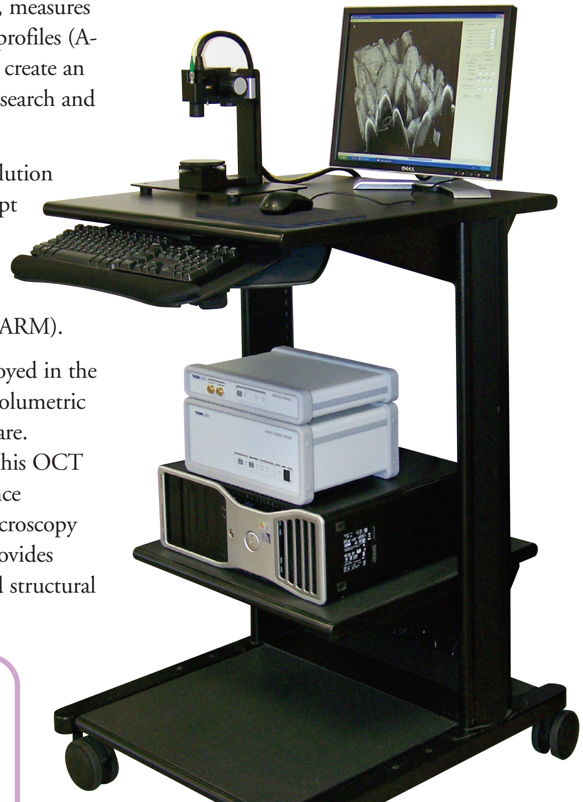
Swept Source OCT Systems: Video Rate OCT Imaging – Page 1 of 6

Swept Source OCT (SS-OCT), like optical frequency domain reflectometry, measures the magnitude and time delay of reflected light in order to construct depth profiles (A-scans) of the sample being imaged. Adjacent A-scans are then synthesized to create an image. Thorlabs now has a complete family of SS-OCT systems ready for research and industrial applications.

Thorlabs' SS-OCT Systems support both 2D and 3D high-speed, high-resolution imaging of turbid media. The design integrates a broadband high-speed swept laser, a fiber-based Mach-Zehnder interferometer with a balanced detection scheme, and a handheld probe to cross-sectional OCT imaging of the sample. The system includes a microscope style mount for the handheld probe. We also offer a flexible arm (see page 11) to mount the probe (OCS-ARM).

Advanced data acquisition and digital signal processing techniques are employed in the SS-OCT system to enable real-time video-rate OCT imaging. Optical 3D volumetric imaging and surface profiling capabilities are included in the standard software. An optional Doppler OCT imaging upgrade is also included (see page 7). This OCT system can provide coherence gated *en-face* images similar to optical coherence microscopy and also enables the generation of images similar to confocal microscopy by summing signals in the axial direction. High-speed 3D OCT imaging provides comprehensive data that combines the advantages of surface microscopy and structural OCT imaging in a single system.



