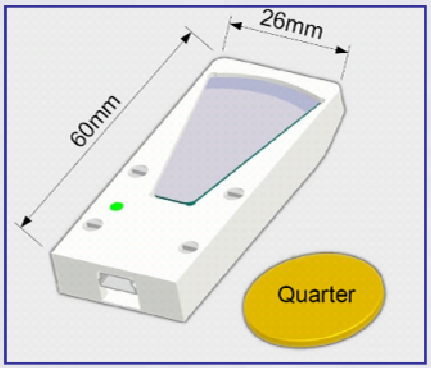




Optomechanics & package:

- USB interface on sensor PCB
- On-board focus adjustments





Camera Performance Comparison

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Conventional Lens
F = 43 mm, F/1.9: >50mm deep

Full 1024x1024field

Conventional Mini-Cam
1.3 Mpix, f=3.9mm lens: ~5mm deep

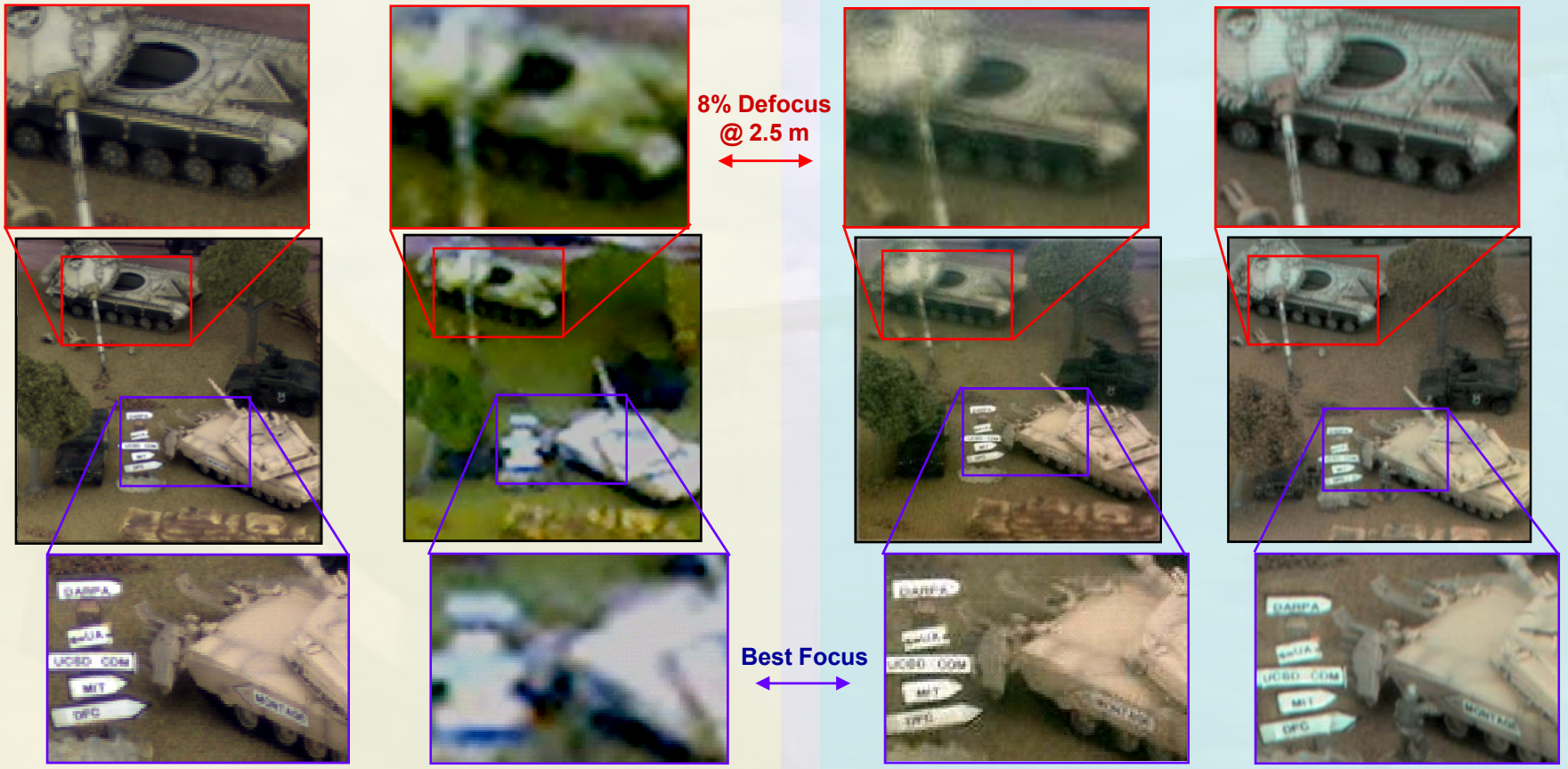
Electronic zoom (~80x80 pixels)

