Coherence & Light

- Two waves coherent if fixed phase relationship between them for some period of time

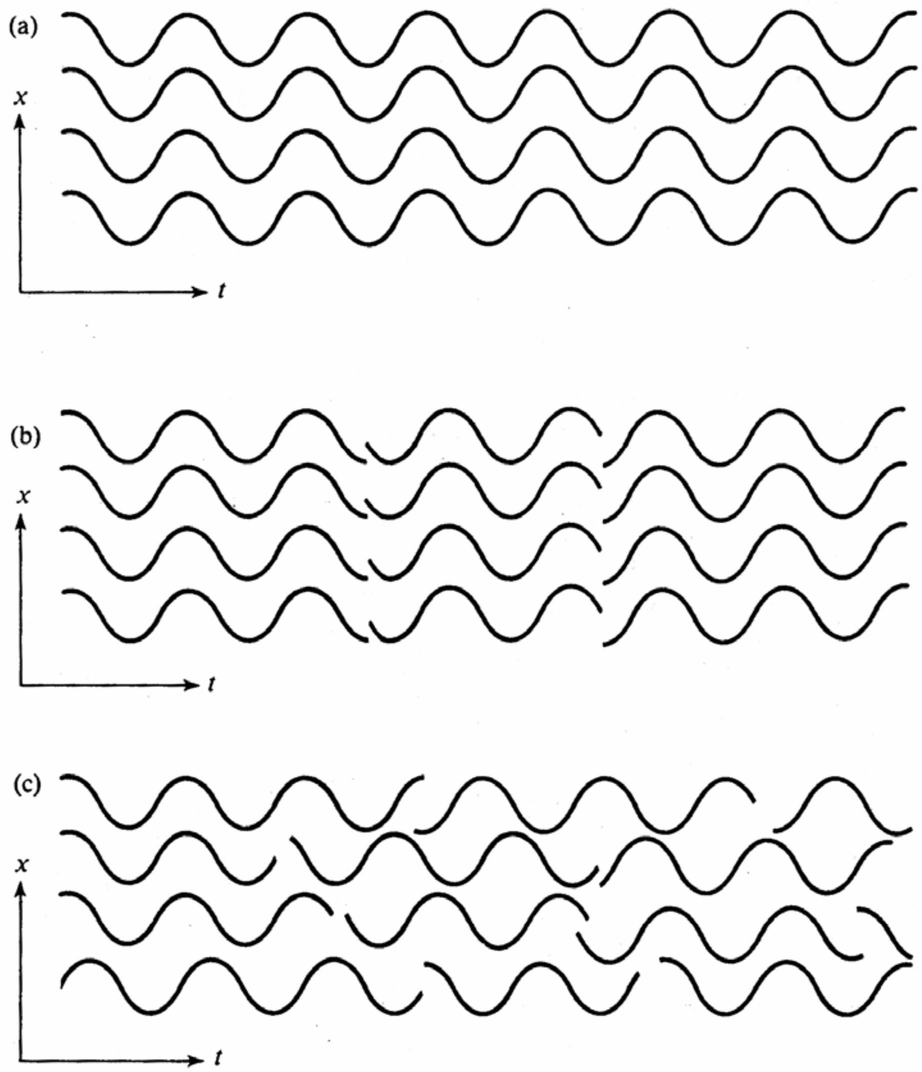

Fig. 3.8 An illustration of coherence. In (a) we show a perfectly coherent beam. All the constituent waves are in phase at all times. In (b) we have a beam which is spatially coherent, but which exhibits only partial temporal coherence. This is because the waves simultaneously change their phases by an identical amount every few oscillations. In (c) we show an almost completely incoherent beam where the phases of each wave change randomly at random times. Note however that even in this case some small degree of temporal coherence remains, since over very short time intervals the phases are to some extent predictable.

Coherence

- Coherence appear in two ways

Spatial Coherence

- Waves in phase in time,
  but at different points in space
- Required for interference and diffraction
- Before lasers need to place slits far from source
  or pass light through slit so only part of source seen

Temporal Coherence

- Correlation of phase at the same point
  but at different times
- Regular sources rapidly change phase relationships
- Single atom on 10^{-8} sec coherent
  lifetime of atom in an excited state
- Much shorter for groups of atoms
- For lasers in single mode much longer time

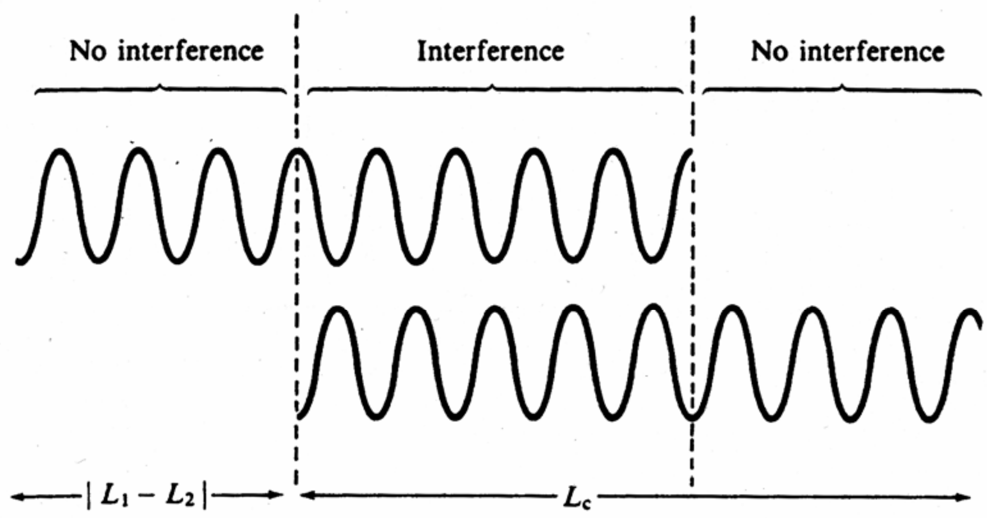

Fig. 3.10 When two identical wavetrains of length L_c which have traveled different distances (L_1 and L_2) are recombined they can only interfere over a length $L_c - |L_1 - L_2|$.

Coherence Length and Time

- Time of coherence given by τ_{coh}
- Coherence time about time taken for photon to pass a given distance (Coherence length) in space
- Coherence length is

$$L_{coh} = c\tau_{coh}$$

- Best seen in Michelson-Morley experiment
- Beam is split into two beam paths, reflected and combine
- If get interference pattern then within Coherence lengths
- Before lasers paths needed to be nearly equal
- With lasers only require

$$2(L_1 - L_2) < L_{coh}$$

- Coherence last 50 - 100 m with lasers

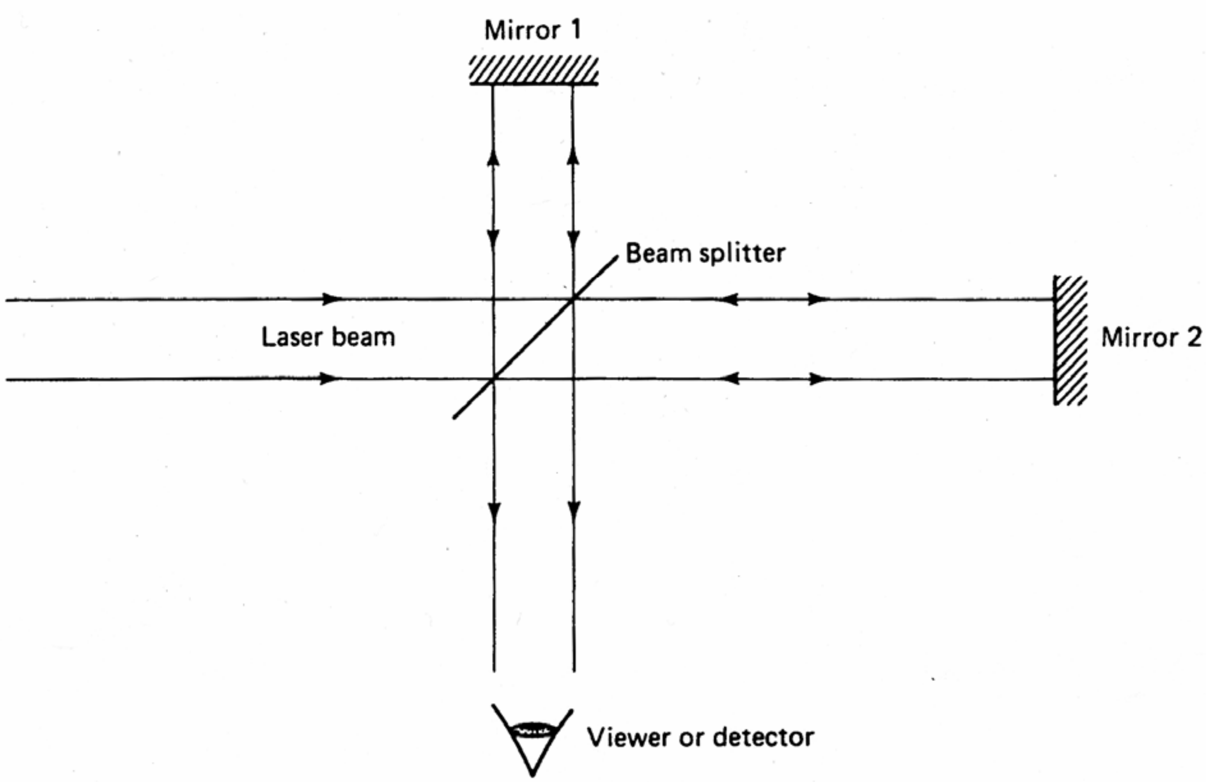

Figure 1-24 Michelson interferometer.