OCS1300SS
(Patent Pending)
Shown With Optional Cart
OCM-CART

Video-Rate OCT Imaging Applications

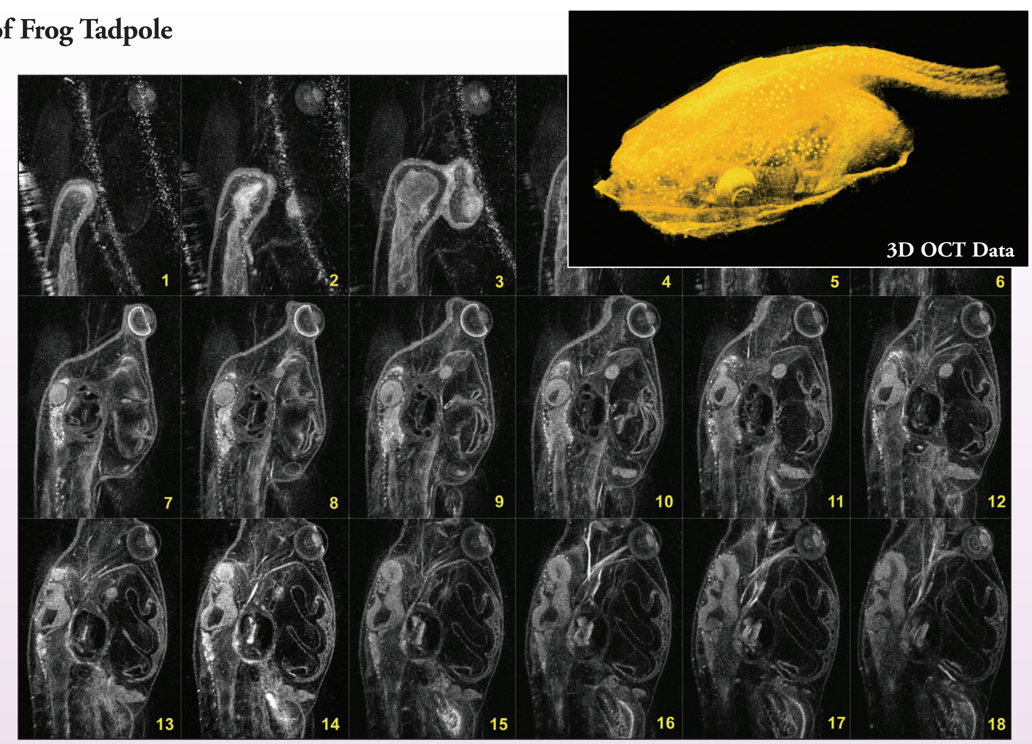
- Biomedical Imaging
- Real-Time Surgical Monitoring
- Material Inspection and Quality Control
- Thin Film Test and Measurement
- 3D Optical Profilometry and Volumetric Imaging

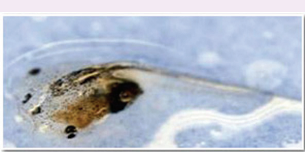
Biological Imaging

Three-Dimensional Imaging of Frog Tadpole

The data shown represent a series of *en-face* images of an African frog tadpole and a 3D image reconstruction. The data was acquired using the Thorlabs **OCS1300SS** OCT microscope system. All images are 6 mm x 8 mm and were taken from the posterior to the anterior of the tadpole in 100 µm depth increments.

Reference: R. Huber, *et al.*, *Optics Express* **13**, 10523 (2005)





African Frog Tadpole

Swept Source OCT Systems — Page 2 of 6

System Description

Figure 1 shows the schematic of Thorlabs' **OCS1300SS** OCT system. This system incorporates a high-speed frequency swept external cavity laser (Thorlabs **SL1325-P16**), which has a 3 dB spectral bandwidth (larger than 100 nm). The swept source has a built-in Mach-Zehnder Interferometer (MZI, Thorlabs **INT-MZI-1300**) that provides the frequency clock for the laser. The main output of the laser is coupled into a fiber-based Michelson interferometer and split into the reference and sample arms using a broadband 50/50 coupler (Thorlabs **FC1310-70-50-APC**).

In the reference arm of the interferometer, the light is reflected back into the fiber by a stationary mirror. The reflectivity is controlled by a variable optical attenuator. In the sample arm, the light is fiber coupled into the microscope head and focused onto the sample by a long working distance objective. The sample is placed on a stage that provides XY and rotational translation. An integrated CCD camera in the microscope head provides a conventional microscopic view of the sample, which aids sample alignment. A pair of XY galvo mirrors scans the beam across the sample surface, creating 1D, 2D, or 3D images.

