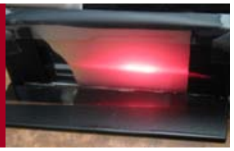
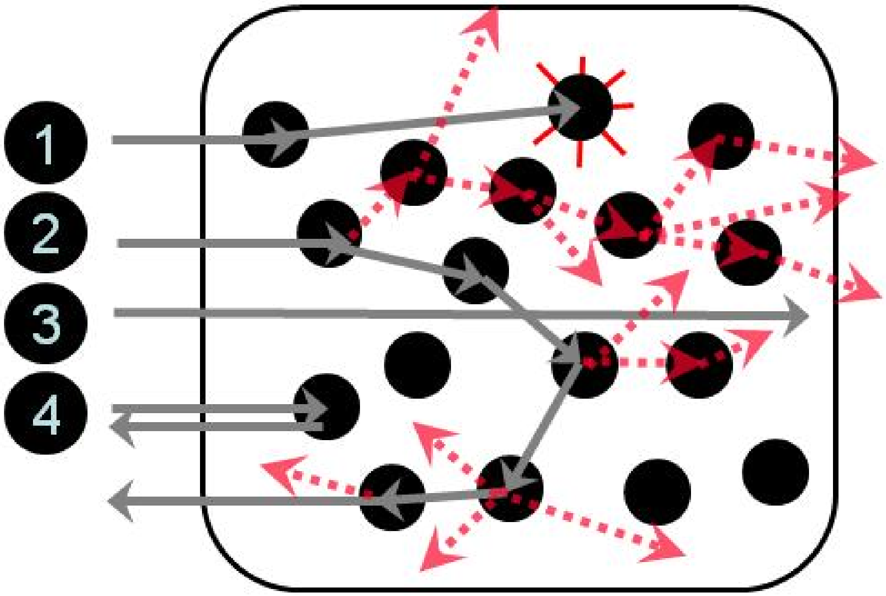
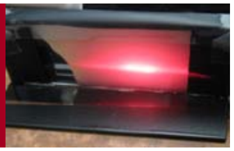
Diffusion of Photons in Scattering Media



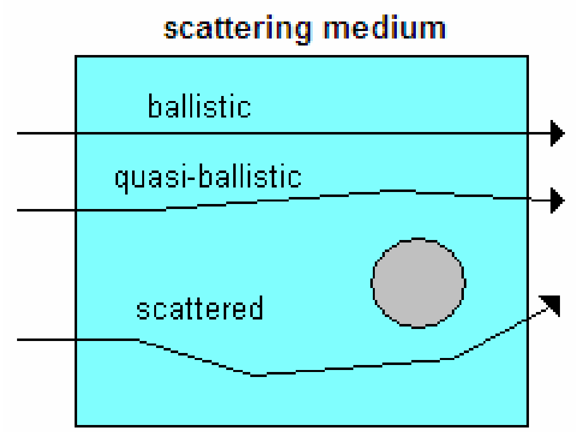
- Light entering scattering medium breaks into different types
- 1 Photons may be absorbed
- 2 Photons may be highly scattered (many paths) until nearly uniform
- Scattered photons lose almost all information of internal structure
- 3 Photons may travel without scattering: called Ballistic photon
- If photon scattered: but nearly ballistic path called quasi-ballistic
- 4 Photons may be reflected back from the medium



Optical Tomography (OT)



- OT technique for highly scattering media
- Assume the Beer-Lambert Law
  - Light scattering grows exponentially
    - Tissue is forward scattering (g ~ 0.9)



$$I_{out} = I_{in} \exp[-(\mu_a + \mu_s)d] \qquad \mu_{seff} = \mu_s(1-g)$$

- Scattering Ratio (SR) for the test samples
  - Scattered to ballistic/quasi-ballistic photon ratio
    - Reduced scattering ratio is measured

$$SR = \frac{I_0}{I_{bq}} - 1$$

- This work presents diode sources for optical imaging
  - Experimented with 670 nm (red) diode
    - Will implement 808 nm and 975 nm diode lasers
- Applied to scattering fluids and animal tissue