8-Refl. Camera
F = 38 mm, 5mm deep

Full 1024x1024 field

Arc-Sectioned 8-Refl.
F = 38 mm, 5mm deep

Full 1024x1024 field



Resolution Over a 30% deep field: Images

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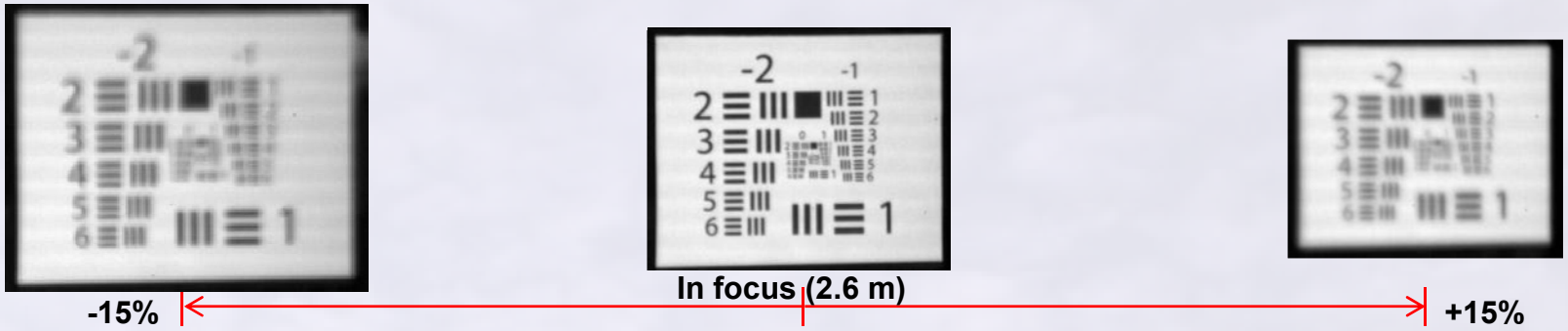
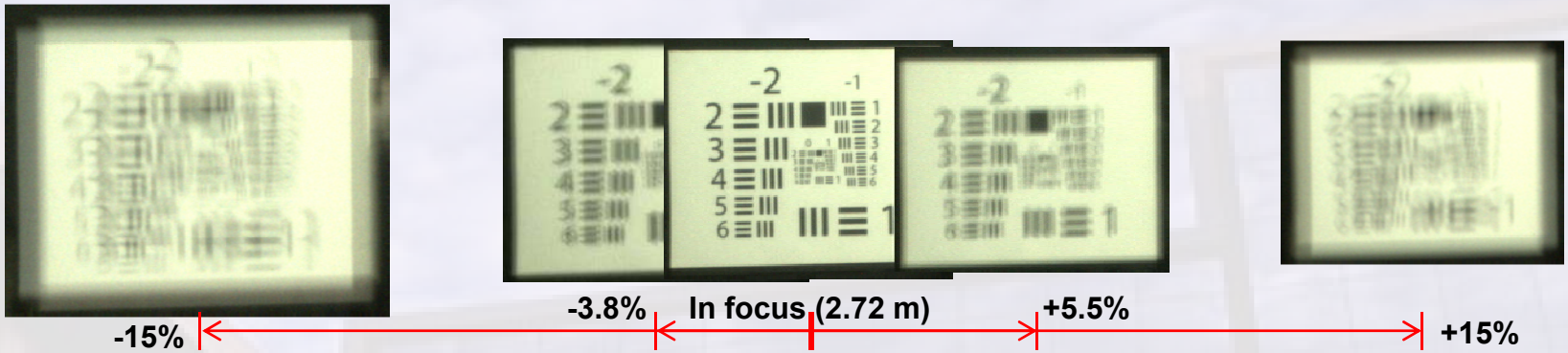
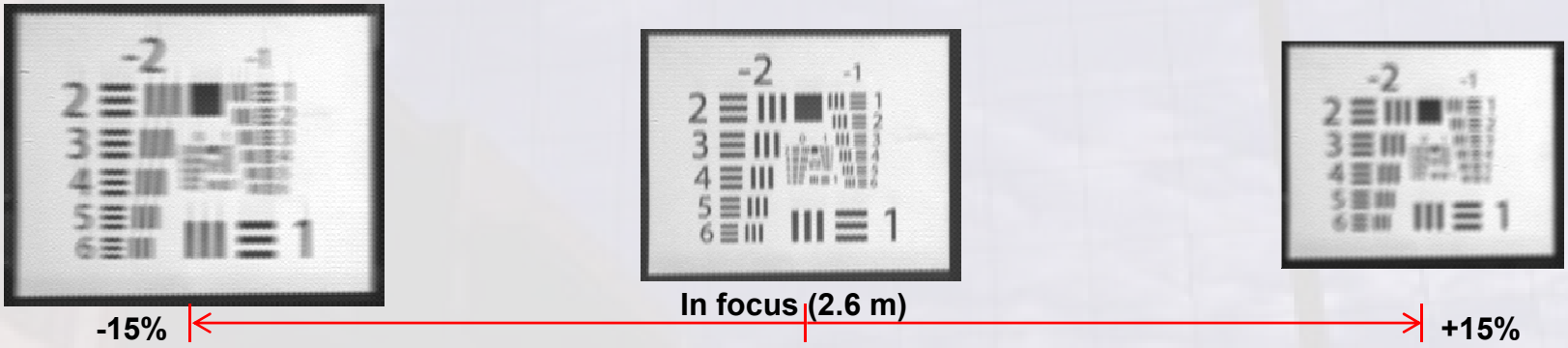
Conventional Lens
Tokina F/1.9
f = 40 mm