Coherence Length and Lasers

- As the coherence length is

$$L_{coh} = c\tau_{coh}$$

- If want interference distances < coherence length
- Lasers have high coherence
- It can be shown Coherence time related to laser frequency width $\Delta\nu$ (linewidth)

$$\tau_{coh} = \frac{1}{\Delta\nu}$$

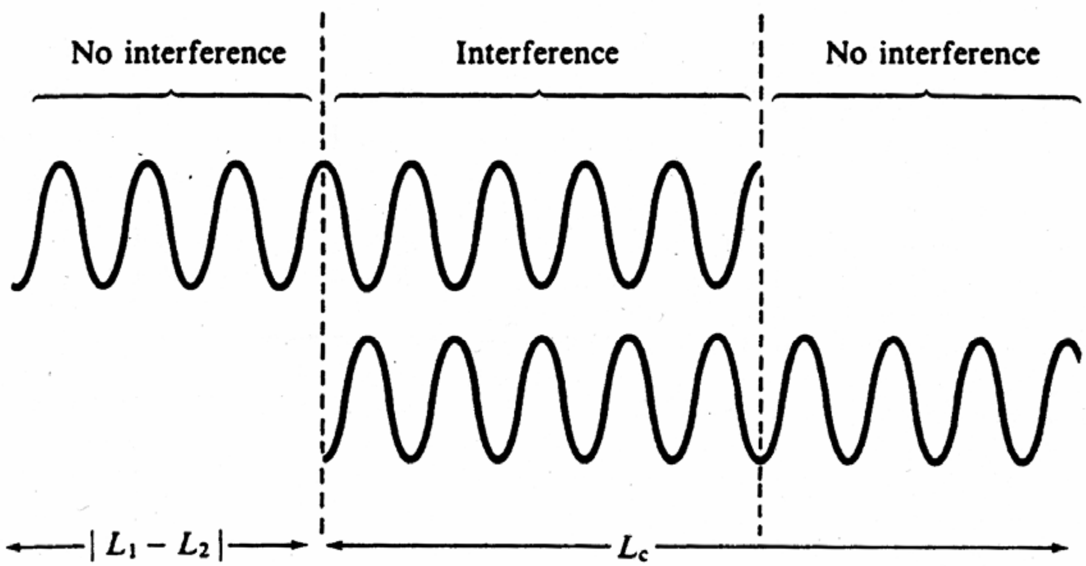

Fig. 3.10 When two identical wavetrains of length L_c which have traveled different distances (L_1 and L_2) are recombined they can only interfere over a length $L_c - |L_1 - L_2|$.

Example of Coherence Length

Sodium vapour lamp yellow "D" line

- λ = 589 nm and linewidth $5.1x10^{11}$ Hz
- Thus coherence time and length is

$$\tau_{coh} = \frac{1}{\Delta\nu} = \frac{1}{5.1x10^{11}} = 1.96x10^{-12}\ sec$$

$$L_{coh} = c\tau_{coh} = 2.98x10^{8}\left(1.96x10^{-12}\right) = 5.88x10^{-4}\ m = 0.59mm$$

- Coherence small hence hard to create holograms

- HeNe laser in multimode operation
- λ = 632.8 nm and linewidth 1500 MHz
- Thus coherence time and length is

$$\tau_{coh} = \frac{1}{\Delta\nu} = \frac{1}{1.5x10^{9}} = 6.67x10^{-10}\ sec$$

$$L_{coh} = c\tau_{coh} = 2.98x10^{8}\left(6.67x10^{-10}\right) = 0.2\ m$$

- If single mode HeNe operation linewidth goes to 1 Mz
  and cohrence time is 1 microsec, cohrence length 300 m

Fourier Domain
Optical Coherence Tomography
(FD OCT)

Marinko V. Sarunic, Ph. D.

Assistant Professor

School of Engineering Science

Simon Fraser University

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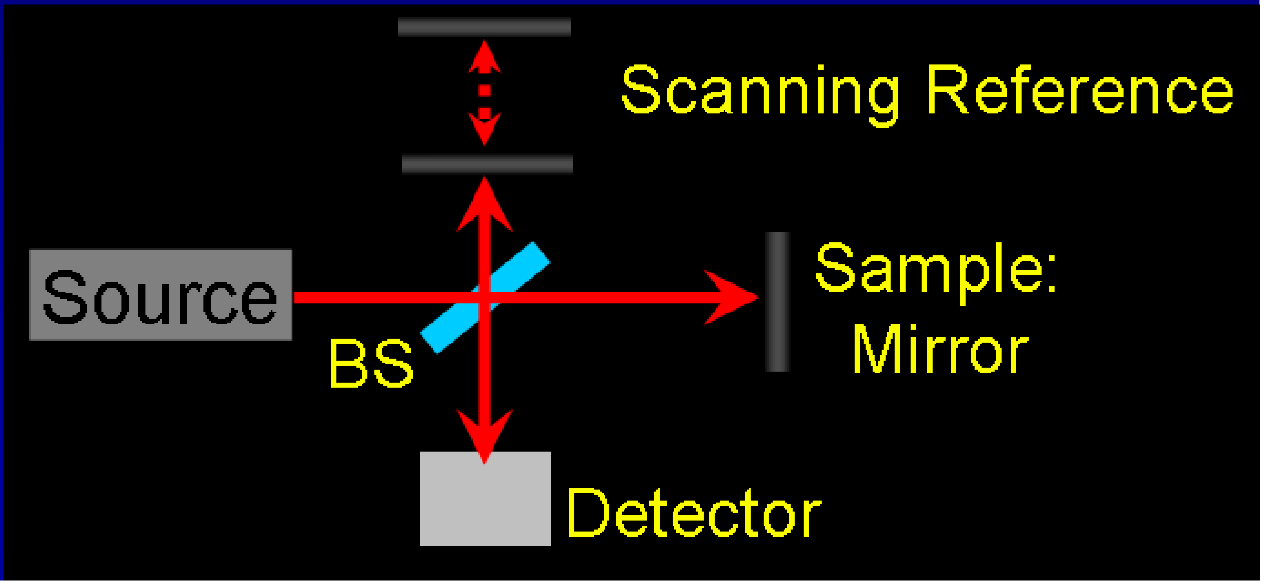
Common Patient Imaging Modalities

Imaging Method	Resolution	Penetration Depth	Source of contrast	Cost
Computed Tomography (X-rays)	2 – 3 mm	Entire body	Attenuation	$$$
Magnetic Resonance Imaging	2 – 3 mm	Entire body	[H^+]	$$$$
Ultrasound	500 μm	10 – 20 cm	Acoustic scattering	$$
Visual Examination	100 μm	Surface	Natural Colouring	$
Coherence Domain Optical Imaging	1 – 10 μm	2 – 3 mm	Optical scattering & absorption	$$
Histology	1 μm	5 – 10 μm sections	Histological stains	$$