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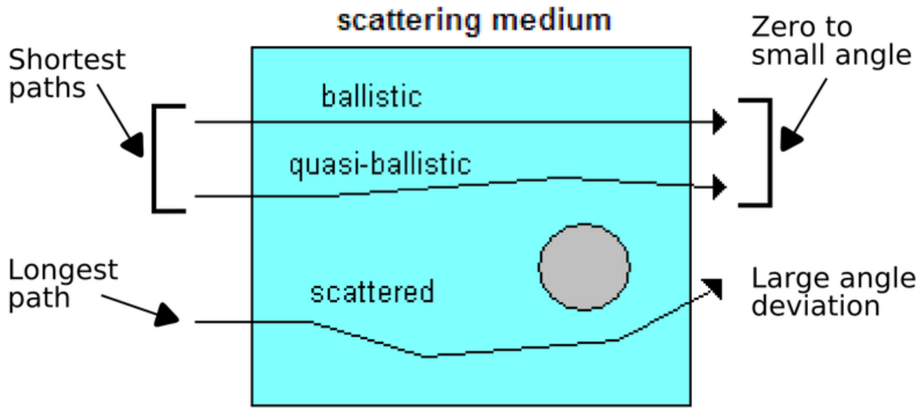
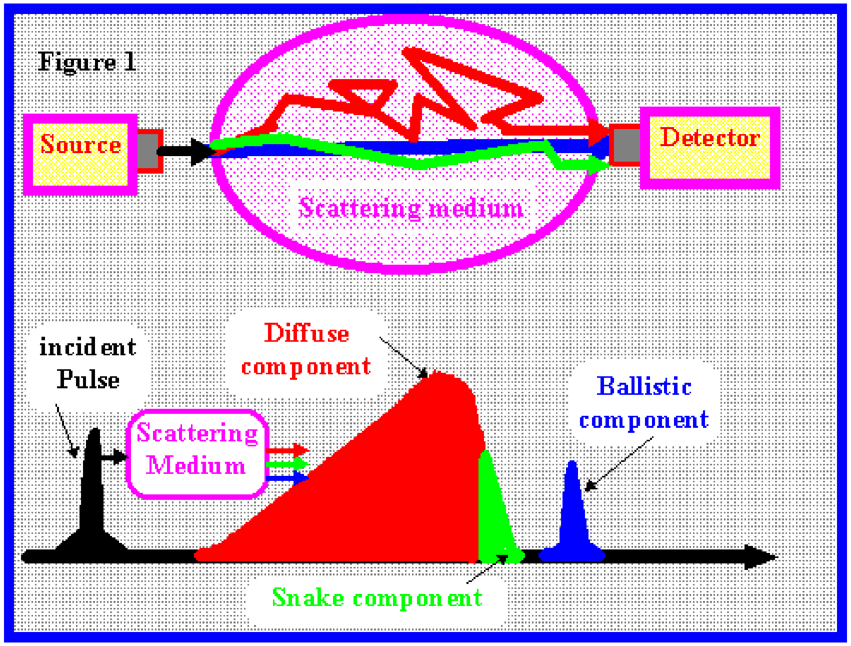
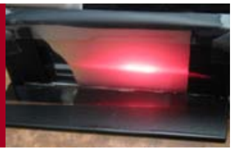
Existing OT Methods

- Three OT methods:
  - Time of flight (Time Domain)
  - Phase Coherence Domain
  - Angular Domain Imaging
- Time Domain
  - Based on path length
  - Shortest path photons arrive first
- Launch very short pulse
  - Few Femtosec
  - Ballistic arrive first
  - Quasi ballistic next
  - Scattered last
- Use high speed shutter to select

