SD-OCT Base Unit

Spectral Domain
OCT System Base Units:
Telesto, Ganymede, and
Callisto Series

User Manual

Original User Manual – not translated

Table of Contents

Chapter 1 Introduction

ATTENTION

Please read the instruction manual carefully before operating the OCT base unit. All statements regarding safety and technical specifications will only apply when the unit is operated correctly.

This equipment is intended for laboratory use only and is not certified for medical applications, including but not limited to life support situations.

Refer to this manual whenever the following symbols are encountered on the OCT base unit:

Attention symbol indicates that additional information is given in this manual.

Laser Safety symbol indicates that laser radiation is present.

This manual describes the SD-OCT base units of the Telesto, Ganymede, and Callisto Series.

If not specified, the base units of the Telesto-PS Series are incorporated in the Telesto Series.

ATTENTION

Check the supply voltage of the system before plugging in the computer. Make sure the included power cords for the base unit, computer, and monitor are connected to a properly grounded outlet (100 – 240 VAC; 50 – 60 Hz).

Transportation and delivery may cause the OCT base unit to be warm or cool upon receipt. Please wait for the system to reach room temperature before attempting to operate.

Operate this system on a flat, dry, and stable surface only.

WARRANTY WARNING

Do not open the base unit, imaging scanner or PC. There are no user serviceable parts in this product. Opening the device will void your warranty. Any modification or servicing of this system by unqualified personnel renders Thorlabs free of any liability. This device can only be returned when packed into the complete original packaging, including all foam packing inserts. If necessary, ask for replacement packaging.

1.1. Safety

SHOCK WARNING – HIGH VOLTAGE

Before applying power to the system, make sure that the protective conductor of the three-conductor mains power cord is correctly connected to the protective earth contact of the socket outlet. Improper grounding can cause electrical shock resulting in severe injury or even death. Make sure that the line voltage rating agrees with your local supply and that the appropriate fuses are installed. Fuses should only be changed by qualified service personnel. Contact Thorlabs for assistance. Do not operate without cover installed. Refer servicing to qualified personnel.

ATTENTION

Do not obstruct the air-ventilation slots in the computer housing. Do not obstruct air-ventilation into the bottom of the base unit or out of the exhaust fan on the rear of the unit.

Mobile telephones, cellular phones, or other radio transmitters are not to be used within the range of three meters of this unit, since the electromagnetic field intensity may exceed the maximum allowed disturbance values according to IEC 61000-6-1:2005.

The safety of any system incorporating the equipment is the responsibility of the assembler of the system.

If equipment is used in a manner not specified by the manufacturer, the protection provided by the equipment may be impaired.

LASER RADIATION WARNING

Laser emission may be emitted

a) from the scan lens of a scanner (intended use)

b) from the back of the base unit when the fiber cap is removed and the fiber disconnected

c) from the output of the fiber when the fiber is not connected to a scanner

Do not look into the optical output when the device is operating. The laser radiation is not visible to the human eye and can cause serious damage to your eyesight.

The laser class information is also stated on the laser safety labels on the back of the housing.

Example given for class 1M LASER product:

INVISIBLE LASER RADIATION

DO NOT STARE INTO BEAM OR VIEW
DIRECTLY WITH OPTICAL INSTRUMENTS

CLASS 1M LASER PRODUCT

CLASSIFIED ACCORDING TO DIN EN 60825-1:2014

1.2. Care and Maintenance

Handle the system with care during transportation and unpacking. Banging or dropping the system can damage the unit or lower system performance. If the system is mishandled during shipment, the optical components may become misaligned, which could lead to a decrease in image quality. If this occurs, the system will need to be realigned by qualified personnel. Please contact Thorlabs technical support for more information.

- Do not store or operate in a damp, closed environment.
- Do not store or operate on surfaces that are susceptible to vibrations.
- Do not expose to direct sunlight.
- Do not use solvents on or near the equipment.
- Keep away from dust, dirt, and air-borne pollutants (including cigarette smoke). The system is not designed for outdoor use. Protect the equipment from rain, snow, and humidity.
- Do not expose to mechanical and thermal extremes. Protect the equipment from rapid variation in temperature.
- Handle all connectors, both electrical and optical, with care. Do not use unnecessary force, as this may damage the connectors.
- Handle the optical fiber with care. Mechanical stress can decrease performance and potentially destroy the fiber. Continual bending of the optical fiber can cause damage. It is important, therefore, to keep the optical fiber patch cable as straight as possible to minimize bending.

Note: The most common cause of low signal intensity is contamination of the fiber due to airborne pollutants. To minimize exposure, avoid unnecessarily disconnecting the optical fiber patch cable. In addition, it is advisable to check the fiber before making other adjustments to the optical system, such as changing the focus or optical path length. Be sure to check the patch cord for a loose connection, and make sure that the fiber is kept as straight as possible.

All lasers, especially lasers with resonator cavities that are defined by mechanical tolerances, are delicate precision instruments and must be handled accordingly. The OCT base unit is designed to withstand normal transportation and operating conditions. Do not move the system while it is connected and in operation.

1.2.1. **Optical Cleaning**

Good performance and image quality of the OCT imaging system relies on clean optical connections. Whenever using the Thorlabs OCT system, the following guidelines for optical fiber connection should be followed:

1) Always make sure that the light source is switched off when you clean the fiber.
2) Always inspect and clean the fiber end before plugging it into a receptacle.
3) Always cover the fiber end that is not in use with a fiber cap or dust protection cover.

The cleaning procedure sucess could be visualized using a fiber inspection scope

Figure 1 Fiber Inspection Scope FS201

1.2.2. **Fiber Cleaning Techniques Using the FBC1**

This section details how to clean fiber bulkheads and fiber connectors using the FBC1 one-step cleaner.

Using Extended Mode

Figure 2 FBC1 Extended Mode

To use extended mode, pull the tip outward while simultaneously pushing down on the lock button. Extended mode is useful for panels with multiple bulkhead connectors or other tight spaces.

