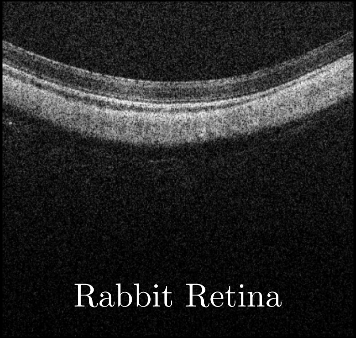
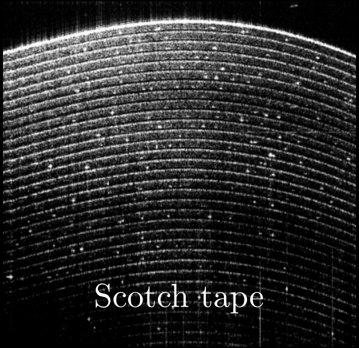
ELEG404/604: Imaging & Deep Learning

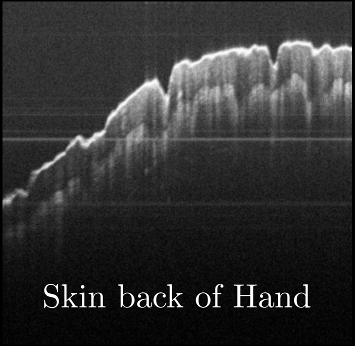
Gonzalo R. Arce

Department of Electrical and Computer Engineering
University of Delaware

Optical Coherence Tomography





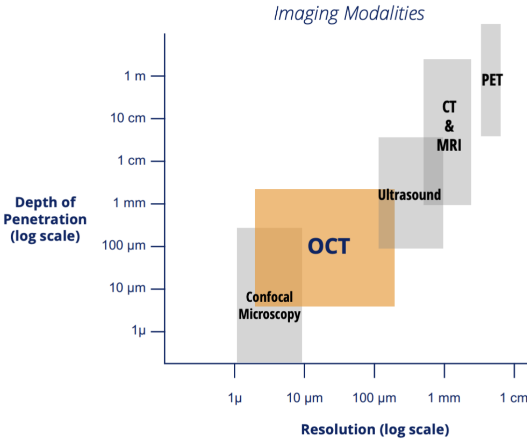


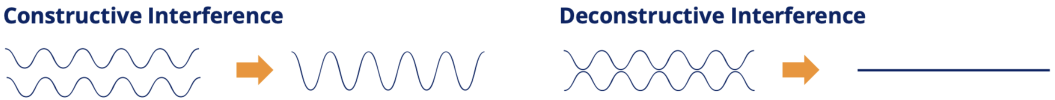
3D Imaging with OCT

- Optical coherence tomography (OCT) is the miniature equivalent of radar
- Unlike radar, sonar, and ultrasound, OCT cannot rely on simply measuring the echoes quickly enough to form a 3D image.
- Ultrasound can see centimeters into tissue with mm resolution; OCT sees a few mm into the tissue, but with µm level resolution. In translucent samples, OCT can see even deeper

3D Imaging with OCT

- X-ray CT, MRI, and PET can see through the entire human body, with a resolution similar to ultrasound.
- OCT's $\sim 10\,\mu\text{m}$ resolution, $\sim 1\,\text{mm}$ penetration
  - Retinal imaging, where 9 distinct layers are densely packed into a $500\,\mu\text{m}$ thickness, with all layers important to functioning vision.
  - OCT light can pass readily through the eye to the retina.
  - The eye is meant to transmit light efficiently.