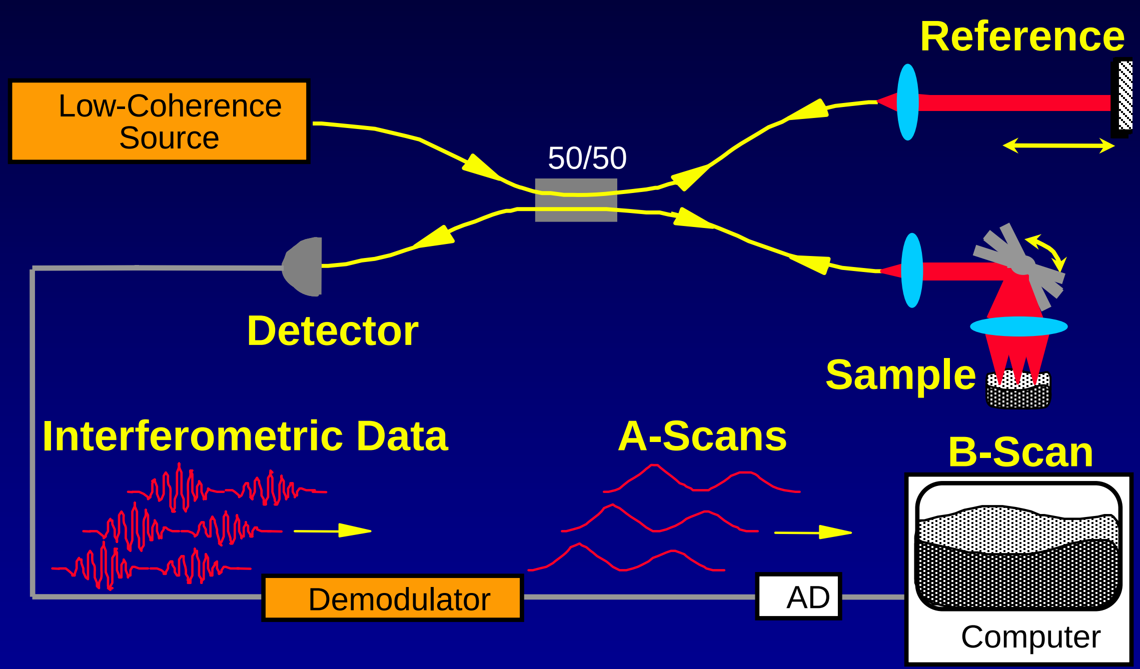
Modified from J.A. Izatt, OCT Short Course

Optical Coherence Tomography

- In tissue shortest path photons are least scattered
- Consider starting with a coherent source (laser)
- 2 paths: one to tissue, other to reference
- Use Michelson interferometer methods
- By adjusting reference delay scan return in phase
- Hence can separate scattered from unscattered
- Called Time Domain OCT



Optical Coherence Tomography



Longitudinal Resolution:

$$l_c = \frac{2\ln 2}{n\pi}\frac{\lambda^2}{\Delta\lambda}$$

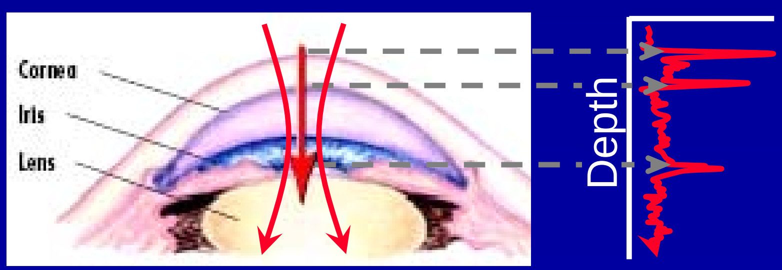
$$\sim 1.5 - 15\ \mu m$$

Transverse Resolution:

$$\Delta x = 1.22\frac{\lambda}{2N.A.}$$

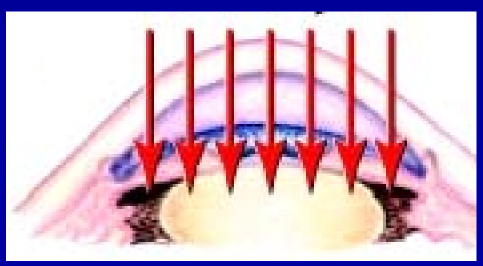
$$\sim 2 - 25\ \mu m$$

Axial A-scan

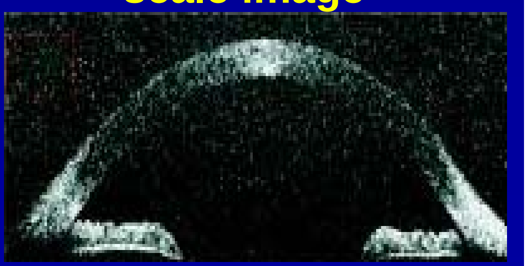


Log scale intensity (dB)

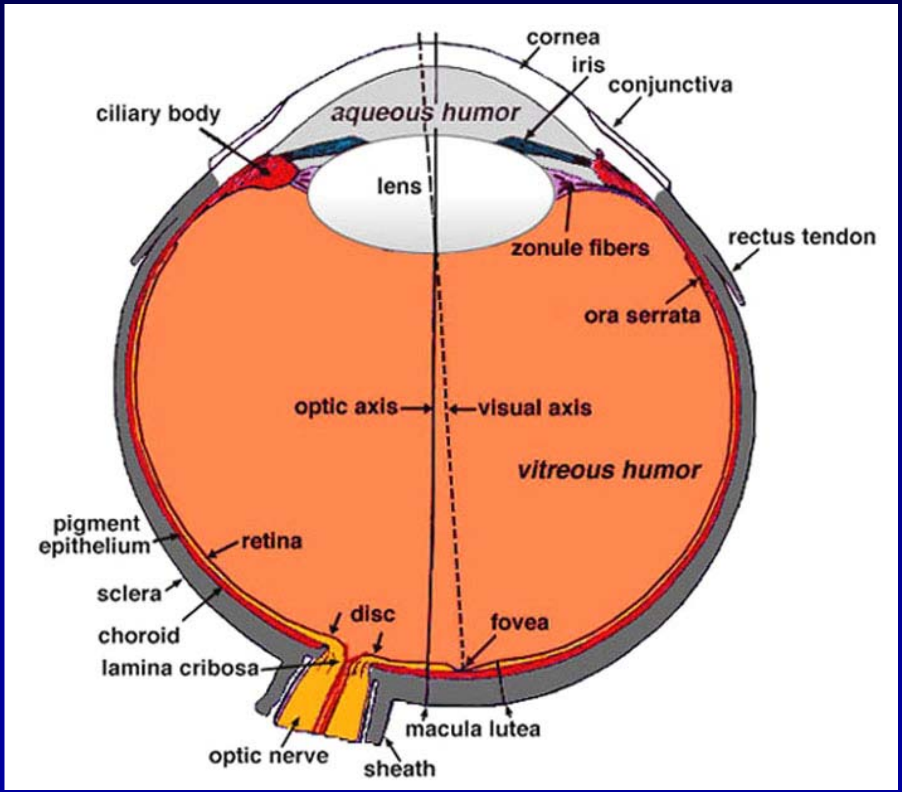
B-scan



B-scan: log scale image

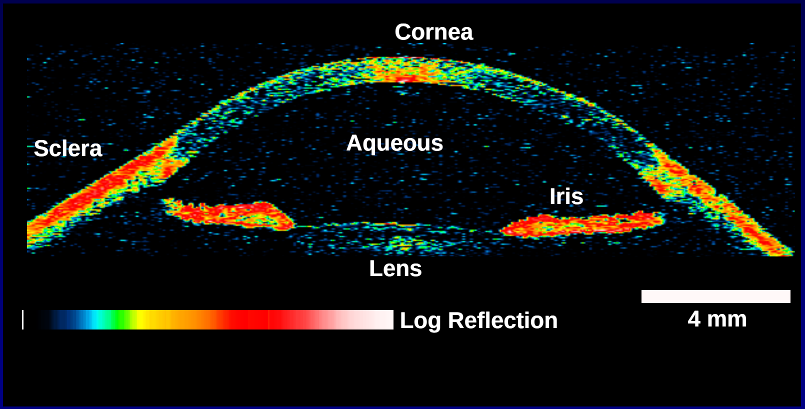


Ophthalmic Optical Coherence Tomography



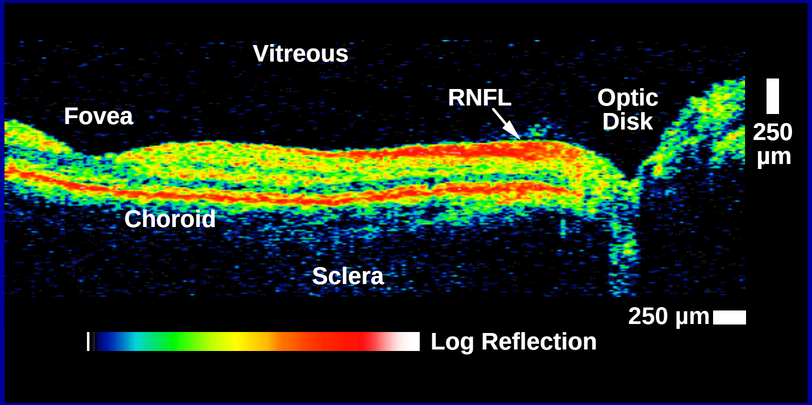
Anterior Segment

Izatt, et. al., Arch. Ophthalmol. 112:1584-1589, 1994.