Full Aperture 8-Reflection Lens



Arc-Sectioned 8-Reflection Lens



Resolution over a 30% deep field

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USAF resolution target:

Measure object space resolution (lp/mm)

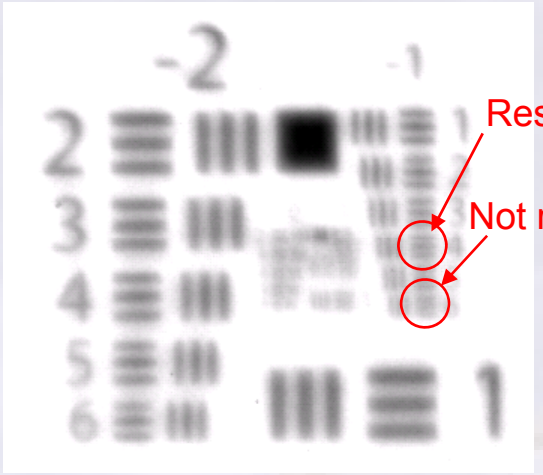
Measured both horizontal and vertical resolution

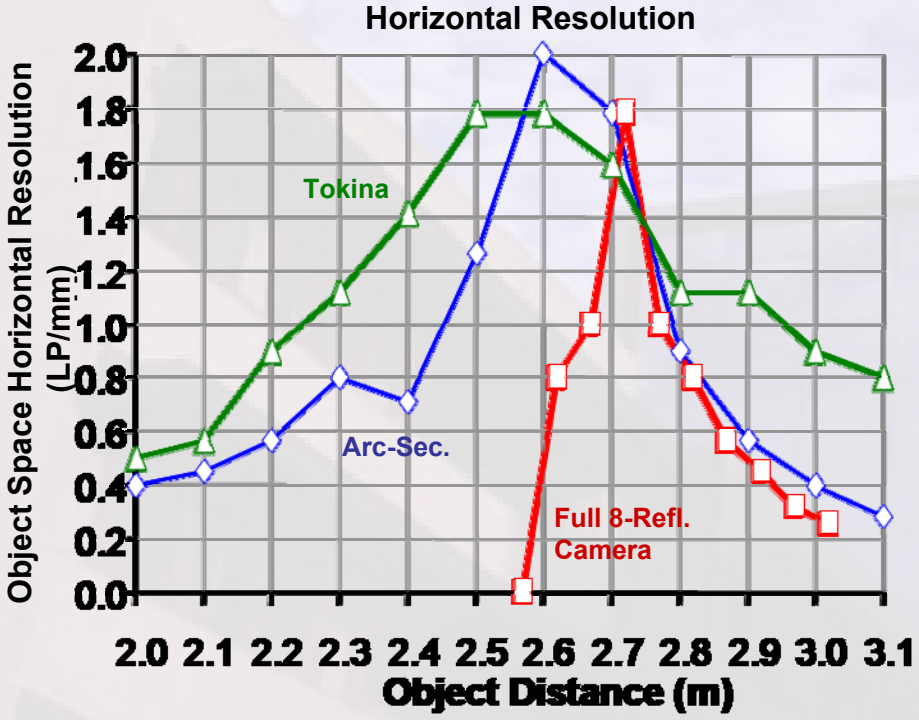
Imagers:

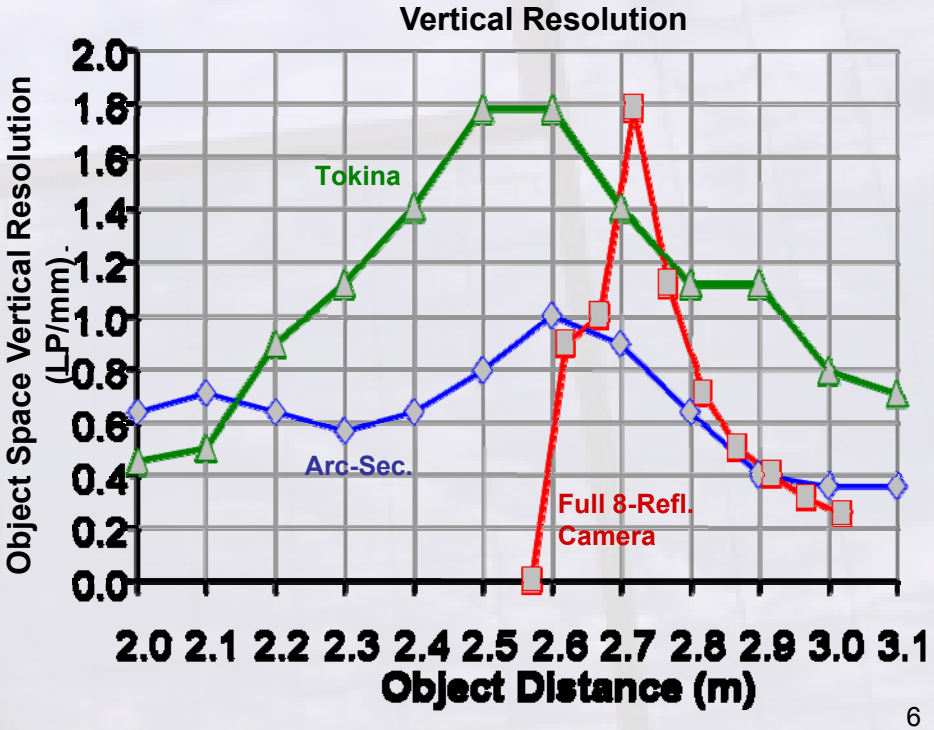
- Tokina F/1.9, f = 40 mm
- Full 8-Refl.
- Arc-sectioned 8-Refl.

} Al-CMOS sensor

Cu-CMOS sensor

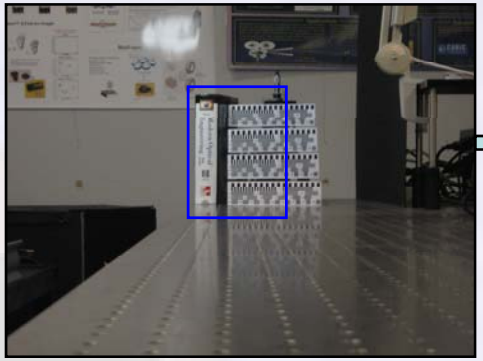




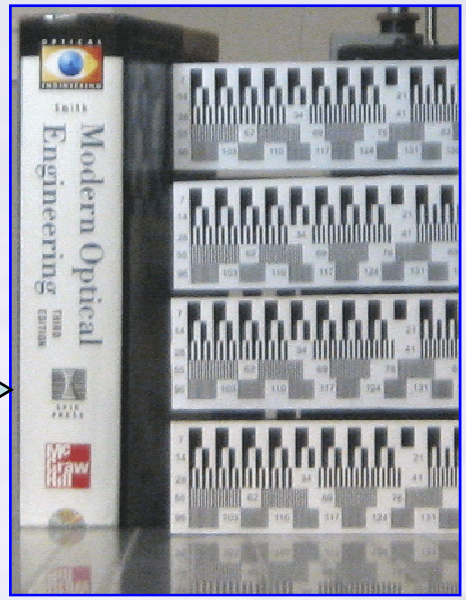


Comparison: Canon SD-30 to the Arc-Sectioned Prototype

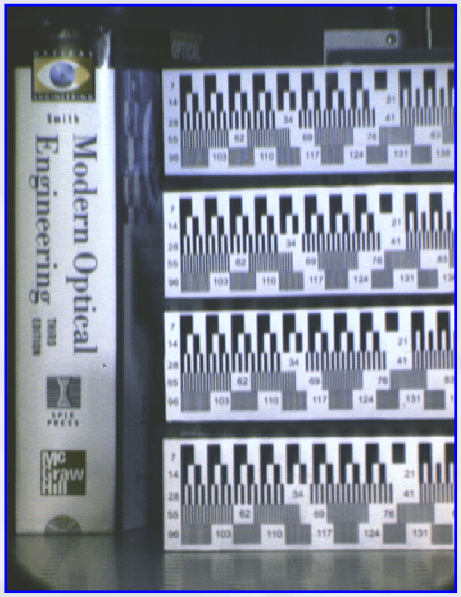
UCSD Photonics



Canon SD-30 (jpeg!)



Arc-Sectioned Camera (raw)



	Canon SD30	Arc-Sectioned
Optical track	~30mm	5mm
Light collection	< 20mm^2	80mm^2
Resolution (2.2m range)	~30 lp/mm	100 lp/mm
Focal length	6.3 – 14.9mm	38mm
Lens design	Multi-element refractor	Single element folded reflector