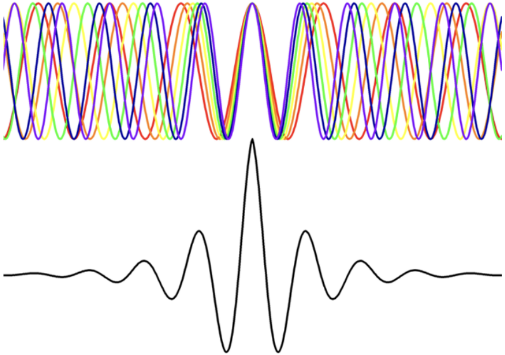


Low Coherence Interferometry

- Imagine a light beam with a single frequency, which can be represented in space and time as a sine wave.
- If we split that light into two paths, which may or may not be the same length, and then recombine the two paths, we will observe interference.
- If the two paths were exactly equal in distance, then the two beams would recombine constructively.
- If the two paths were different by half a wavelength, these two waves would destructively interfere and cancel each other out.
- A device that splits and recombines a wave is an interferometer.

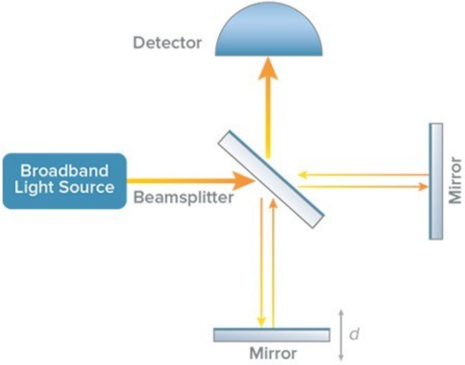
Low Coherence Interferometry

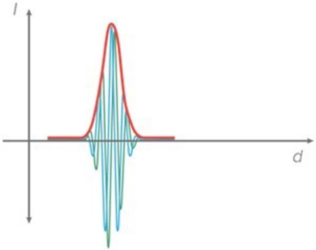
- **Integer Wavelength Difference:** Constructive interference occurs even if the paths differ by a whole wavelength.
- **Single-Frequency Interferometry:** Any integer wavelength difference yields constructive interference, making them indistinguishable.
- **Multitude of Wavelengths:** Light source lacks periodicity, hindering interference observations.
- **Matching Paths:** Constructive when paths match precisely; destructive otherwise.
- **Broad Bandwidth Light:** Interference only at exact path match due to low coherence.
- **Coherence Length:** Inversely related to light source bandwidth; determines the margin of error for maintaining coherence.



Imaging from Interferometry to Images

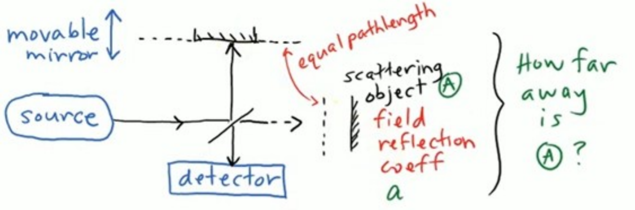
- Pencil beam is split into two paths called the reference and sample arms of the interferometer.
- Light from each arm is reflected back and combined at the detector.
- Interference appears at the detector only if the time traveled by light in the reference and sample arms is nearly equal.
- The presence of interference serves as a relative measure of distance traveled by light.





Interference Depending on the Source

- **Idea:** Measure the reflectivity of a tissue specimen as a function of depth.
- Based on the idea of **Michelson interferometer**:
  1. Source with some spectrum.
  2. Source is directed off of a beam splitter
  3. Some of the light goes to a reference **movable** mirror
  4. Some of the light continues where we have a specimen
  5. Light recombines coming back from the mirror and from the sample region
  6. Beams recombine and some of that light goes to a detector