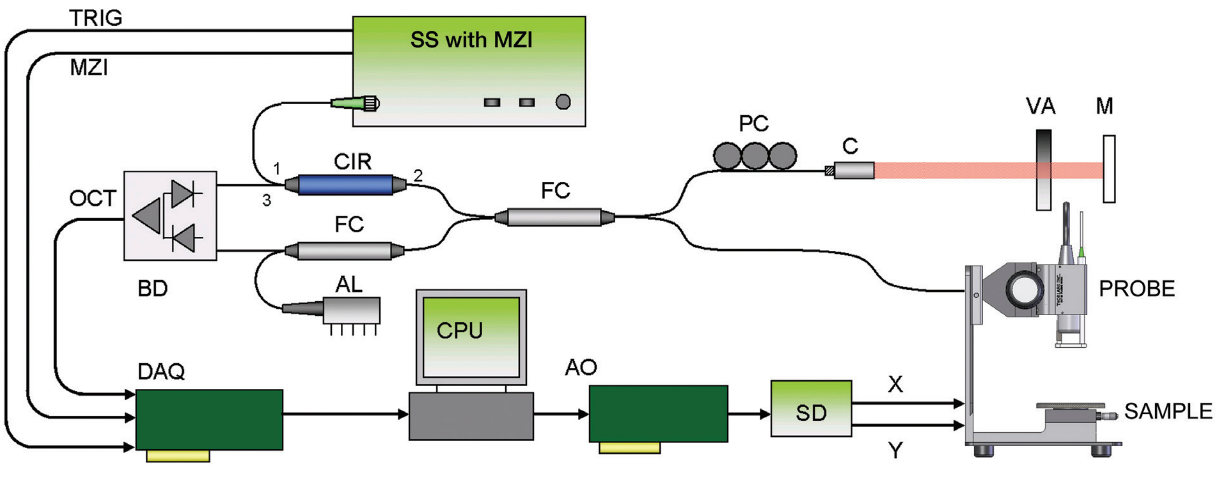
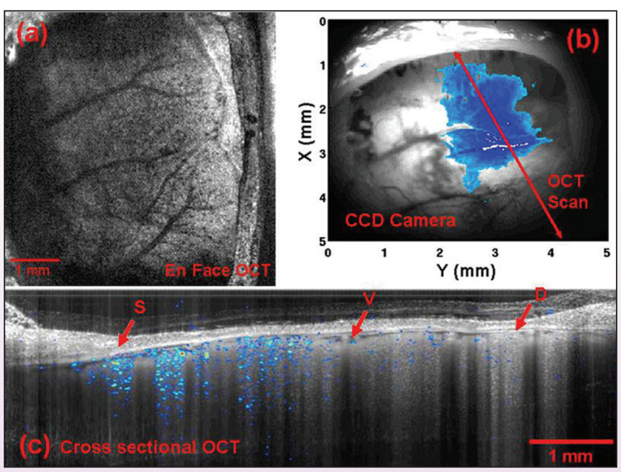


Figure 1
Schematic of Thorlabs' Swept Source OCT: swept source (SS), fiber coupler (FC), polarization controller (PC), circulator (CIR), collimator (C), variable attenuator (VA), mirror (M), balanced detector (BD), data acquisition board (DAQ), XY scanners driver (SD), CCD camera (CCD), objective (OBJ), microscope (MS), analog output (AO), aiming laser (AL). A Mach-Zehnder interferometer (MZI), which is built into the swept light source, provides the frequency clock signals for the laser.

Brain Functional Imaging

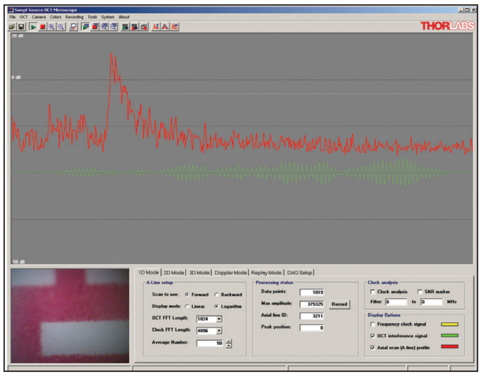
The pictures to the right show OCT images representing the functionally active region of a rat brain. Images were taken by researchers at MIT and Massachusetts General Hospital using a modified Thorlabs Swept Source OCT system.

The OCT scan is directed to the region of interest using a video microscope. The OCT image enables identification of the skull (S), surface vasculature (V), and meningeal layers, including the dura mater (D). The blue colored areas show the functionally active regions of the cortex, which were co-registered on the CCD camera and OCT channels.