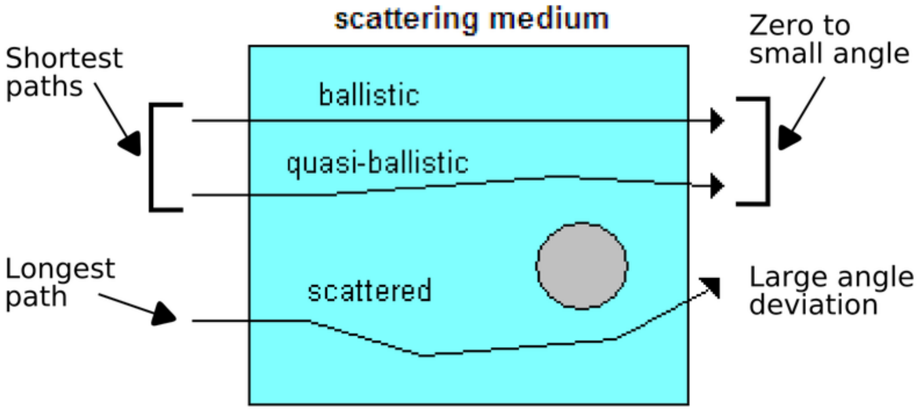


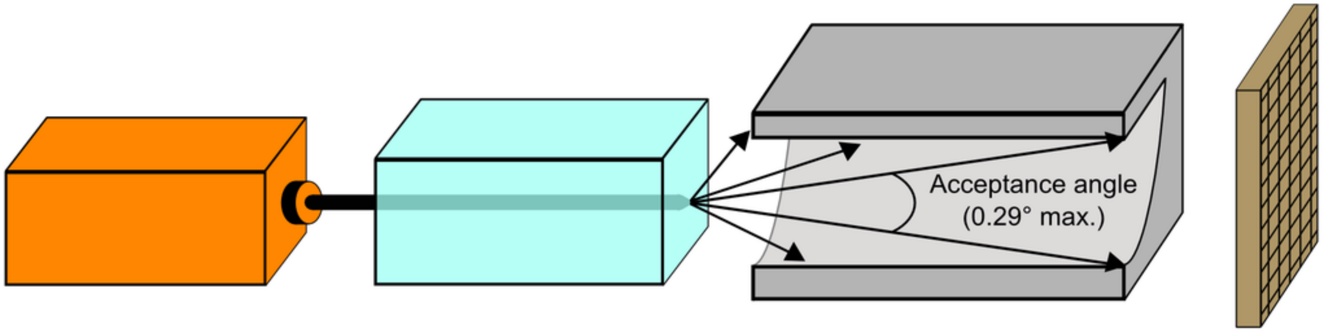


Existing OT Methods

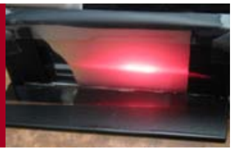


- This work uses Angular Domain Imaging (ADI)
  - Laser source aligned to small acceptance angle angular filters
  - Ballistic/quasi-ballistic light deviates only small angles
    - Most scattered light outside acceptance angle

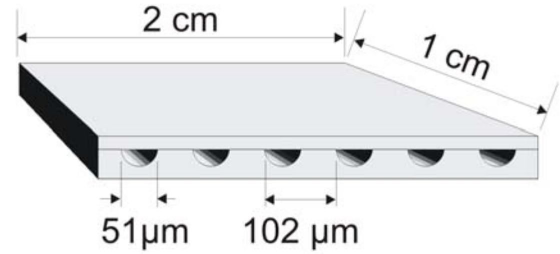


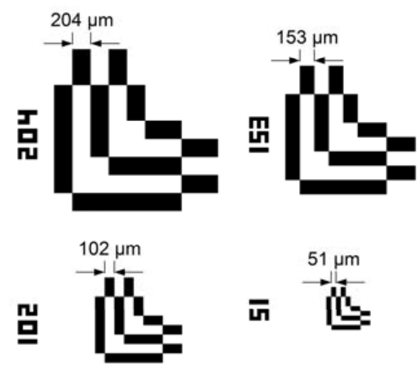


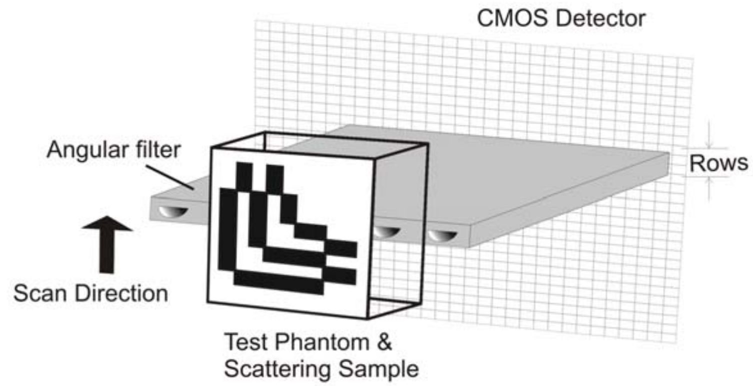
ADI and Angular Filters



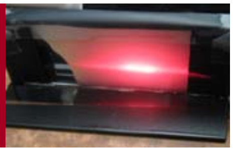
- Use high aspect ratio micromachined tunnels
  - 51 µm diameter x 1 cm length
  - Tunnels spaced on 102 µm centers
  - Aspect ratio ~200:1
  - Acceptance angle ~0.29º
- Use test phantoms in 5 cm scattering fluid
  - Use lines/spaces (204, 153, 102, 51 µm)
- Experimentally calibrate scattering solution
  - Water with partially skimmed milk
    - SR increases with milk concentration
- Angular filter images one line
  - Sample is vertically stepped (52 µm)
  - Lines assembled into 2-D image