Interference Depending on the Source

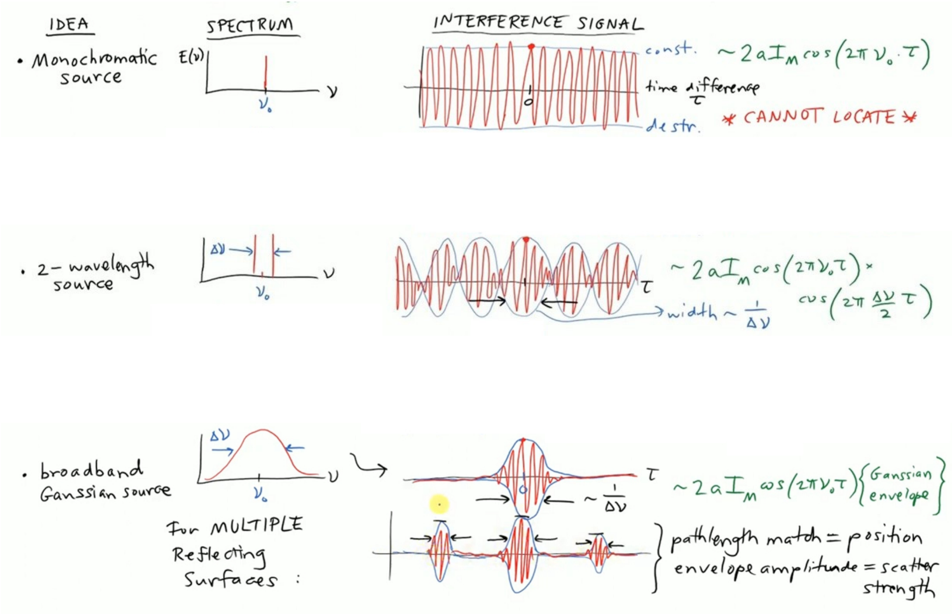
Interference at detector:

$$I_d = I_m + a^2 I_m + 2aIm$$

- I_d: total signal at the detector
- I_m: amount of reflected light (intensity arriving at the detector)
- $a^2 I_m$: amount of signal that we would get if we only got the reflection off of the scattering object with a field reflection coefficient a
- $2aIm$: interference signal (function fo the mirror position)

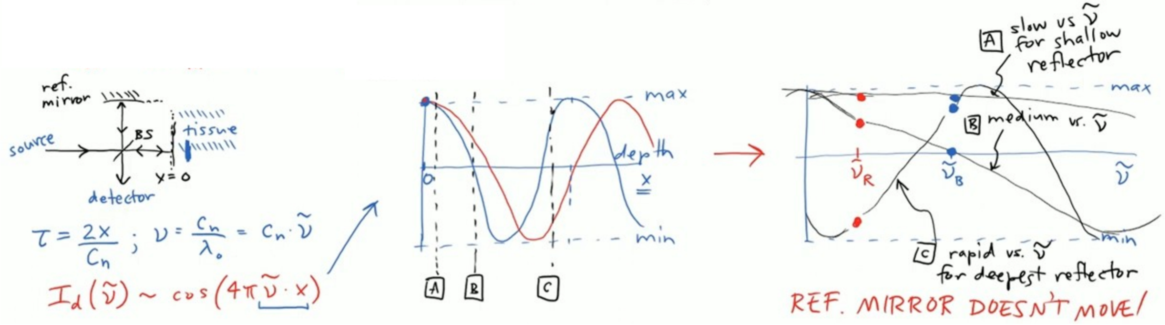
We want a way to isolate the interference signal and figure out where the reflector is.
Our approach: Scan the Mirror!