Cleaning Fiber Bulkheads

Figure 3 Cleaning Fiber Bulkheads

Remove the guide cap completely from the device, and insert the tip of the cleaner into the bulkhead connector. Push the case to start the cleaning process; a click indicates that the cleaning is complete.

Cleaning Fiber Connectors

Figure 4 Cleaning Fiber Connectors

Open the cover on the guide cap, and insert the fiber connector over the guide cap. Push the case to start the cleaning process; a click indicates that the cleaning is complete.

1.2.3. Service

Only trained and approved Thorlabs personnel are allowed to service the system. Please contact Thorlabs technical support for more information.

1.2.4. Accessories and Customization

The OCT base unit can easily be adapted for custom interfaces. To achieve the listed specifications, however, this system should only be used with the accessories that Thorlabs provides. Any modification or maintenance by unqualified personnel will render the warranty null and void, leaving Thorlabs free of liability. Please contact Thorlabs technical support for questions on customization.

Chapter 2 Setup

2.1. Unpacking

Carefully unpack the components from the transport boxes. Make sure that all components are delivered according to the packing list included in the transport box. After unpacking, store the packing cartons and inserts. You may need them in case of a service or upgrade of your OCT system.

2.2. System Connections

2.2.1. Base Unit Connections

All OCT base unit connections are located in the rear (see Figure 5).

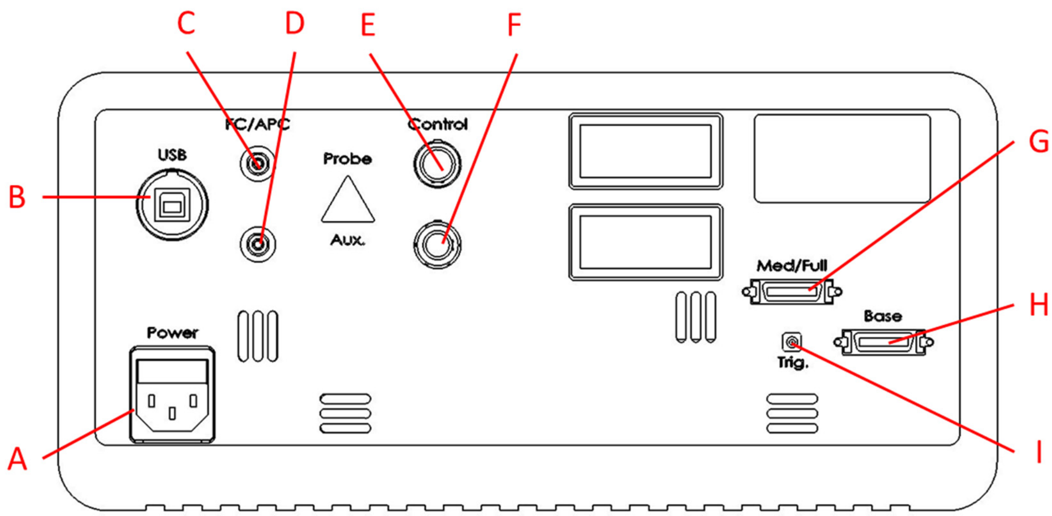

Figure 5 Rear View of OCT Base Unit

- **A.** Power Plug
- **B.** USB Data Port to Connect PC (USB 2.0 Type B Interface)
- **C.** Fiber Connection to the Imaging Scanner (FC/APC)
    - In Telesto-PS Series base units a fiber cable is permanently installed
- **D.** Auxiliary Fiber Connection to Imaging Scanner (FC/APC) – Not in Telesto Series and some Ganymede Series base units
- **E.** Probe Connection Port (LEMO, 19 Pin)
- **F.** Auxiliary Connection Port (LEMO, 14 Pin)
- **G.** CameraLink Connection:
    - Med/Full – Only in some Ganymede and some Telesto Series Base Units
    - Camera 0 – Only in Telesto-PS Series base units (not shown above)
- **H.** CameraLink Connection
    - Base – Not in Callisto Series base units
    - Camera 1 - Only in Telesto-PS Series base units (not shown above)
- **I.** Trigger Connection SMB – Not in Callisto Series base units

2.2.2. Internal Electrical Connections

The USB connection to the PC is used for the control communication between the Software and base unit. The acquisition and synchronization of the spectral information is using the CameraLink and the Trigger connection.

2.2.3. Electrical Interfaces to Probe

For the connection to a scanner application there are two different interfaces available.

- The probe connection port is intended to be used together with dedicated Thorlabs imaging scanners OCTG and OCTP.
- The auxiliary connection port is intended to be used together with dedicated Thorlabs imaging scanner OCTH and furthermore allows the use of a custom scanner. It hosts two analog signals for driving separate actuators (e.g. Galvanometer scanner), communication lines and supply voltages.

Electrical Probe Connection Interfaces	
Probe Connection Port	Lemo ECG.2B.319.CLL
Auxiliary Connection Port	Lemo ECA.1B.314.CLL

Table 1 Electrical Probe Connection Interface

Please contact Thorlabs' tech support for information regarding the pin configuration.

2.3. Optical Interface to Probe

The base unit can incorporate one or two FC/APC fiber interfaces depending on the internal fiber architecture (see also chapter 3.1.2):

- Base units with an integrated circulator-support-only port.
- Base units comprising an internal coupler support two FC/APC interfaces. These ports could be used to build a dual path setup with minimum optical loss. The optical path length difference between the two ports is not defined.
- The Telesto-PS Series base units already comes with an attached polarization maintaining fiber and no additional fiber is needed.