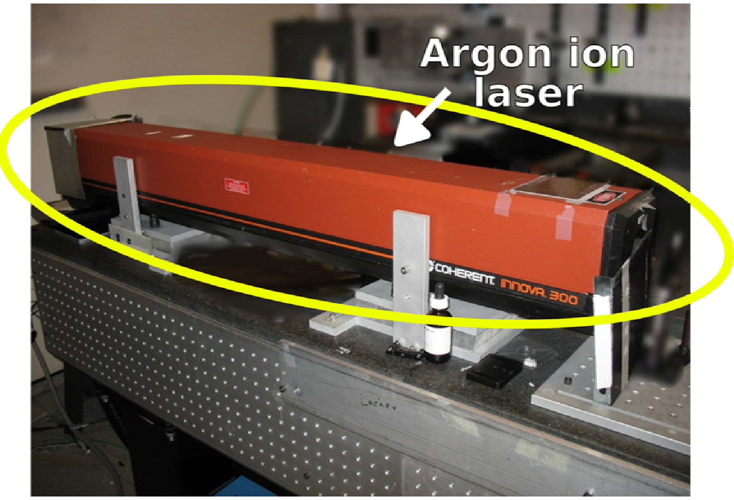


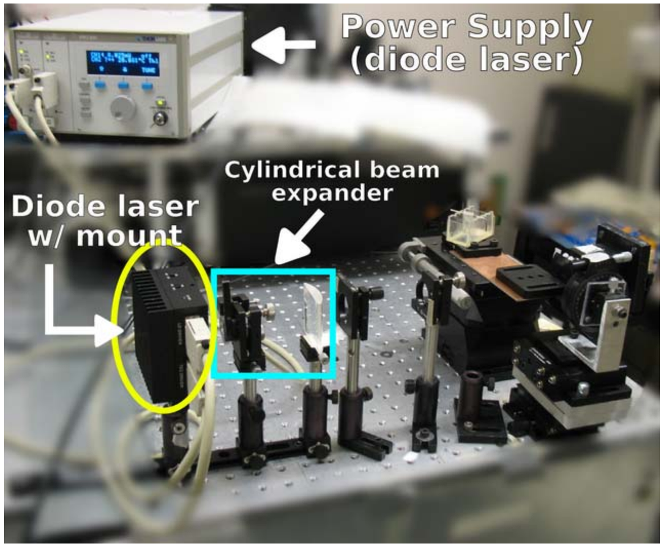


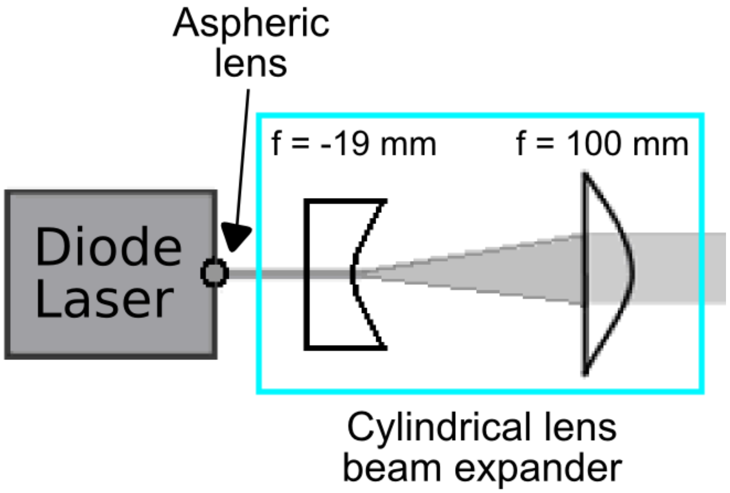
670 nm Laser Diode system



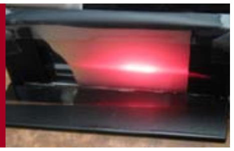
- New work with 670 nm diode laser
  - Low cost, low power, highly portable
  - Many diode wavelengths available
- Problem: asymmetric beam divergence
  - Typical: 23º (V) and 8º (H)
  - High-power aspheric lens (f = 4.5 mm)
    - Collimates vertical, overcorrects horizontal
- Corrected by cylindrical lens system
    - Beam expander collimates horizontally