Interference Depending on the Source

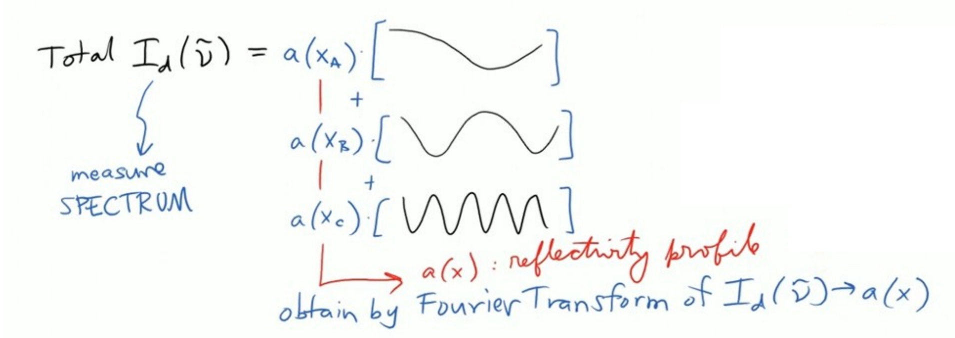


Interference Depending on the Source

$I_d = aI_m \cos(2\pi \upsilon \tau)$ For a single reflector



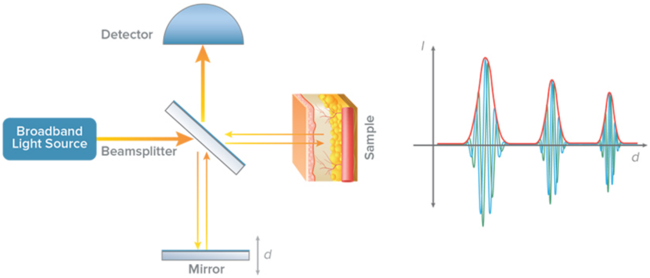
Interference Depending on the Source



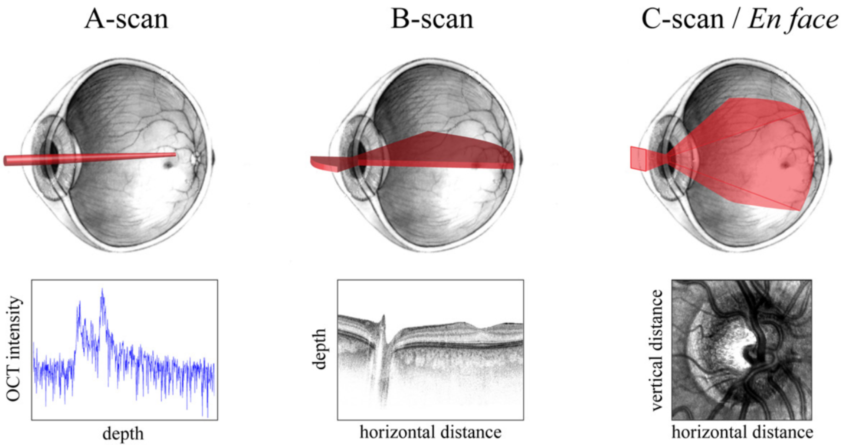
- Key advantage: All light contains information
- 2 ways to gather:
  - Simple Source + Spectrometer
  - SWEPT Source + Single Detector

Optical Coherence Tomography (OCT)

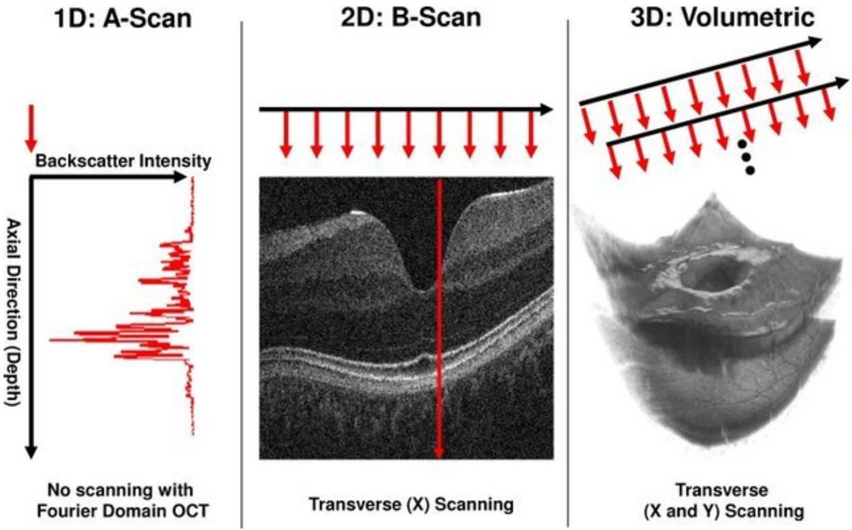
- OCT replaces the mirror in the sample arm with the sample to be imaged
- Reference arm is then scanned in a controlled manner and the resulting light intensity is recorded on the detector.
- Rapid modulation interference pattern occurs when the mirror is nearly equidistant to one of the reflecting structures in the sample.
- Distance between mirror location and reflecting structure where interference occurs corresponds to the optical distance between two reflecting structures of the sample in the path of the beam.
- Even though the light beam passes through different structures in the sample, the low-coherence interferometry described above helps to distinguish the amount of reflection from each unique structure in the path of the beam