If not different due to customization the single mode fiber used in the base units is given in Table 2:

Optical Probe Connection Interface		
Base Unit Series	**Fiber Connector**	**Single Mode Fiber**
Callisto / Ganymede	FC/APC	Nufern 780
Telesto	FC/APC	Corning SMF28 Ultra or Corning HI-1060
Telesto-PS	Permanently Attached to Base Unit	Corning PANDA PM13-U25A Key Aligned to Slow Axis

Table 2 Optical Probe Connection Interface

2.4. System Installation

ATTENTION

Make sure the included power cords for the base unit, computer and monitor are connected to a properly grounded outlet (100 – 240 VAC; 50 – 60 Hz).

Transportation and delivery may cause the OCT base unit to be warm or cool upon receipt. Please wait for the system to reach room temperature before attempting to operate.

Operate this system on a flat, dry, and stable surface only.

1) Install the PC, monitor, mouse and keyboard according to the documentation provided by the PC manufacturer.

2) If applicable, assemble the OCT-STAND as described in the documents provided in the OCT-STAND box.

3) If applicable, mount the scanner in the OCT-STAND by sliding the dove tail at the back of the scanner into the dove tail slide of the OCT-STAND.

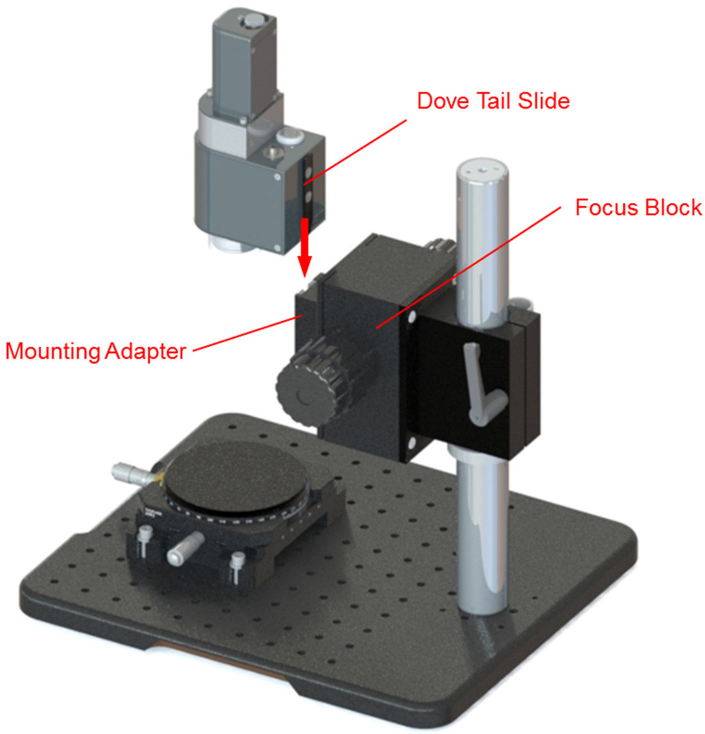

Figure 6 Mounting the OCTG Scanner into the Dove Tail Slide of the OCT-STAND

4) Connect the CameraLink and the SMB cables between the base unit and the PC (not for CAL-Series base units).

   a. In the Telesto-PS Series base units connect the long SMB cable between the base unit and the SMB tee connector which is plugged into the PC. Use the short cable to connect the second framegrabber with the open port of the SMB tee connector.

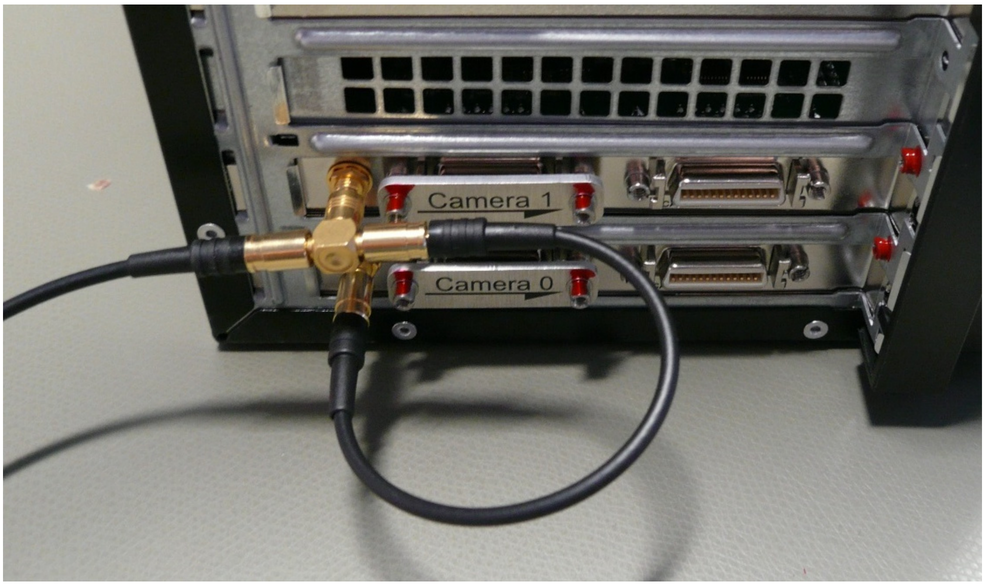

Figure 7 Connection of SMB to both Framegrabber Cards (Telesto-PS Series Base Units only)

5) Attach the USB cable to the base unit and to the PC.

6) Connect the power supply plug to the socket of the base unit and connect the other end to an electrical outlet.

7) Attach the electric connection cable to the imaging scanner.

Align the red dot of the plug to the alignment mark of the electric connection port of the scanner (e.g.: OCTG).