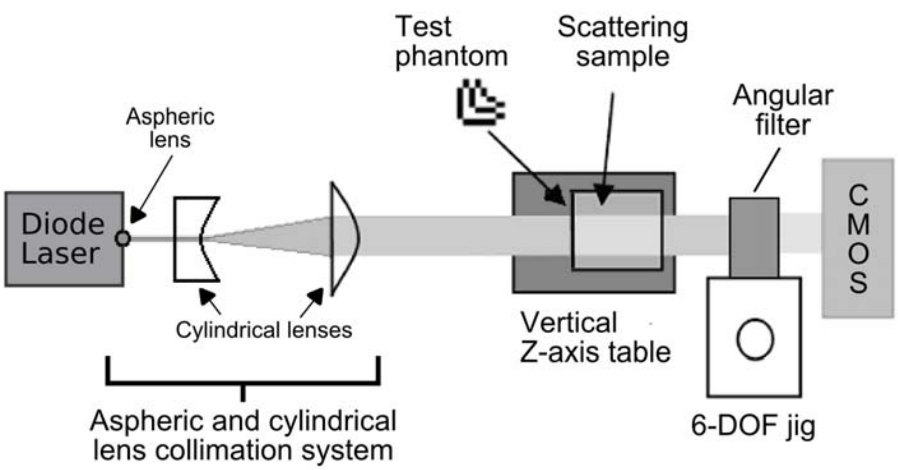


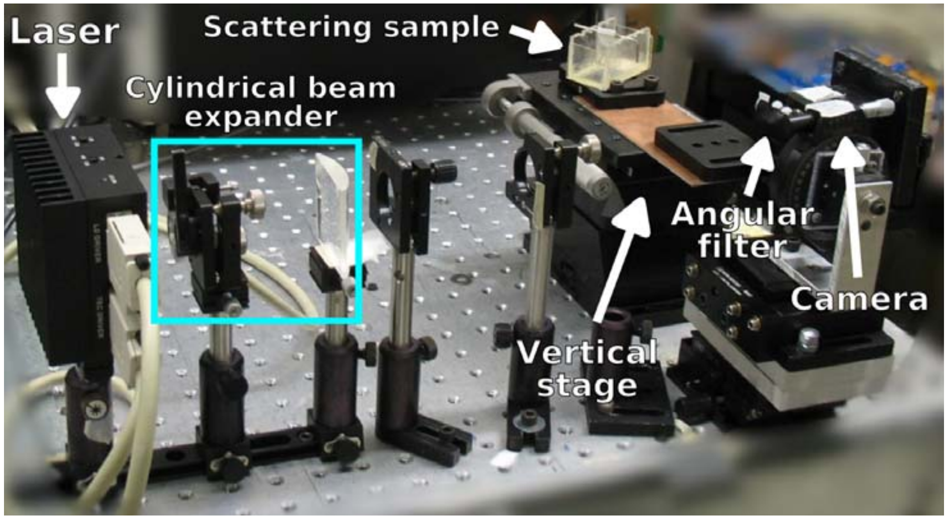


ADI setup with 670nm Laser Diode

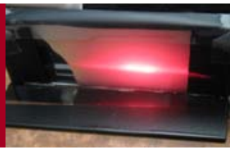


- Diode laser with aspheric and cylindrical lens system
- Produces 5 cm wide beam x 3.5 mm high line
- Test phantoms and scattering sample as before
  - Vertical stage raises scattering sample
- Angular filter aligned to laser and CMOS camera