Optical Coherence Tomography Scanning

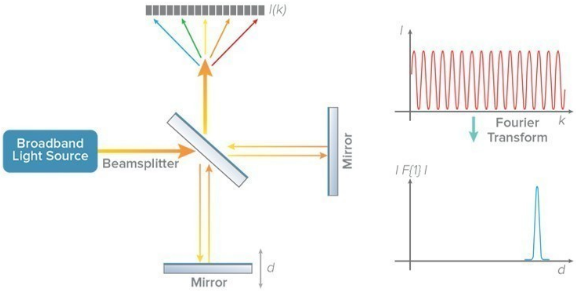


Optical Coherence Tomography Scanning



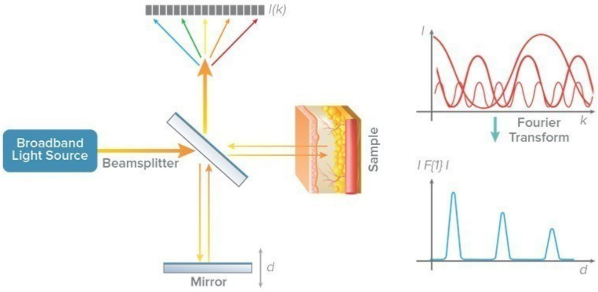
Fourier Domain Optical Coherence Tomography (FD-OCT)

- Intensity measurements at various reference mirror positions.
- Recorded Intensity: Function of wavelengths.
- Spectral Interference: Intensity modulations across frequencies, indicating reflecting layers' locations.
- Fourier Transform: Extracts information equivalent to physically moving the reference mirror.



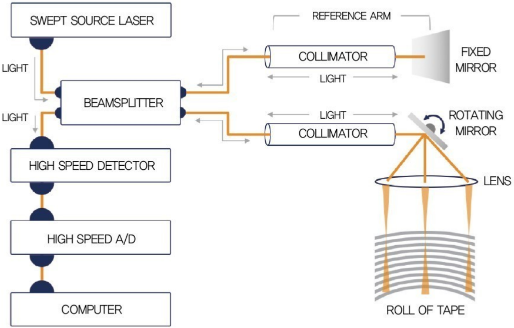
Fourier Optical Coherence Tomography

- **SD-OCT:** Uses broadband light source and spectrometer for simultaneous measurement of multiple wavelengths.
- **SS-OCT:** Light source sweeps through wavelengths, converting temporal output to spectral interference.
- **Fourier-Domain OCT:** Enables faster imaging by measuring all back reflections simultaneously.



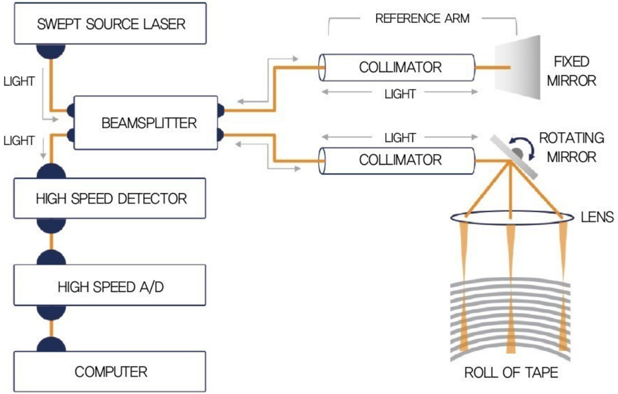
Swept Source OCT (SS-OCT)

- **Wavelength Sweeping**: Use a tunable laser to temporally sweep the wavelength of a narrowband source.
- **Reference Arm:** Similar to spectral domain OCT, the reference arm maintains a fixed path length.
- **Detector Arm Setup:** Employs a single high-speed photodiode.
- **Generating Spectrum:** Each time point matches a wavelength, enabling spectrum generation by measuring interference signal over time.
- **A-Scan Generation:** One wavelength sweep of the laser produces one A-scan.
- **Hardware Requirements:** Photodiode and electronics must digitize the entire spectrum swiftly as the laser sweeps.