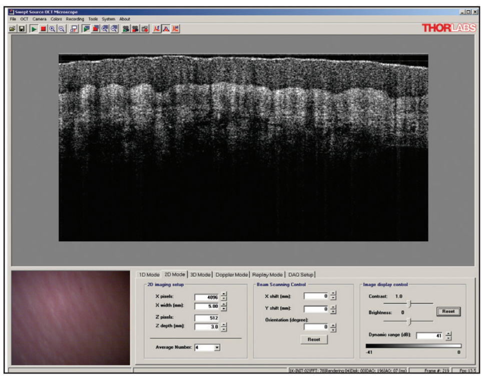


Reference: A. D. Aguirre, *et al., Optics Letters* **31**, 3459 (2006).

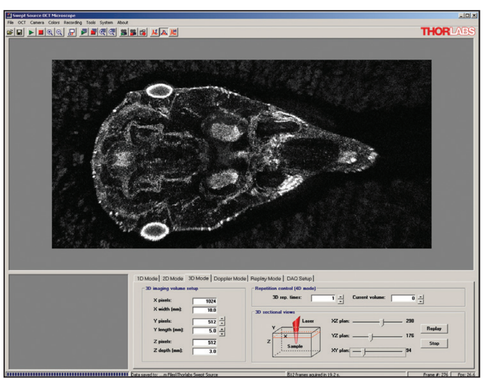
Swept Source OCT Systems — Page 3 of 6



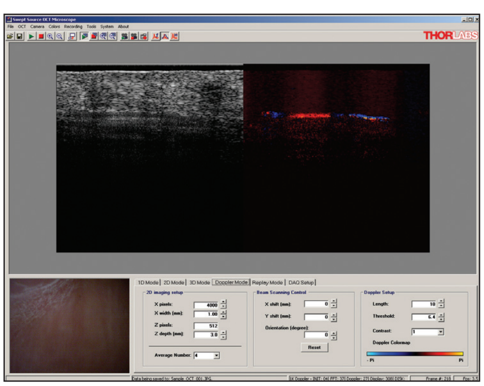
1D Mode: OCT Interference Fringe Diagnosis



2D Mode: Cross-Sectional Imaging



3D Mode: Volume and *En-Face* Imaging



Doppler Mode Imaging

Signal Processing

In the Thorlabs SS-OCT, the interference signal is detected using a high-transimpedance gain-balanced photodetector (**PDB145C**) that suppresses the DC and autocorrelation noise in the interference signals. A 14-bit, high-speed digitizer is used to sample the OCT interference fringe signals, which are first converted from time to frequency space using a fast Fourier transform (FFT) and then recalibrated. The FFT of the interference signal yields the depth-dependent reflectivity profile for the OCT image.

Software

The screen captures for three different imaging modes of the software GUI are shown to the left. In the 1D imaging mode, there is no transverse scanning of the probe beam in the sample arm. Real-time display of the recalibrated interference fringe signals and the Fourier transformed point spread functions aid optimization of the signal and system parameters. In the 2D imaging mode, the probe beam is scanned in one direction and cross-sectional OCT images are displayed in real time. The software provides flexible control of image size, brightness, contrast, and the A-line average. For the 3D imaging mode, the probe beam is sequentially scanned across the sample surface area, and the 3D volume data set under this area is acquired, processed, and stored. 3D volume rendering capability of the data is provided with the preinstalled software. The OCT data may be displayed in 2D or 3D mode.

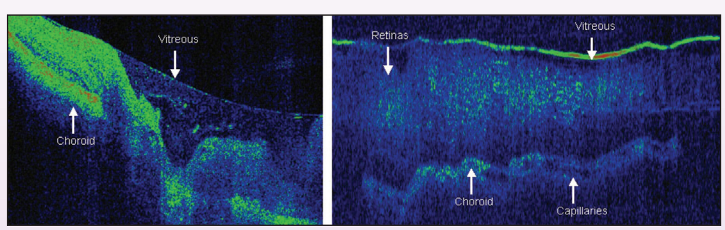
The software allows real-time recording of 2D or 3D data into disk files at full imaging speed. The recorded binary data files can be exported into standard image files (jpeg, bmp) or converted to movie files (avi). A software program that provides 3D graphics rendering of acquired OCT data is also provided in the software package.