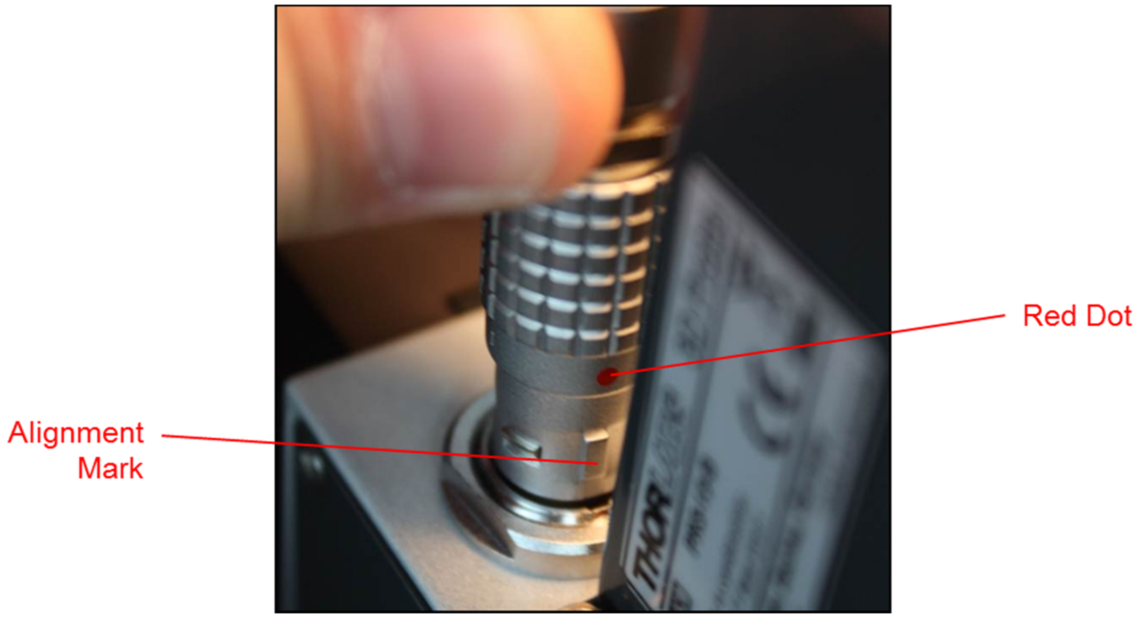

Figure 8 Plugging the Electric Connector into the Scanner

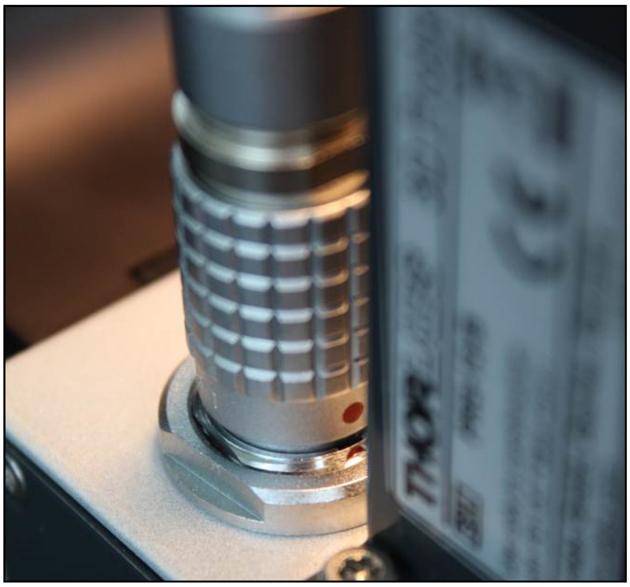

Figure 9 Electric Connector Plugged into the Scanner

Push the connector into the receptacle until a “click” sound is heard.

8) Connect the fiber to the imaging scanner.

ATTENTION

When installing the fiber, make sure that the fiber tip does not get contaminated by dust.

Do not touch the fiber tip!

Remove the dust caps from one fiber end and from the FC/APC fiber connection at the imaging scanner. Store these with the system packaging.
Inspect the fiber and clean it according to chapter 1.2.2.

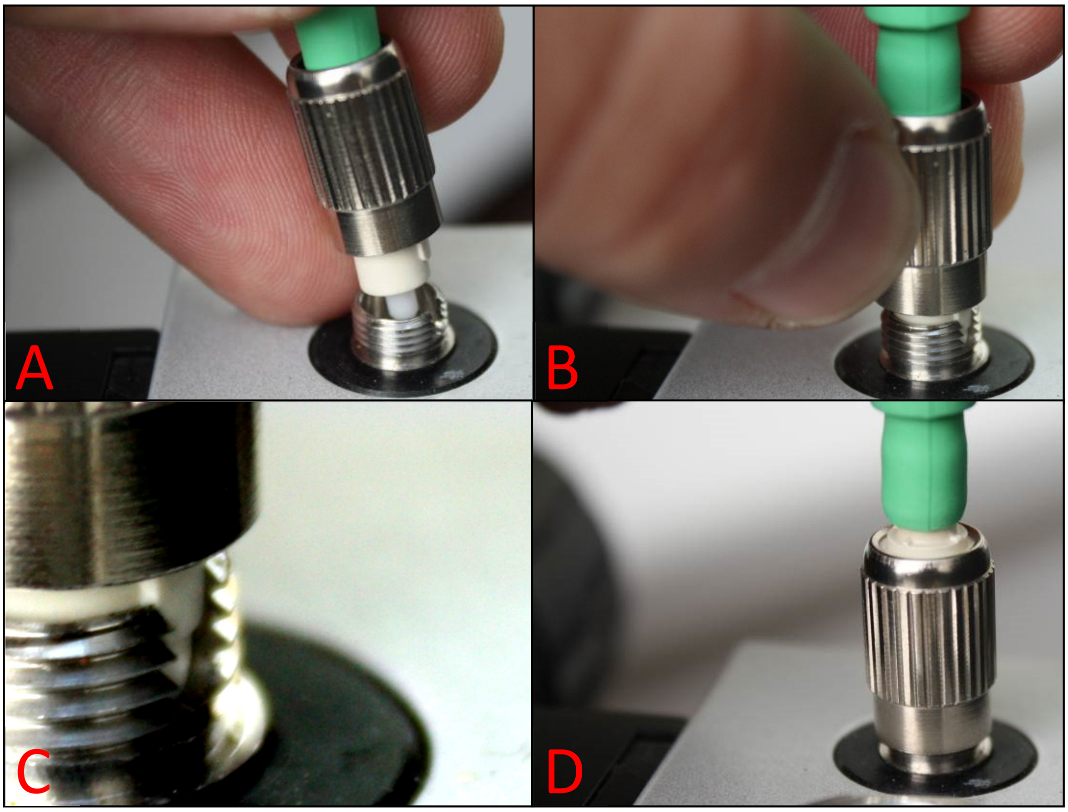

Figure 10 Fiber Connection to the Imaging Scanner

A) Slide the fiber tip into the center bore of the fiber connection.