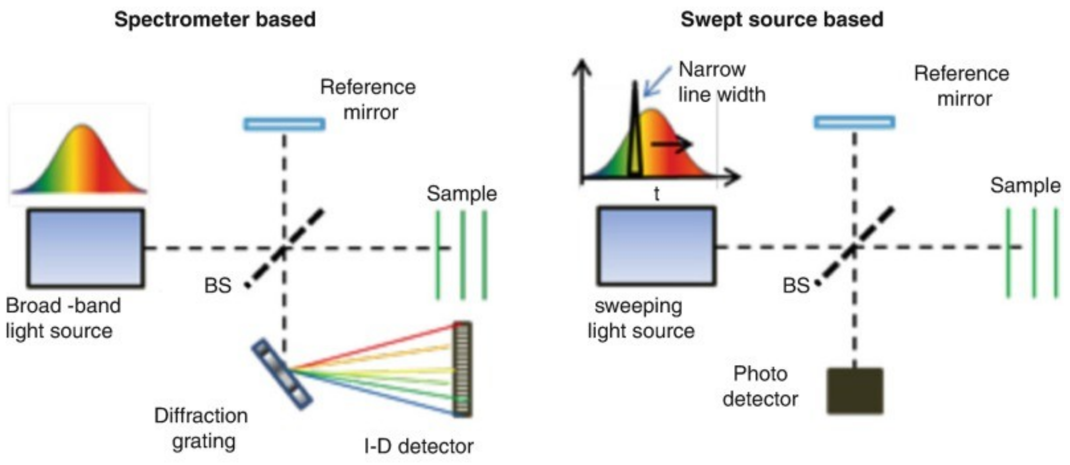


Swept Source OCT (SS-OCT)

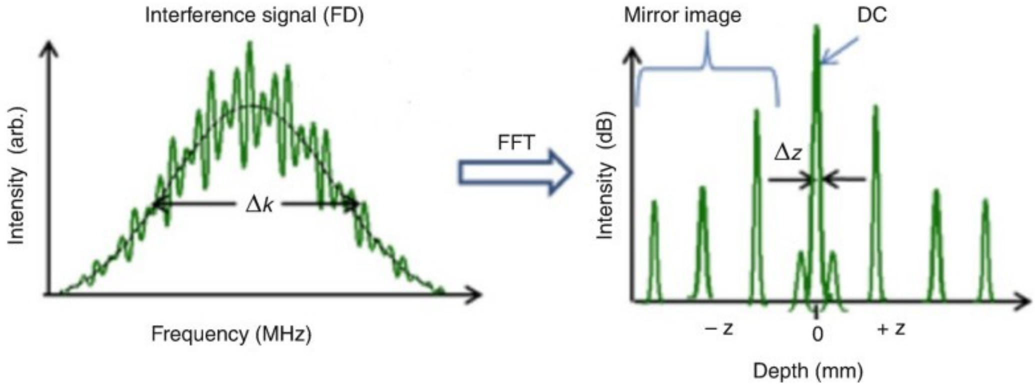
- The digitized spectrum is then Fourier transformed by the processor to generate a depth profile of the scattered light.