Flexible OCT System Integration

Thorlabs' swept source OCT systems are highly customizable. The basic OCT engine includes the swept light source, optional interferometer module, and the software development kit (SDK). The OCT engines are readily adapted to various industrial and biomedical applications. Customers can choose one of our standard microscope or probe options, or they can engineer application-specific probes, which may be directly interfaced wtih Thorlabs' OCT systems for research or OEM applications.

Endoscopy

Yang and his research group at CalTech have developed a new forward-looking endoscopic probe for OCT imaging applications and demonstrated this probe using a modified Thorlabs SS-OCT system. The *in vitro* procine retinal images (2.5 x 2.3 mm) shown below were obtained using a pair-angled rotating scanner (PARS). This probe was developed because standard side-imaging probes do not provide the real-time cross-sectional imaging desirable for guiding retinal surgery.



References:
1. M. V. Sarnic, *et al.*, BIOS 2007.
2. J. Wu, *et al.*, *Optics Letters* **13**, 1265 (2006).

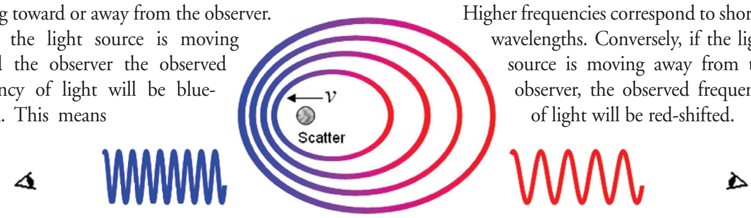
Swept Source OCT Systems — Page 4 of 6

New Doppler Upgrade Option for Swept Source OCT

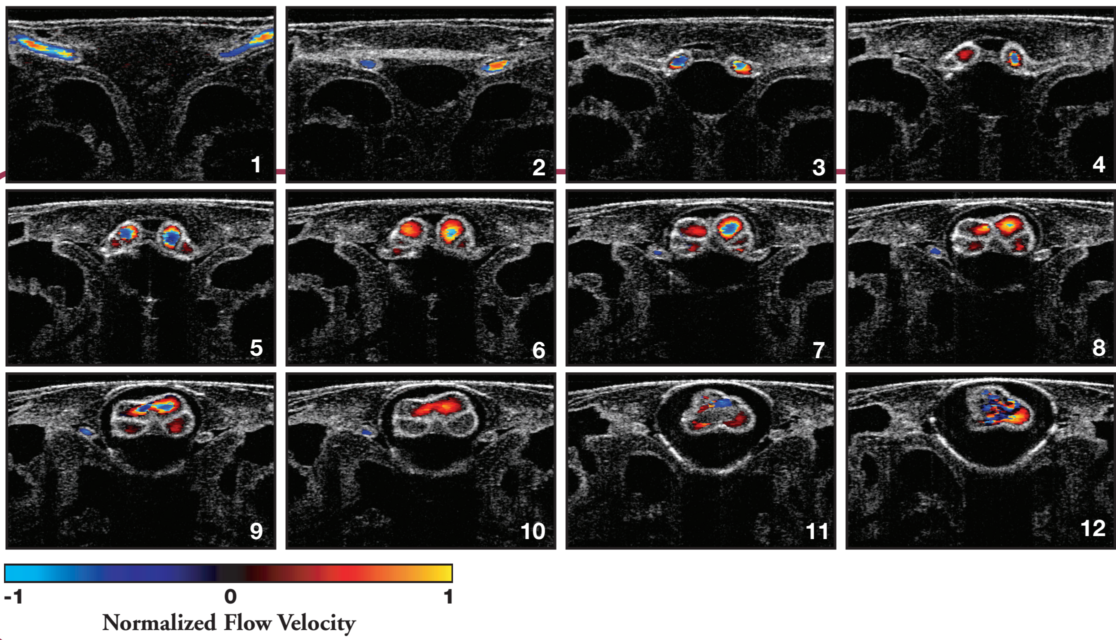
Doppler OCT, also known as ODT (Optical Doppler Tomography), is a noninvasive imaging technique that provides relative flow velocity measurements in the sample. This enhanced imaging capability was developed in collaboration with Adrian Mariampillai and Victor Yang at the University of Toronto.