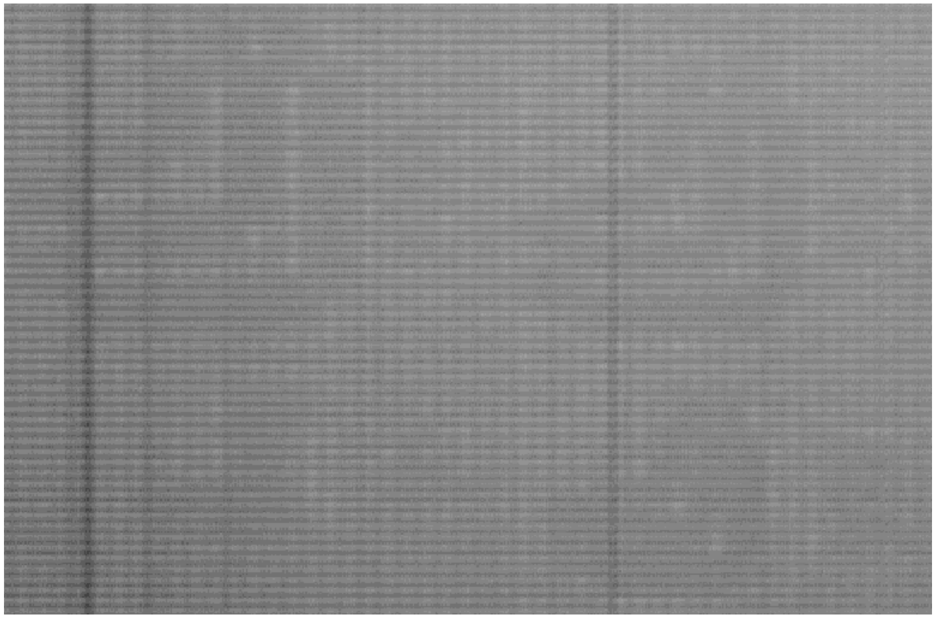




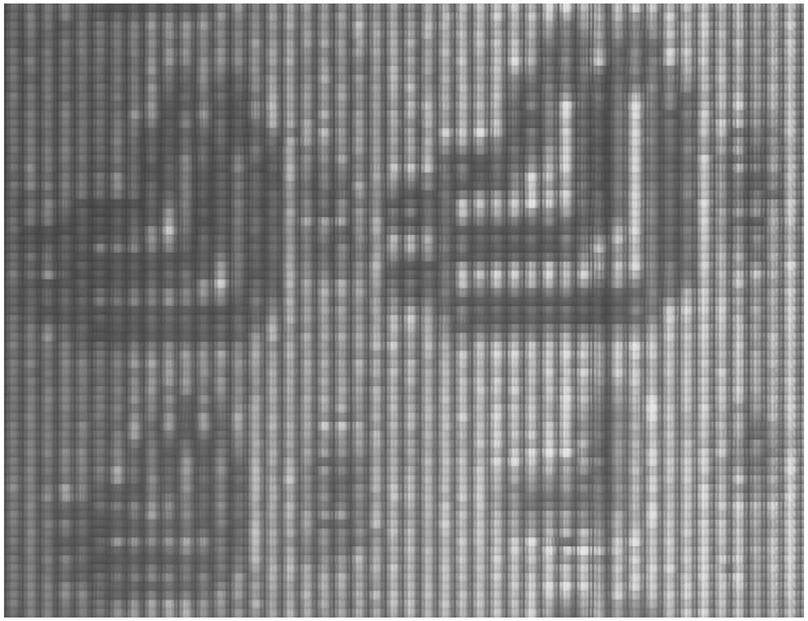
Argon vs. 670 nm @ SR = 10^6:1



- Comparable performance for SR = 10^6:1 (μ_{seff} = 2.76 cm^{-1})
  - Contrast decreased for both
  - Results at 670 nm are on par or better
    - Improvement due to narrower line of illumination (3.5 mm vs. 25 mm)
    - Lines and gaps of 204 μm and 153 μm individually resolvable
    - Detectable 102 μm and 51 μm test phantoms

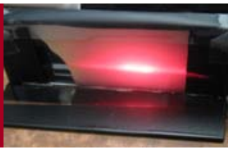


SR = 10^6:1 with 488-514 nm (Argon) (2.5 cm diameter beam)

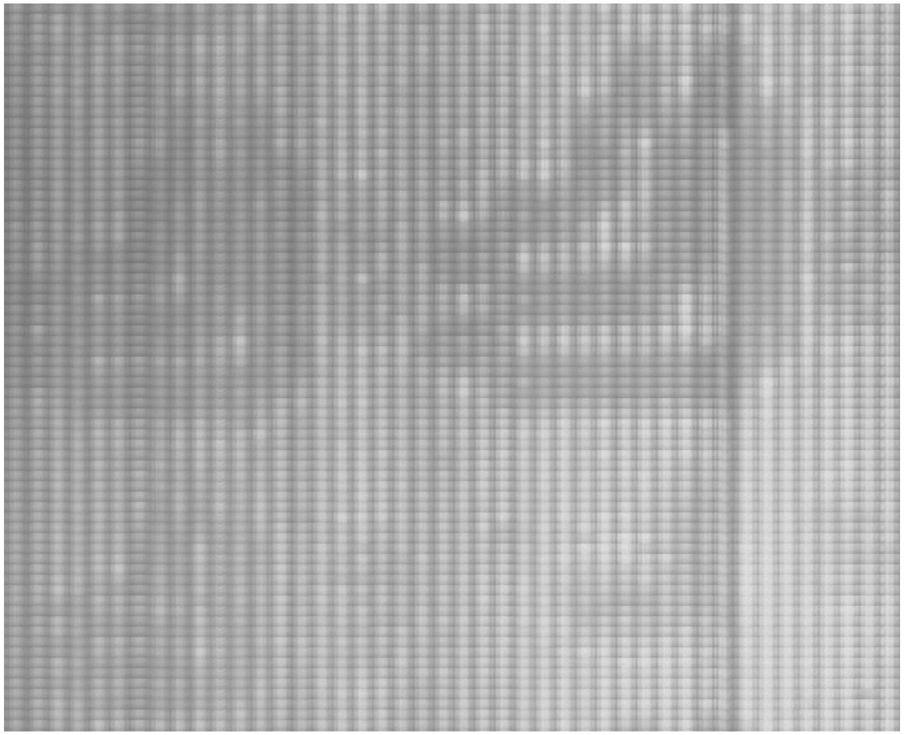


SR = 10^6:1 with 670 nm diode laser (2.3 cm x 3.5 mm line)

670 nm @ SR = 10^7:1 with image processing



- Successful results at SR = 10^7:1 (μ_{seff} = 3.22 cm^{-1}) @ 670 nm
  - More background scattered light than 10^6:1
  - Digital image processing can improve contrast
  - Further improvement requires new optics for narrower 670 nm line