B, C) The fiber needs to be oriented in rotation so that the alignment key slides into the mating part of the probe connector as shown in Figure 10C.
NOTE: If the key is not properly aligned, you will still be able to secure the fiber, but there will be significant light losses produced by this incorrect connection.

D) Secure the fiber connection by turning the lock cap clockwise. No force is needed for this operation.

9) Attach the electric connection cable to the base unit.

Align the red dot upwards, facing the alignment mark in the base unit.

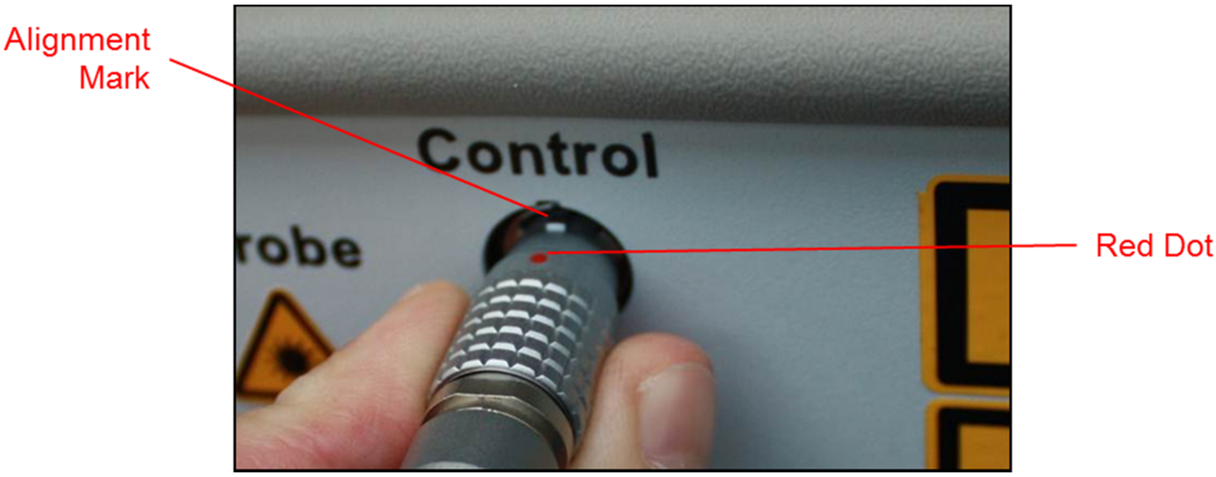

Figure 11 Installing the Electric Connection Cable at the Base Unit

Push the connector into the receptacle until a “click” sound is heard.

10) Connect the fiber to the base unit. (Not in Telesto-PS Series base units.)

ATTENTION

When installing the fiber, make sure that the fiber tip does not get contaminated by dust.

Do not touch the fiber tip!

Remove the dust caps from the fiber end and from the FC/APC fiber connection at the base unit. Inspect the fiber and clean it according to chapter 1.2.2.