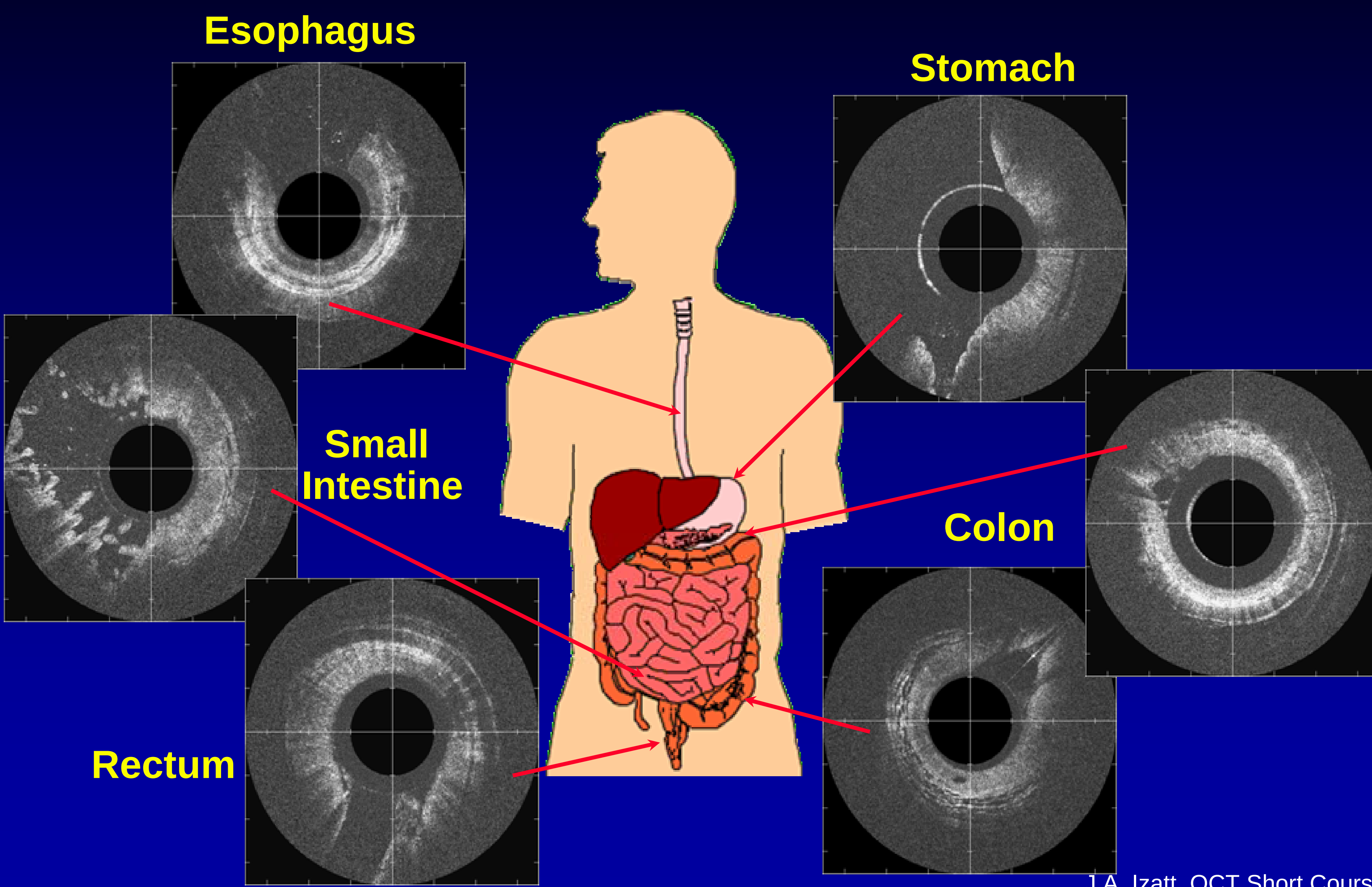


Retina

Hee, et. al., Arch. Ophthalmol. 113:325-332, 1995.