SR = 10^7:1
(2.3 cm x 3.5 mm line)

With digital image processing

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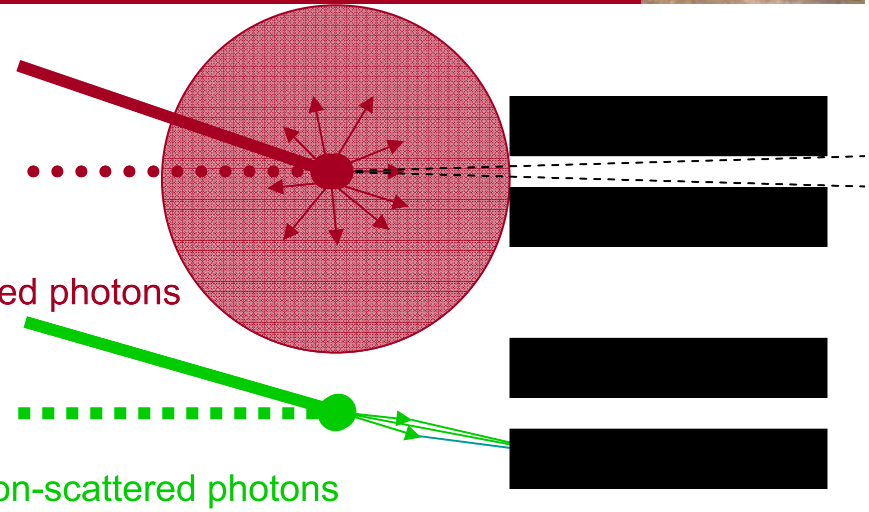
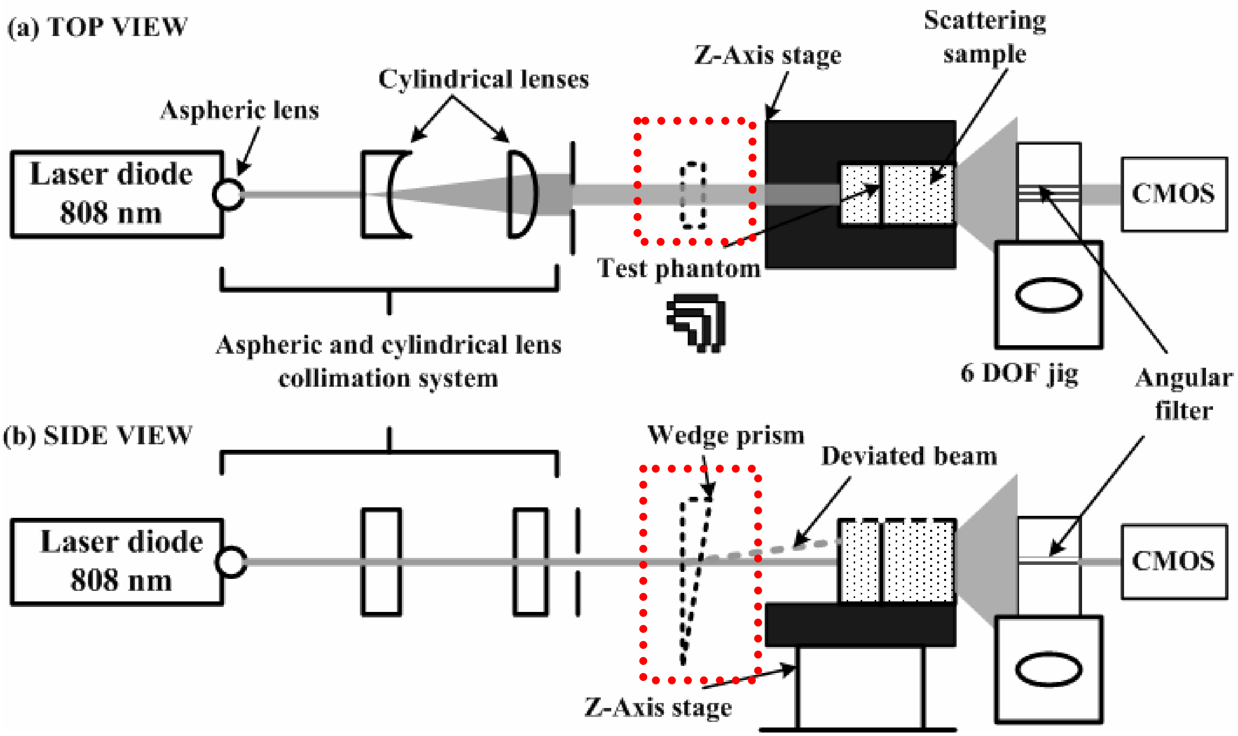
Introduce angular deviation of the light source