As a functional extension of OCT, Doppler OCT relies on the low coherence detection of the light interference signals but uses the laser-induced Doppler frequency shift as the contrast mechanism for image construction. When combined with standard OCT imaging, the high spatial resolution of OCT (2-10 µm) and high velocity sensitivity of Doppler OCT (50-100 µm/s) provide simultaneous structural imaging and flow velocity measurements in the sample, which can be useful for studying embryo cardiac dynamics, vascular functional imaging, or vascular treatment response. It is also ideal for general flow velocimetry used in microfluidic channel monitoring.

A stationary observer will observe a Doppler shift in the frequency of the light emitted from a source moving toward or away from the observer. When the light source is moving toward the observer the observed frequency of light will be blue-shifted. This means the observed frequency of the light will be higher than the frequency of light emitted by the source. Higher frequencies correspond to shorter wavelengths. Conversely, if the light source is moving away from the observer, the observed frequency of light will be red-shifted.



In Doppler OCT, this small observable frequency shift of the reflected (scattered) light from a moving object is measured in the OCT interference fringe signal, allowing the relative object motion in the light probing direction to be measured.

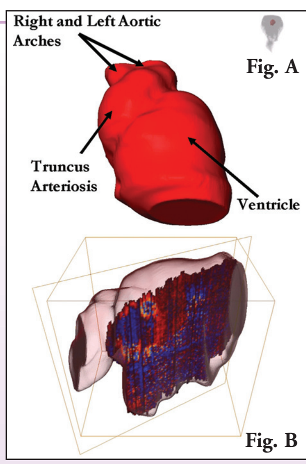


Images represent *in vivo* cross-sectional images of a beating African tadpole heart superimposed with Doppler velocimetry data. The OCT data shows structural information, while also showing heart beat motion and relative blood flow velocity. These images were taken using a Thorlabs **OCS1300SS** OCT with the Doppler software upgrade.

Developmental Biology

The images here show how the Thorlabs swept source OCT was used by researchers at the University of Toronto to study the cardiovascular system of a living tadpole. An optical Doppler cardiogram was obtained using a gated technique to increase the effective frame rate and improve the signal-to-noise ratio. The gating technique provides ultra high-speed visualization of the heart blood flow pattern in developing African frog embryos in both 3D and 4D (i.e. 3D + time) modes. This allows detailed visualization of the complex cardiac motion and hemodynamics in the beating heart.

Reference: A. Mariampillai, *et al.*, *Optics Express* **15**, 1627 (2007).



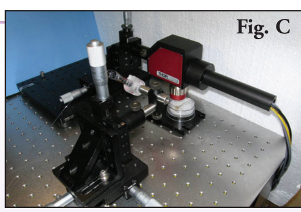
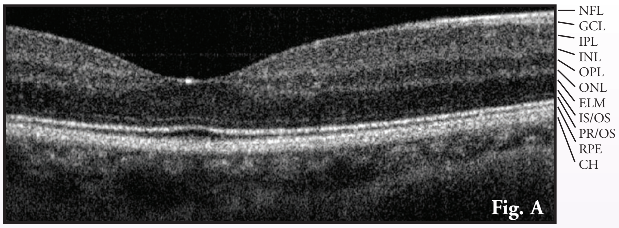
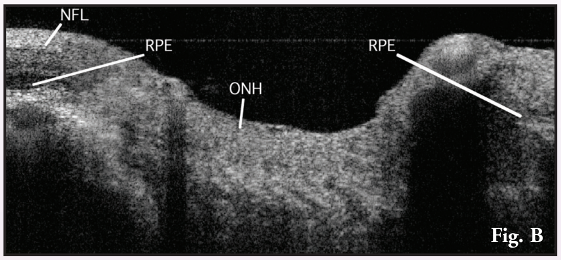


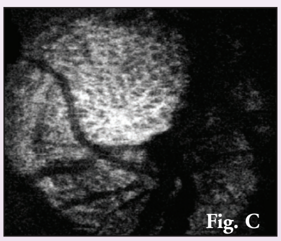
Fig. A shows the 3D surface reconstruction of the tadpole heart, while Fig. B demonstrates the complex blood flow pattern of the heart via a 3D color Doppler map. Fig. C shows the experimental apparatus using an early prototype of Thorlabs' handheld probe, which is mounted into the Doppler imaging setup.