Fourier vs Swept Source OCT

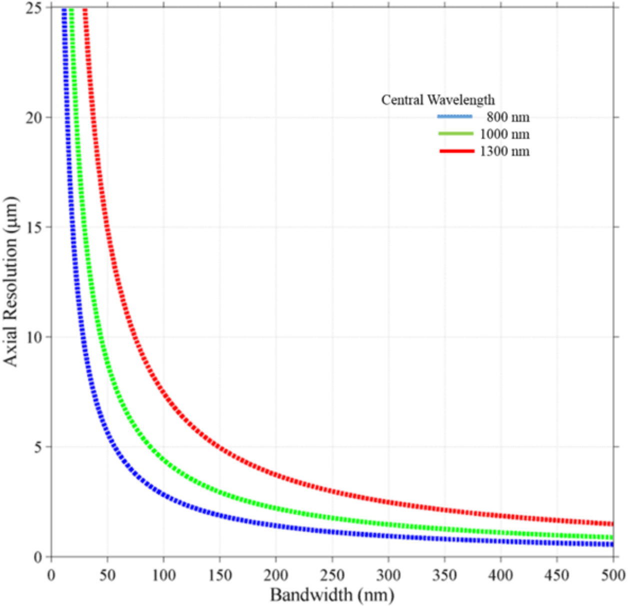


Signal Formation in OCT



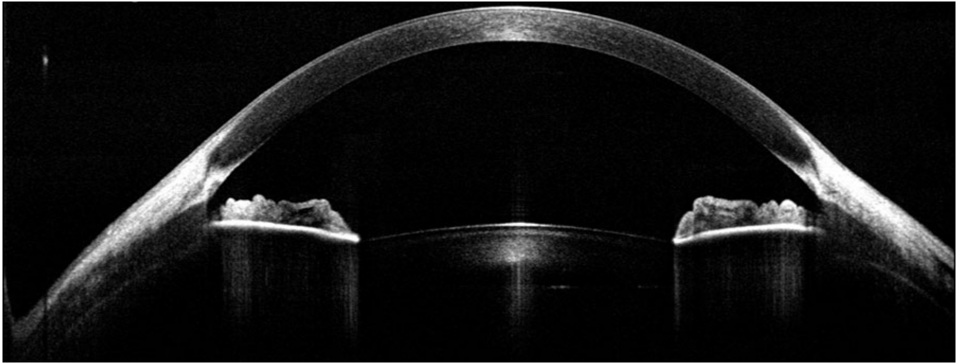
Signal Formation in OCT

- Resolution Independence:
  - Axial and transverse resolution in OCT are independent.
- Axial Resolution:
  - Defined by source bandwidth/coherence length.
  - Formula: $\lambda_c = \frac{\lambda}{\Delta\lambda}$ ($\lambda =$ central wavelength, $\Delta\lambda =$ bandwidth)
- Bandwidth Impact on Resolution:
  - Plots illustrate how source bandwidth affects axial resolution in different near-infrared bands.



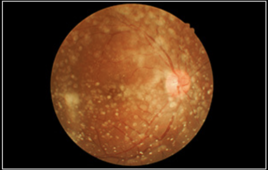
3D OCT Imaging

- Mapping sample in x and y with a scanning arm while collecting depth using interferometry gives a 3D picture of the sample.



3D OCT Imaging - Limitations

- Depth limited by light source penetration.
- In Fourier-domain OCT (FD-OCT):
  - Depth constrained by the spectrometer's finite pixel count and optical resolution.
  - Total depth after Fourier transform limited by spectral data's sampling rate, per Nyquist theorem.
- Formulae for Calculating Imaging Depth:
  - Wavelength sampling rate: $\delta\lambda = \frac{\Delta\lambda}{N}$.
  - Conversion of wavelength to frequency: $\delta\nu = \frac{c\cdot\Delta\lambda}{\lambda^2}$.
  - Maximum time delay: $t_{\text{max}} = \frac{1}{2}\delta\nu$.
  - Maximum depth: $z_{\text{max}} = c \cdot t_{\text{max}}$.

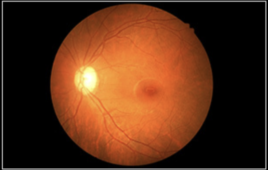


Diabetic Retinopathy

Damage to the retina onset by diabetes, often leads to blindness. Accounts for 12% of all new cases of blindness in the US, and affects approximately 80% of those suffering from diabetes for an extended period.