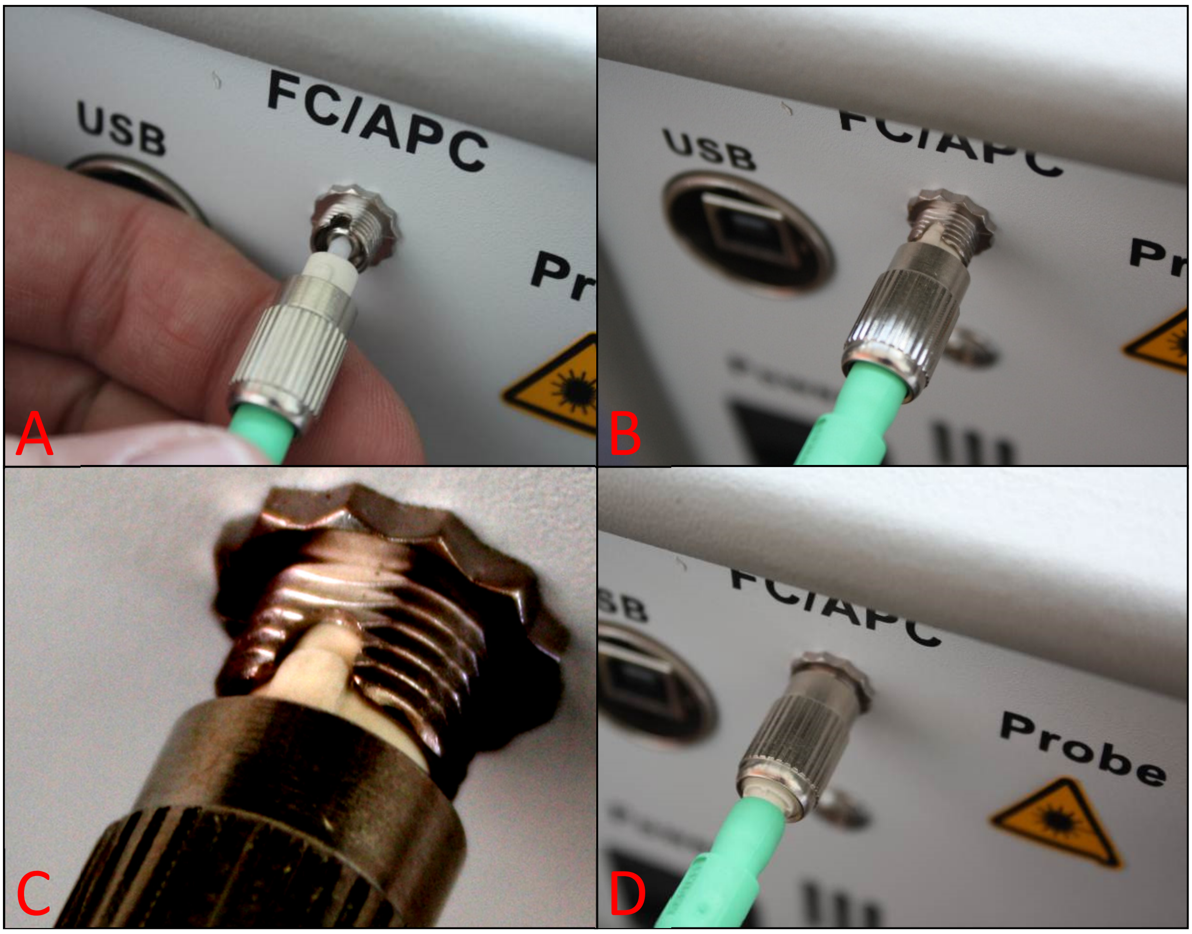

Figure 12 Fiber Connection to the Base Unit

A)	Slide the fiber tip into the center bore of the fiber connection.
B), C)	The fiber needs to be oriented in rotation, so that the alignment key slides into the mating part of the probe connector.
D)	Secure the fiber connection by turning the lock cap clockwise. No force is needed for this operation.

11) Pull the protective cap off the scan objective.

Do not touch the optical surface of the lens.

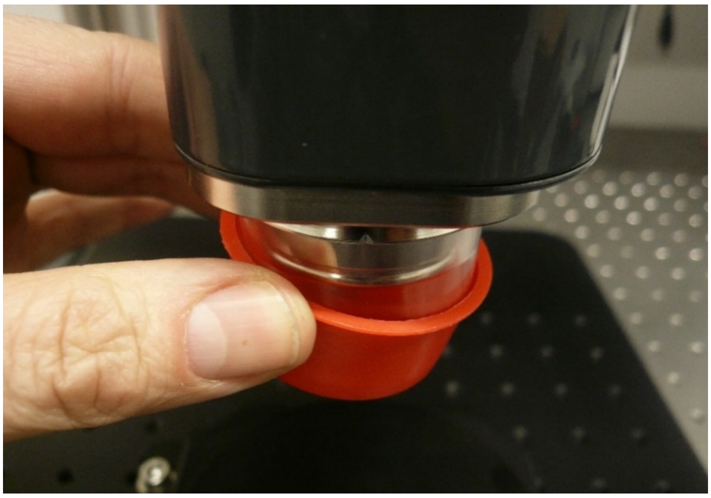

Figure 13 Protective Cap Removal

2.4.1. Enable External Trigger

To enable the option to use an external trigger, a tee connector must be inserted into the trigger connection to allow inserting the trigger signal.

The location of this connector is shown in Figure 14. This option is not available in Callisto and Telesto-PS Series base units.

ATTENTION

To make use of the external trigger the checkbox to activate the external trigger mode under "Hardware" in the "Settings" dialog for external A-scan triggering must be active.

If not, the internal trigger is still active and the scanner process will be disturbed.

For more details, please refer to the OCT software manual.

Figure 14 External Trigger Attached using an SMB Tee Connector

Chapter 3 Description

3.1. Tutorial

Frequency Domain Optical Coherence Tomography (FD-OCT) is based on low-coherence interferometry, which utilizes the coherent properties of a light source to measure optical path length delays in a sample.

To obtain cross-sectional images with micron-level resolution using OCT, an interferometer is set up to measure optical path length differences between light reflected from the sample and reference arms.

There are two types of FD-OCT systems, each characterized by its light source and detection schemes;

- Time-encoded Frequency Domain OCT (teFD-OCT),
  also named Swept Source OCT (SS-OCT).

- Spatially-encoded Frequency Domain OCT (seFD-OCT),
  also named Fourier Transform Domain OCT (FD-OCT) and Spectral Domain OCT (SD-OCT).

Thorlabs uses the abbreviations SD-OCT for the spatially-encoded camera-based OCT systems and SS-OCT for the time-encoded systems.

In both types of systems, light is split by a fiber coupler into the sample and reference arms of an interferometer setup.

Back reflected light, attributed to variations in the index of refraction within a sample, recouples into the sample arm fiber and then combines with the light that has traveled a fixed optical path length along the reference arm. The resulting interferogram is measured by either a spectrometer (SD-OCT) or balanced photodetectors (SS-OCT).

The frequency of the interferogram measured by the sensor is related to the depth location of the reflector in the sample. As a result, a depth reflectivity profile (A-scan) is produced by taking a Fourier transform of the detected interferogram. 2D cross-sectional images (B-scans) are produced by scanning the OCT sample beam across the sample; by doing so, a series of A-scans are collected to create the 2D image. Similarly, when the OCT beam is scanned in a second direction, a series of 2D images is collected to produce a 3D volume dataset.