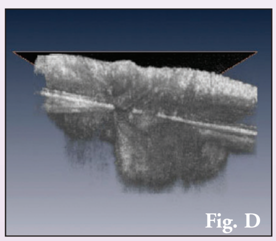
Swept Source OCT Systems — Page 5 of 6

SS-OCT Application - 850 nm Retinal Imaging









Swept source OCT is a promising technique for *in vivo* human retinal imaging. The human retina images shown here were taken using an 850 nm SS-OCT imaging system jointly developed with researchers at MIT. These high-resolution *en-face* images of the macular and the optic nerve head (Figs. A and B, respectively) allow the identification of major intra-retinal layers and optical nerve structures.

This OCT imaging system provides high-speed data collection (16 - 24 kHz A-scan rate) and excellent axial resolution (~7 µm) in tissue samples.

Fig. A: High-Definition OCT Image of the Human Macular.
Fig. B: High-Definition OCT Image of the Human Optic Nerve.
Fig. C: Virtual Image of the Lamina Cribrosa, Created from 3D OCT Data.
Fig. D: 3D OCT Data Consisting of 512 Images x 512 Axial Scans (acquired in 16 s)

Nerve fiber layer (NFL), ganglion cell layer (GCL), inner plexiform layer (IPL), inner nuclear layer (INL), outer plexiform layer (OPL), outer nuclear layer (ONL), external limiting membrane (ELM), photoreceptor inner segment/outer segment junction (IS/OS), photoreceptor outer segments (PR OS), retinal pigment epithelium (RPE), choroid (CH), optic nerve head (ONH).

Reference: V. J. Srinivasan, et al., *Optics Letters* **32**, 261 (2007)

Adaptive Optics Enhanced Retinal Imaging

Researchers at the University of Indiana recently demonstrated enhanced transverse resolution and improved signal-to-noise ratio in ophthalmic retinal imaging using an adaptive optics swept source (AO SS-OCT) system based on the Thorlabs 850 nm swept source laser integrated into an experimental OCT system. The schematic of the AO camera is shown in Fig. 1. The AO OCT subsystem includes a Shack-Hartmann wavefront sensor and a deformable mirror (DM) that dynamically corrects the wavefront aberrations over the 6.6 mm human pupil at a rate up to 25 Hz. The large stroke of the deformable mirror provides quick focusing in the retina.

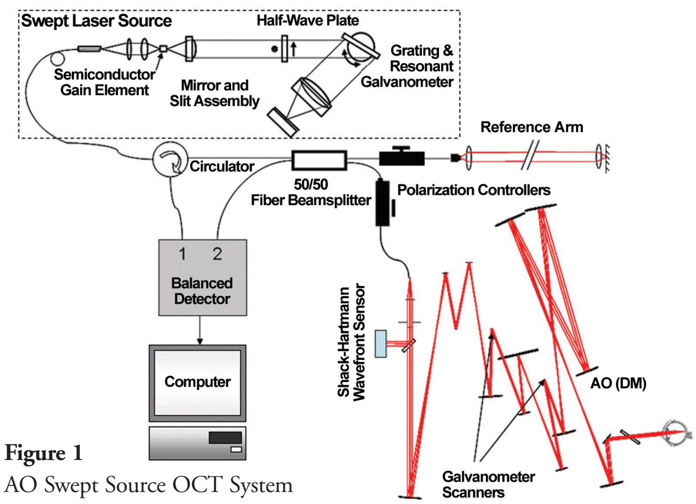
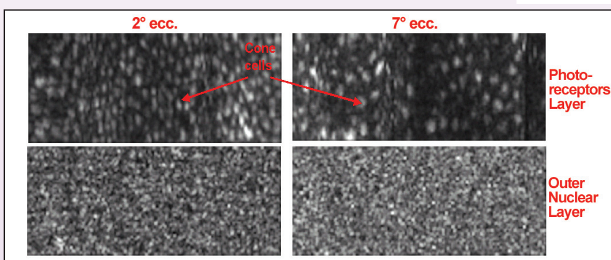