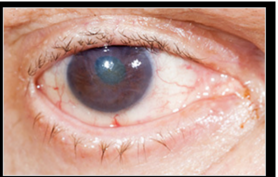
AMD

Age-related macular degeneration, a medical condition that causes blurred or no vision at the central field of vision. This condition is onset by damage to photoreceptors in the macula of the retina and while it rarely leads to total blindness, AMD greatly reduces the ability to see objects or people clearly, if at all.



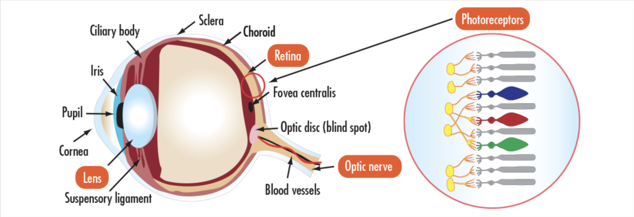
Glaucoma

Eye disease that causes damage to the optic nerve and vision loss. The loss of vision is slow and gradual, making glaucoma often overlooked and untreated. It is the 2nd leading cause of blindness around the world.

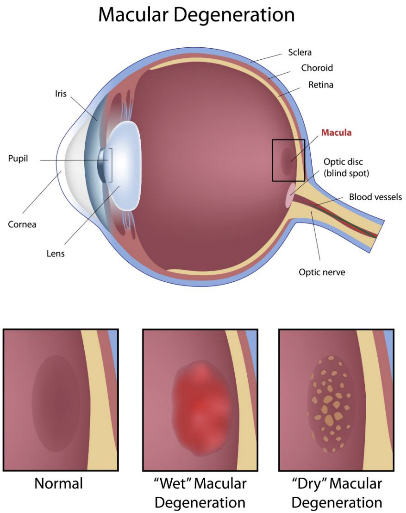


Cataract

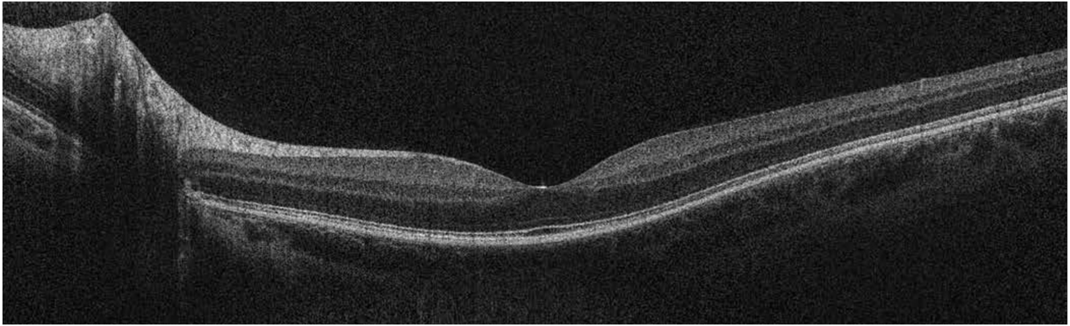
A clouding of the lens in the eye resulting in vision loss. Most commonly onset by age, it can also occur via blunt trauma or poor health. Cataracts account for half of the world's blindness.



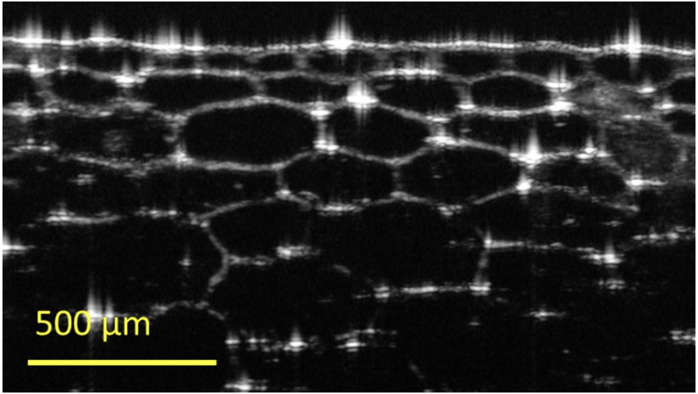
Applications



Applications



Applications



Applications