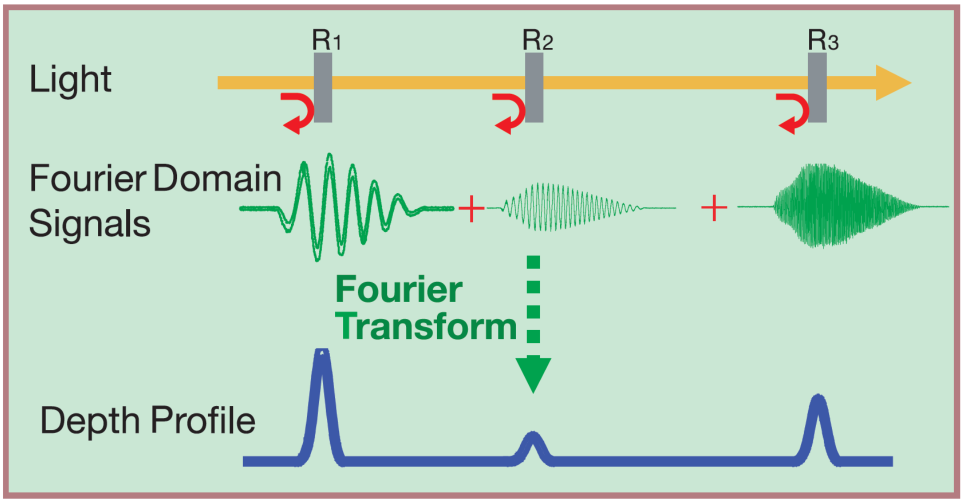

Figure 15 FD-OCT Signal Processing

3.1.1. Theory

The interference equation for the cross-correlated interference term is

$$I_{Interference} \sim 2 \cdot \sqrt{I_{Sample} \cdot I_{Reference}} \cdot \cos(\Delta\varphi)$$

With the phase difference $\Delta\varphi$ being a function of the optical path length difference and the wavenumber

$$\Delta\varphi = k \cdot \Delta \mathrm{z}$$

This optical amplification of a small sample intensity with a strong reference intensity allows the detection of single photons from the sample and is the key to the outstanding sensitivity of OCT.

Due to the reflective character of the measurement modality, the optical path length difference is twice the distances in the image. The maximum imaging depth, and so twice optical path length difference, is defined by the wavenumber spacing of the acquisition δk.

$$\Delta z_{max} = \frac{1}{4 \cdot \delta k}$$

In full-range OCT setups, the image depth could be doubled.

The signal width has two limits:

- One limit for the signal width is given by the spectral distribution of the light source. For a fully used Gaussian-shaped light source in k-space, the equation is:

  $$Signal_{FWHM,LightSource,} = \frac{2 \cdot \sqrt{\ln(2)}}{\Delta k_{LightSource}}$$

  with:
  $\Delta k_{LightSource} = Wavenumber\ Difference\ of\ Gaussian\ Shaped\ Light\ Source\ at\ I = I_0 \cdot e^{-1}$

- The other limitation for the signal width is given by the sampling.
  For a rectangular spectrum the FFT results in a sinc function

  $$Signal_{FWHM,Sampling,} = 1.21 \cdot spacing_z$$

  with:
  $spacing_z = Image\ Depth\ Spacing = \frac{2 \cdot \Delta z_{max}}{N}$
  $N = Number\ of\ aquisition\ points$

A realistic light source does not necessarily have a mathematically ideal shape best-suited for the autocorrelation function. Therefore, it is recommend that the signal be apodized to obtain a smooth, clean point spread function. A good compromise between resolution and side lobe suppression could be a Hanning window showing a signal width of:

$$Signal_{FWHM,Hanning} = 2 \cdot spacing_z$$

In real measurements, the signal width is furthermore limited by noise, dispersion mismatch between sample- and reference arm of the interferometer, and optical path length distribution of the imaging caused by aberration.

3.1.2. Thorlabs SD-OCT System Technology

SD-OCT is a measurement method based on the detection of optical path length differences within an interferometer. The technology incorporates a broadband light source with a high-speed spectrometer to provide depth profiles, acquired using a Fast Fourier Transform, that can be assembled into cross-sectional images. These cross-sectional images can be used for 3-dimensional reconstructions.

The light of a broadband source travels to the sample and illuminates it perpendicularly and with a small focus that provides a good lateral resolution. The back-scattered light travels to the spectrometer where the unique phase delay for each wavelength is detected. To gain access to this back-scattered light, it is necessary to insert a splitting device into the optical path. In Thorlabs' SD-OCT systems, this device could be either a fiber coupler or a circulator.

The two main features of a 2-dimensional scanned image are the axial and lateral resolutions. The axial resolution does not depend on the optics; it is driven by the used spectral bandwidth of the light source. The lateral resolution, on the other hand, is affected by the chosen application optics.

The OCT system has three main parts: the base unit, a PC and a scanner with OCT-STAND. The schematic setup of the SD-OCT system with coupler and circulator is shown in the figures below:

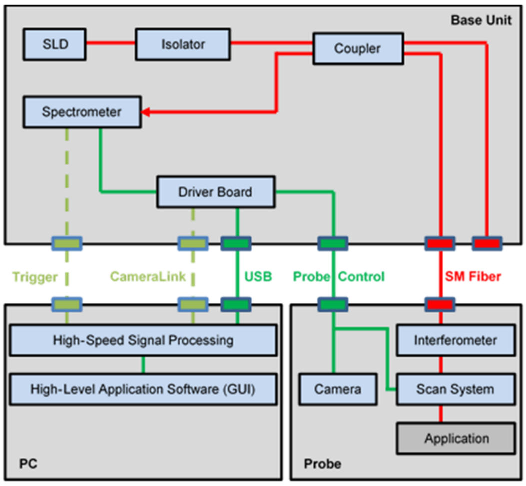

Figure 16 Schematic Diagram of a SD-OCT System with Internal Coupler

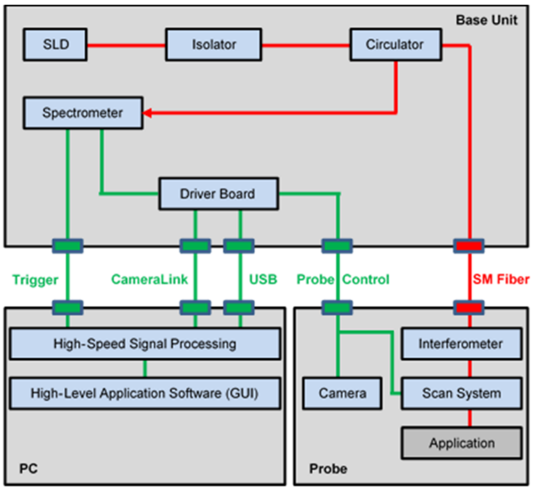

Figure 17 Schematic Diagram of a SD-OCT System with Internal Circulator

3.1.3. Polarization-Sensitive Optical Coherence Tomography

A standard OCT system is able to measure a depth scan of the sample using the phase and intensity of the backscattered light from different positions in depth. Nevertheless, it does not account for polarization effects or birefringence in the sample which might be interesting if the sample shows different birefringent properties locally.