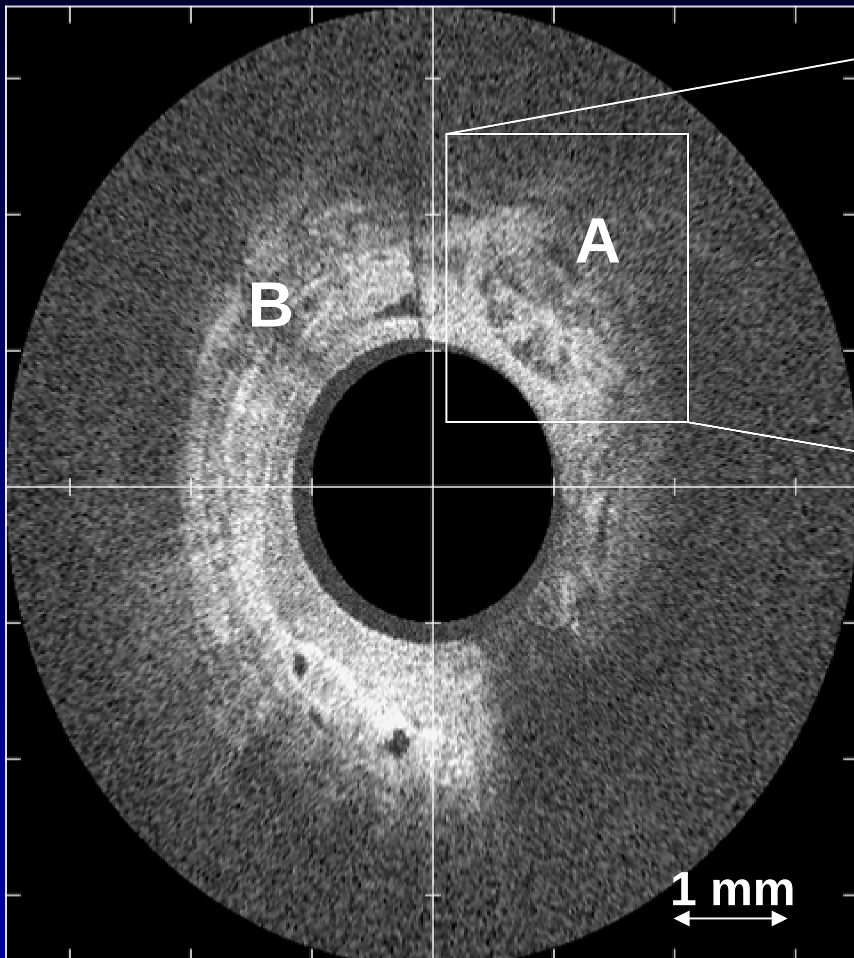
IN VIVO HUMAN ENDOSCOPIC OCT

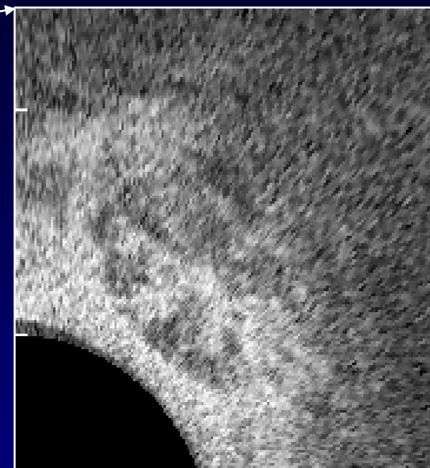


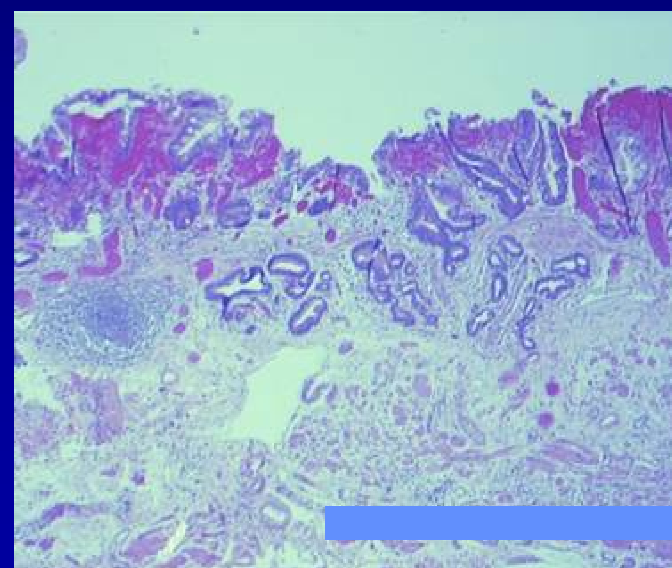
J.A. Izatt, OCT Short Course

CANCER IMAGING WITH ENDOSCOPIC OCT

Invasive Adenocarcinoma in Barrett's Esophagus



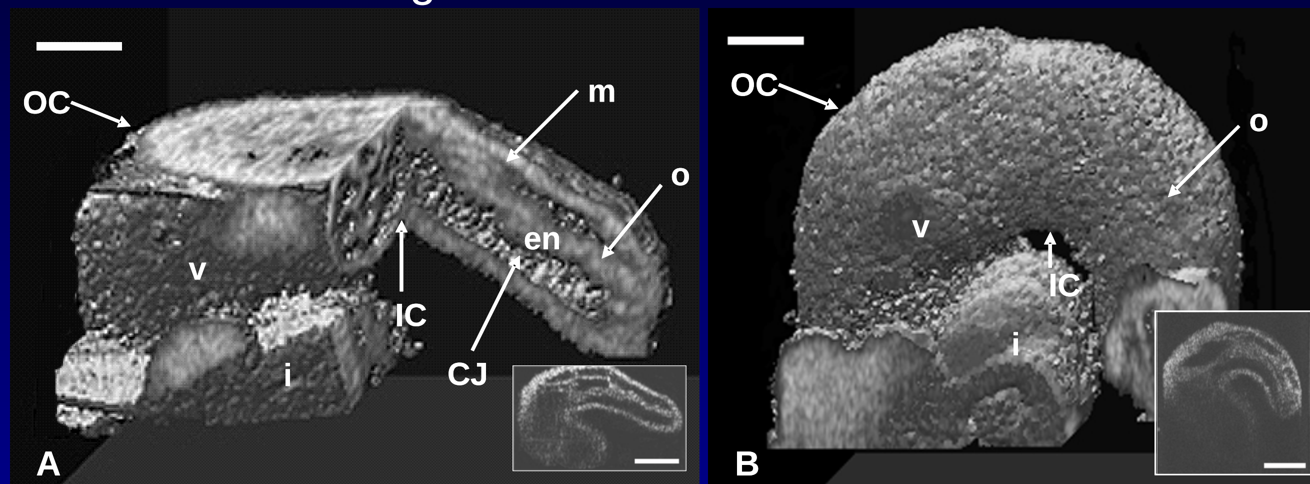


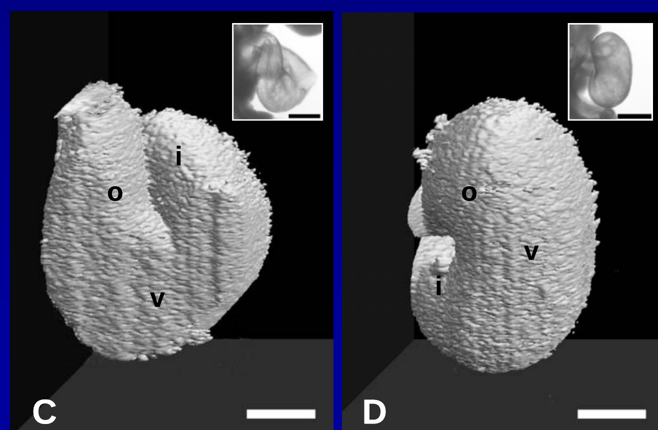


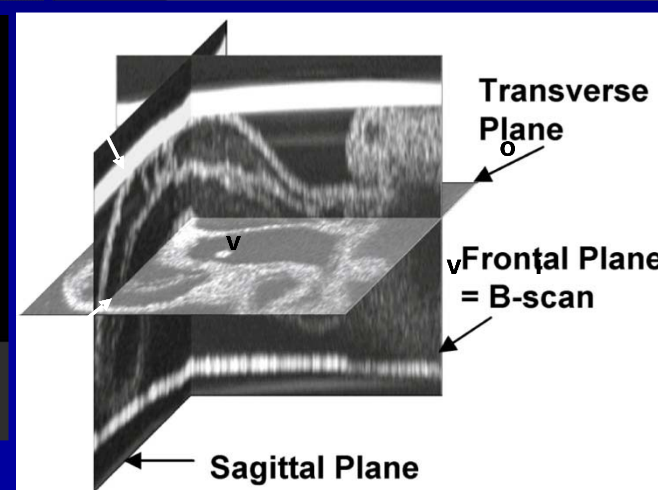
B – Barrett's Esophagus
A – Adenocarcinoma

Cardiac Morphology And Development In Chick Embryos

Heart tube folding







Yelbuz, et.al., Circulation *106: 2771, 2002*

Balance Sheet for OCT

- Non-Contact Measurement
- High resolution: 10 - 20 µm in 3 dimensions
- Compact, Inexpensive Diode-Fiber System
- Compatible with Existing Medical Instrumentation

- Speed limited by maximum optical exposure
  - Particularly important in ophthalmic imaging
    - MPE < 770 µW @ 830 nm
    - MPE < 15.4 mW @ 1310 nm
- High speed systems require complicated rapid scanning optical delay line (RSOD)
- Axial resolution trade-off with sensitivity
- Maximum tissue depth of ~2mm

Fourier Domain OCT

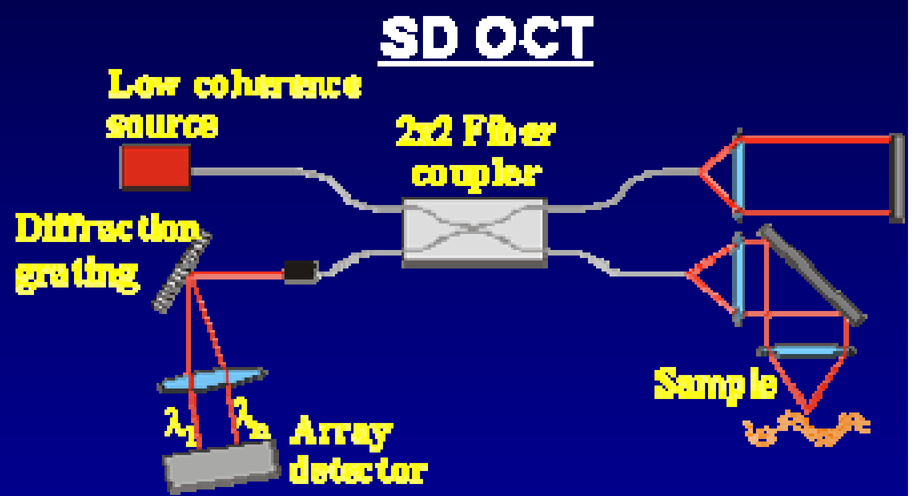
- Time domain OCT: reference moves
- Fourier Domain: reference fixed
- Now look at frequency (wavelength) changes

Spectral Domain

- Diffraction grating spreads spectrum
- Different λ different phase
- Use array type detector

Swept Source

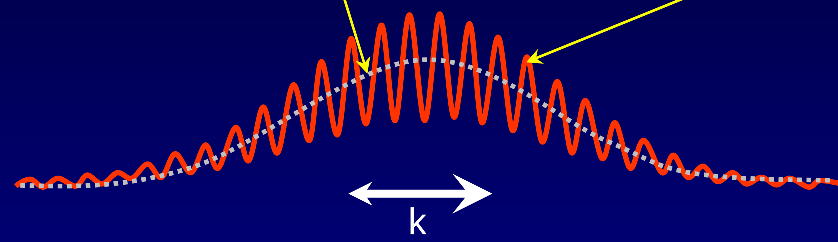
- Sweep Laser source (narrow line)
- Encode spectrum in time