Figure 1
AO Swept Source OCT System



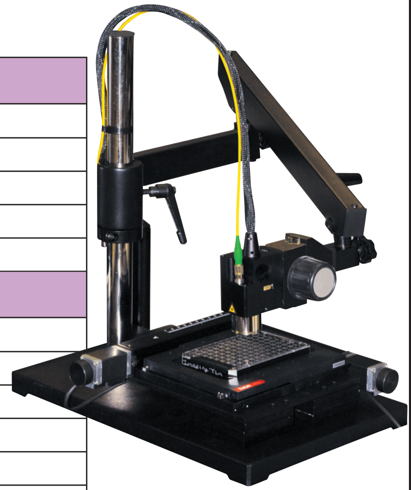
To the left are *en-face* images extracted from the OCT volume data recorded with the AO SS-OCT system. The images are acquired at 2° and 7° eccentricity, providing the definition needed to resolve individual cone photoreceptors. The images are displayed using a linear intensity scale.

References: 1. B Cense, *et al.*, "Retinal Imaging at 850 nm with Swept Source Optical Coherence Tomography and Adaptive Optics," ARVO 2007.
2. Y. Zhang, *et al.*, *Optics Express* **14**, 4380 (2006)

Swept Source OCT Systems — Page 6 of 6

Swept Source OCT System Specifications

Optical	OCS1300SS
Center Wavelength	1325 nm
Spectral Bandwidth	100 nm
Axial Scan Rate	16 kHz
Coherence Length	6.0 mm
Average Output Power	10.0 mW
Electric	
A/D Conversion Rate	100 MS/s
A/D Resolution	14-bit
A/D Channels	2
Analog Output Rate	1 MS/s
Analog Output Resolution	16-bit
Analog Output Channels	4
Computer	
CPU	Dual-Core Intel Processor
Memory	2 GB SDRAM
Operating System	Windows® XP Professional, SP2
Hard Drive	250 GB SATA 3.0 Gb/s
Optical Drives	48X/32X CD-RW and 16X DVD+/-RW
Monitor	Dell 19" UltraSharp™ Flat Panel, VGA/DVI
Imaging Specifications	
2D Cross Sectional OCT Imaging Capability Imaging Speed (on 512 A-Scans Per Frame)	25 fps
Maximum Imaging Size	4,000 (H) x 512 (D) Pixels
Maximum Imaging Width	10 mm
Maximum Imaging Depth	3.0 mm
Transverse Resolution	15 µm
Axial Resolution (Air/Water)	12/9 µm
2D *en-face* Microscope Imaging Capability CCD Camera Pixel	2.0 Mega, 24 Bit RGB
Maximum Resolution Pixels	1600 x 1200
Imaging Speed	100 fps @ 640 x 480 pixels; 20 fps @ 1600 x 1200
3D Volumetric Imaging Capability Maximum Volume Size	10 mm (L) x 10 mm (W) x 3 mm (D)
Maximum Sampling Resolution	640 (L) x 640 (W) x 512 (D) Pixels
Imaging Time	~30 s



Articulated Probe Mount (OCS-ARM)

Handheld Probe Included with OCS1300SS

SS-OCT Systems are also available at 850 nm, 1050 nm, and 1550 nm.
Please contact Thorlabs for more details.

Note: For those familiar with our OCT systems, you will find new part numbers due to our on-going engineering improvements.

ITEM#	$	£	€	RMB	DESCRIPTION
OCS1300SS	$ 60,000.00	£ 37,800.00	€ 55.800,00	¥ 573,000.00	1300 nm SS-OCT Imaging System with Microscope

Accessories

ITEM#	$	£	€	RMB	DESCRIPTION
OCM-ARM	$ 1,000.00	£ 630.00	€ 930,00	¥ 9,550.00	Flexible, Articulated Arm Mount
OCM-CART	$ 2,125.00	£ 1,338.80	€ 1.976,30	¥ 20,293.80	Instrument Cart for Swept Source OCT Microscope System

Visit our new laser imaging web page for up-to-date imaging research and applications: www.thorlabs.com/oct