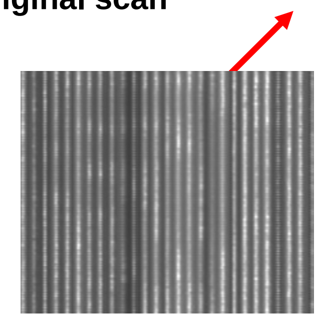
- ADI is filtering by acceptance angle
- Deviate light source by wedge prism
- Everything maintain in two measurements
  - Angular deviation of wedge prism: ~ 2-3x acceptance angle (e.g. 0.5°)
- Deviated system sees only scattered photons
- Get pixel by pixel measure by scatter light
  - More accurate background estimation



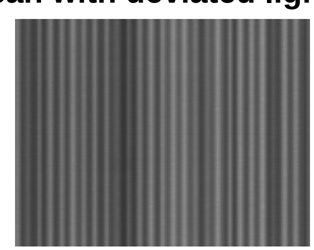


Original scan

200 μm



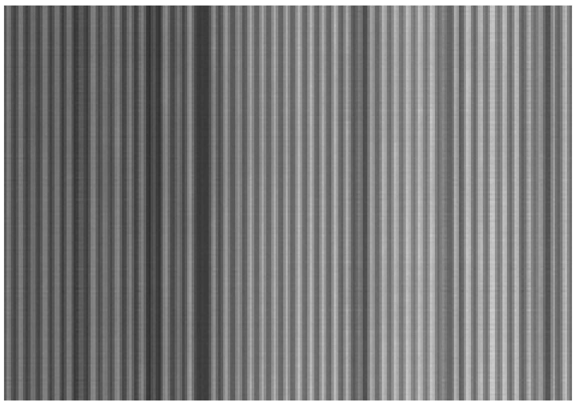
Scan with deviated light source



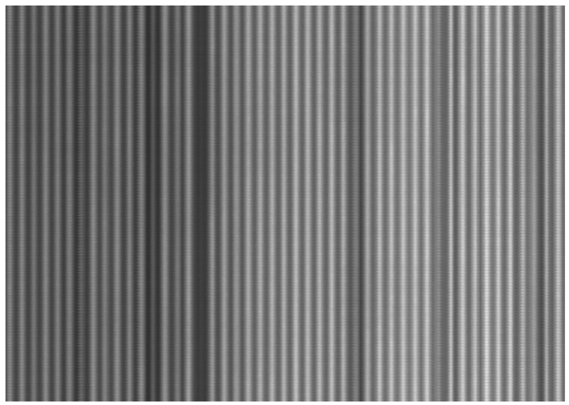
Wedge subtraction at max SR: 4.5×10^8:1

- Maximum SR = 4.5×10^8:1 for current setup
  - Original image not detectable
  - DSP is not enhancing enough
- Wedge subtraction with higher contrast

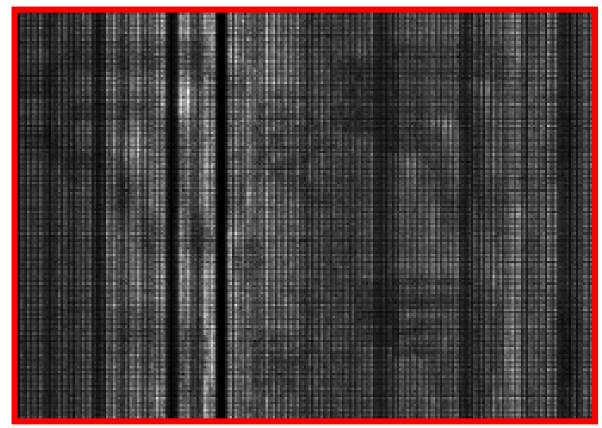
Original image



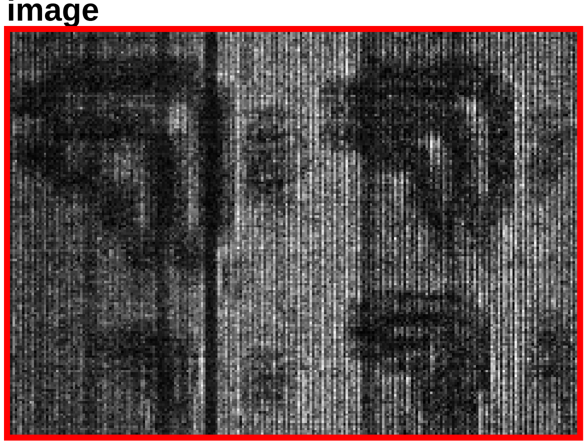
Background scattered light image



Only DSP enhanced



Wedge subtraction: Combined image



Wedge subtraction: DSP enhanced