Fourier Domain OCT

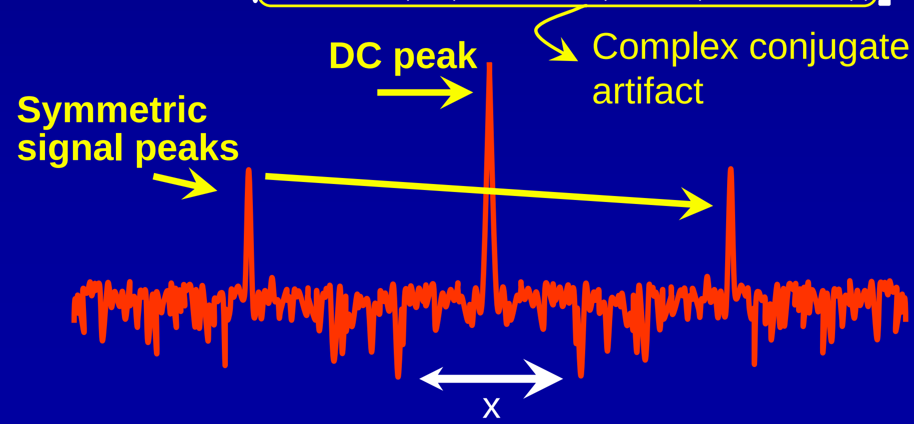
- Fixed reference arm
- Interferogram acquired as function of wavenumber

$$\hat{D}_i[k_m] \propto \hat{S}[k_m] \cdot \left(R_R + R_S + 2\sqrt{R_R R_S} \cos(2\Delta z k_m) \right)$$

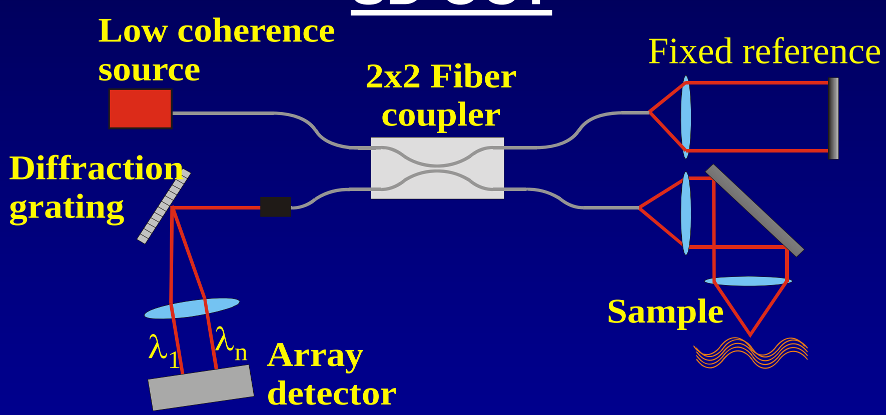


FT

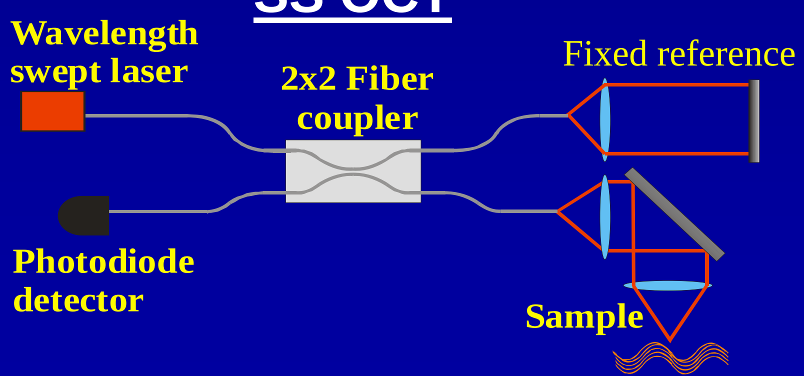
$$D_i[z_n] \propto S[z_n] \otimes \left[(R_R + R_S)\delta(z_n) \quad \ldots \right.$$
$$\left. + 2\sqrt{R_R R_S}\left(\delta(z_n + \Delta z) + \delta(z_n - \Delta z)\right) \right]$$



SD OCT

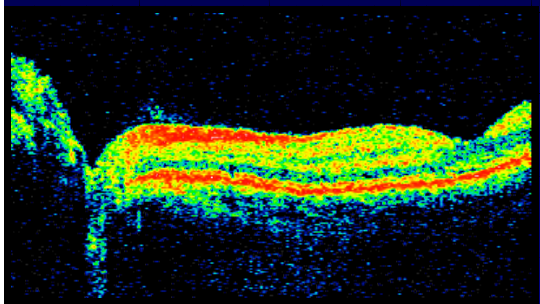


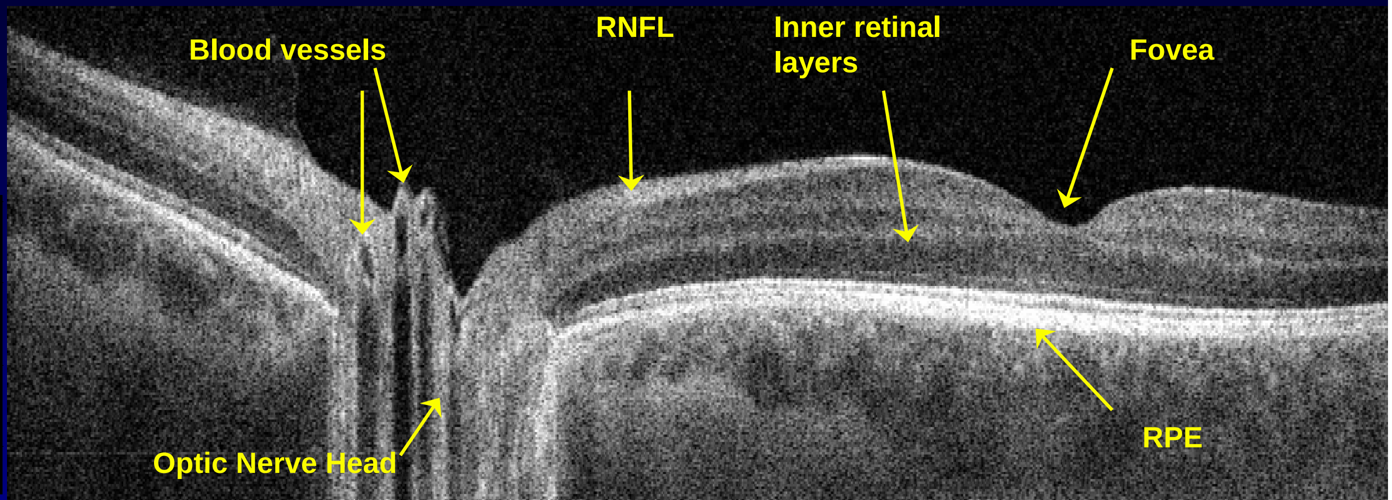
SS OCT



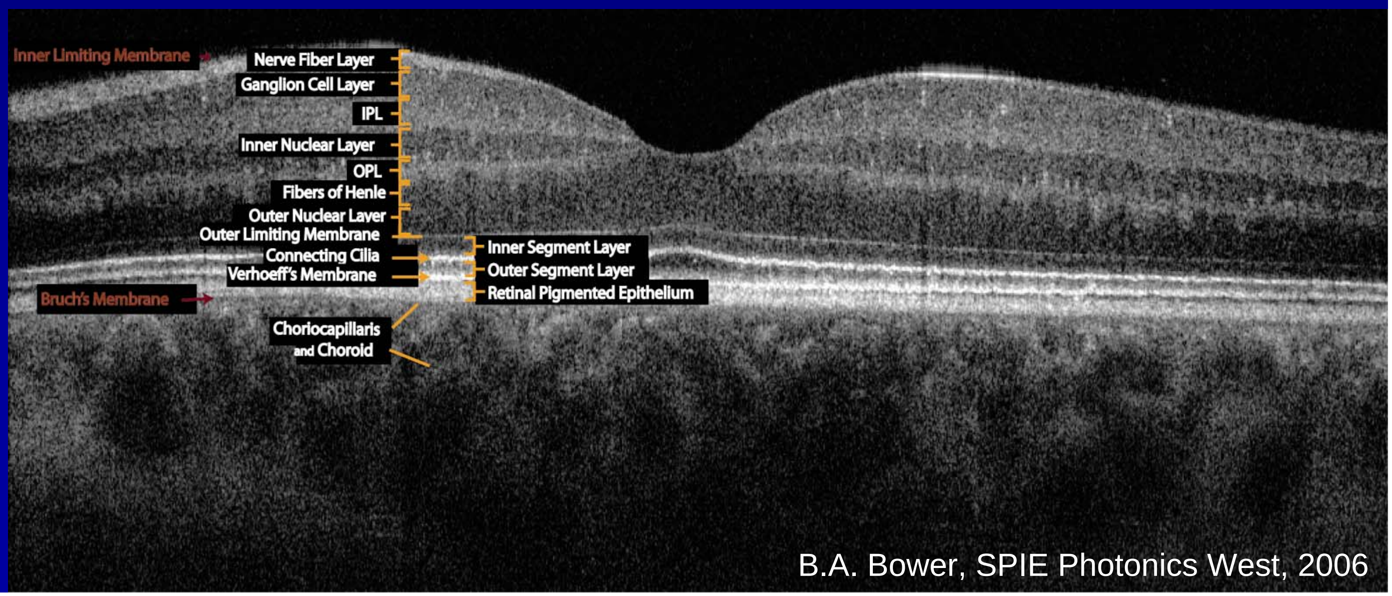
High Resolution Retinal FDOCT

Compare to commercial TD OCT results





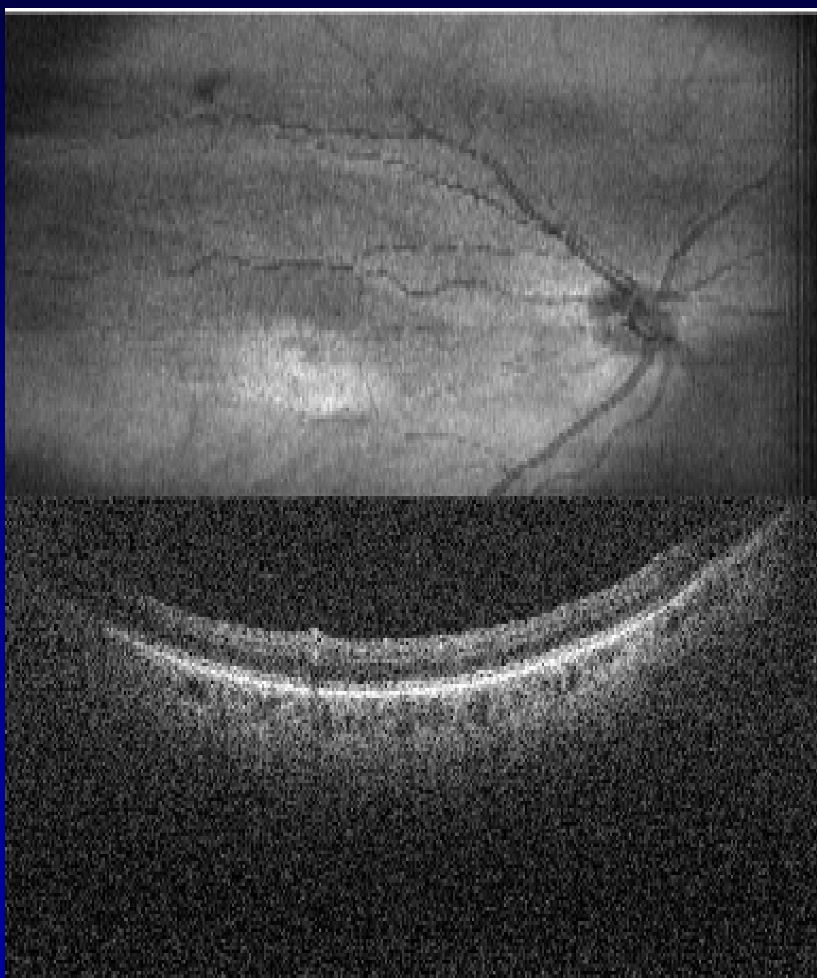
Acquisition Parameters:
- 1000 A-scans/B-scan
- 50μs A-scan int. time (20 kHz)
- 17 frames/sec display
- 11mm lateral scan
- λ_o=841 nm, $\Delta\lambda$=49nm

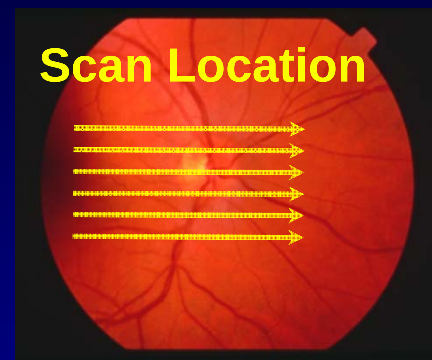


B.A. Bower, SPIE Photonics West, 2006

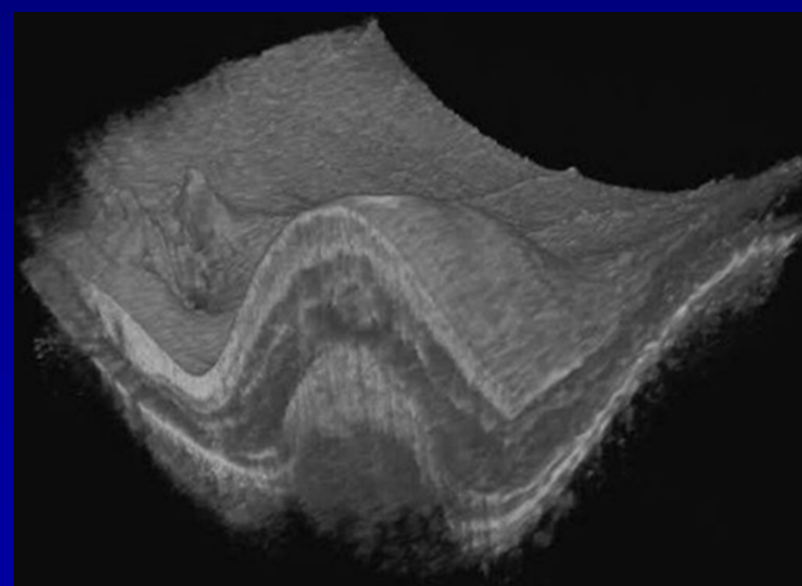
High Speed Volumetric Retinal FDOCT

Summed voxel projection from raster canned OCT Data: “OCT Fundus” Image





Retinal image from fundus camera
- **white light**
- **CCD camera**

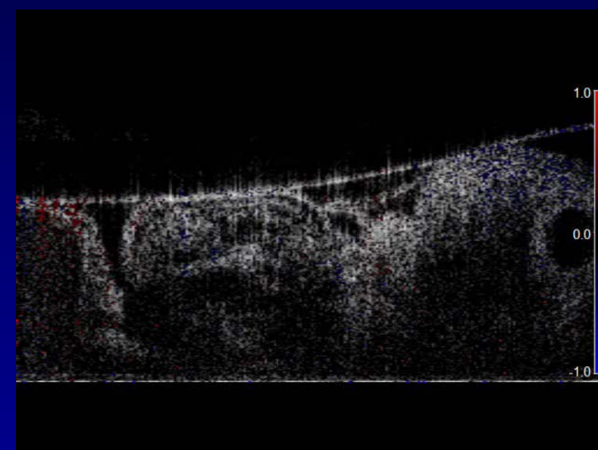


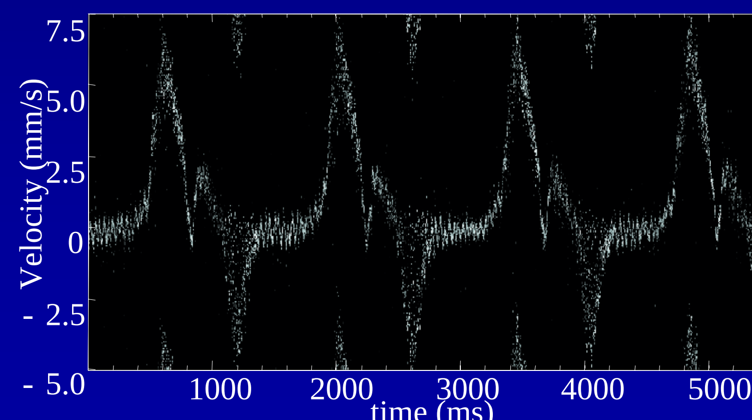
B.A. Bower, SPIE Photonics West, 2006

Small Animal Imaging

- **Video light microscopy, SEM, confocal microscopy often inadequate for quantitative measurements.**
- **OCT is uniquely suited to image popular small model organisms such as fruit fly, chick embryo, zebrafish, and xenopus**

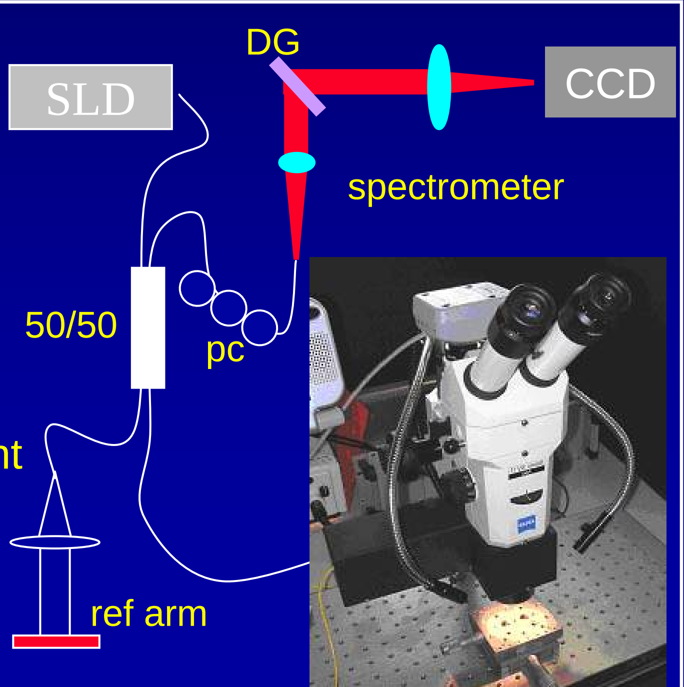
Chick embryo Cardiac Doppler flow measurement





Bioptigen, Inc.
OCT Microscope

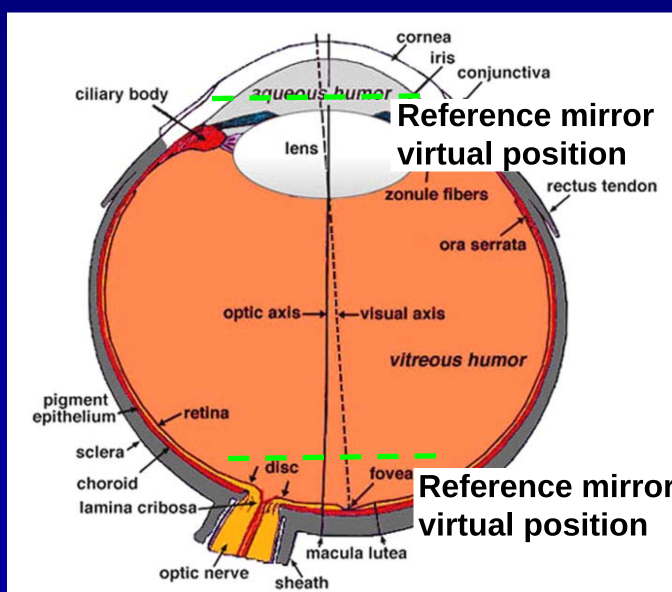
- λ_o=1300 nm,
- $\Delta\lambda$=70nm
- LPS: 6-24 kHz
- FPS: 6-24 Hz
- Volume: 4-25 s
- Flow measurement using Doppler processing



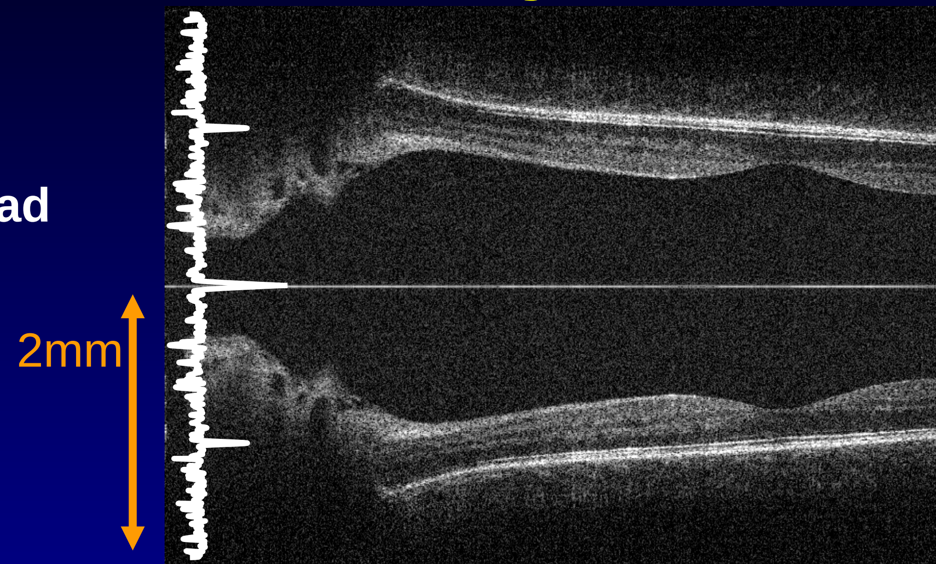
A.M. Davis, OSA Biomed. Topical Meeting, 2006

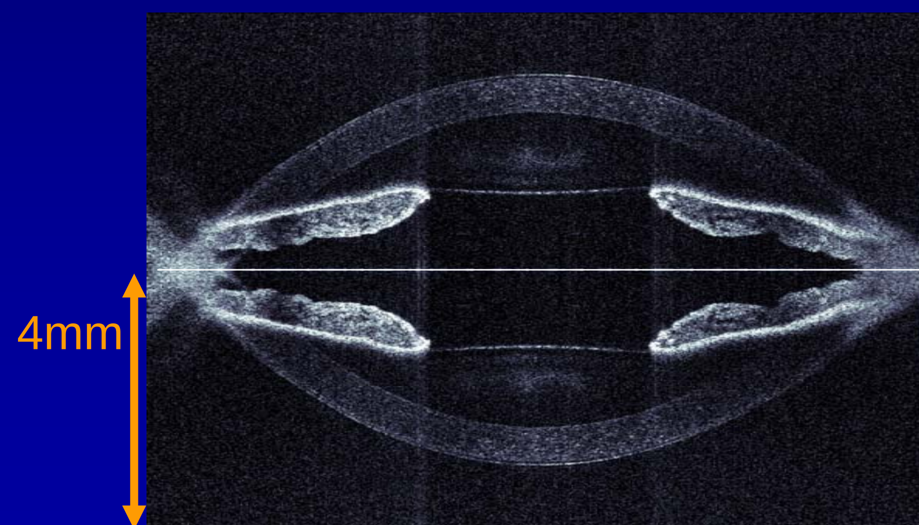
Limited Sample Depth FD OCT: Imaging the Human Eye

- **Posterior Segment**
  - **Retina, macula, optic nerve head**
  - **Structures < 1 mm thick**
- **Anterior chamber**
  - **Cornea, iris, crystalline lens**
  - **> 6 mm sample depth required**



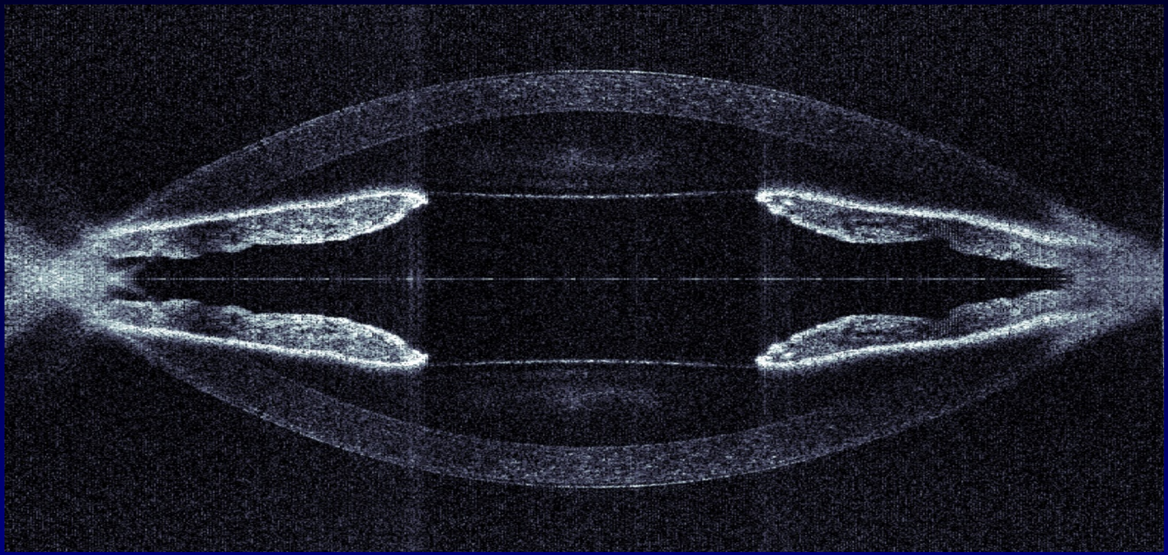
www.webvision.med.utah.edu/ imageswv/sagitta2.jpeg





High Speed Complex Conjugate Resolved Ocular Anterior Segment Images

- **Average all three detector signals**
  - **Image corrupted by complex conjugate artifact**



- **Quadrature projection processing**
  - **Complex conjugate resolved images**