SD-PS-OCT is able to capture and visualize this property. The abbreviation SD-PS-OCT stands for spectral-domain polarization-sensitive optical coherence tomography. This SD-OCT system uses a known and controlled polarization state of the incident light which is changed by the birefringent properties of the sample. Maintaining the polarization information from to sample to the spectrometer, the polarization state can be deconvolved into the two polarization axes: s ('senkrecht', German for vertical) and p ('parallel'). The s and p polarization components are detected in two separate sensor units.

The controlled polarization state of the light is achieved by the broadband light source being linearly polarized and guiding the light using polarization maintaining fibers. The magnitude of coherent interference between the reference and the sample beam depends on the similarity between the polarization states of both beams. To achieve a good sensitivity for both polarization axes, the polarization state of the reflected beam needs to be rotated by 45° when interfering with the sample beam. To implement this, a quarter-wave plate (QWP) is used in the reference arm. The polarization axis is rotated by 22.5° to the incident linearly polarized light which results in elliptically polarized light. Being reflected at the retro reflector the phase of the polarized light is shifted by π. Thus, traversing back through the QWP with an angle of 22.5° generates linearly polarized light which is rotated by 45° to the incident linearly polarized light. This change in polarization is independent of the sample and only affects the reference beam.

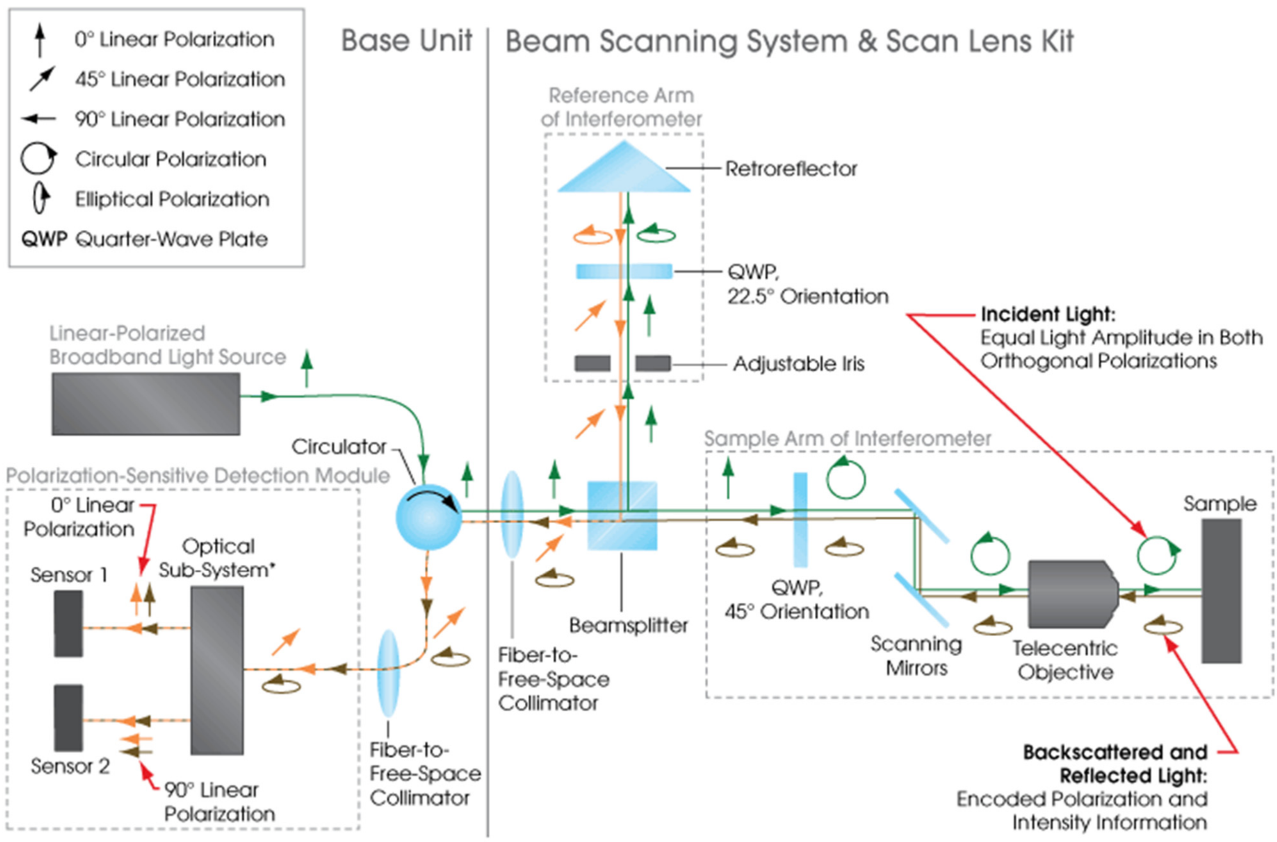

Figure 18 Schematic Diagram of an SD-PS-OCT System

In order to be sensitive to all polarization effects introduced by the sample and to be independent of the sample orientation in plane, the sample is probed with circularly polarized light. To obtain circularly polarized light, another QWP is placed in the sample arm which is turned by 45° to the incident, linearly polarized light. In case the sample is a mirror, the circularity stays unchanged in the reflected light and after traversing through the QWP a second time, linearly polarized light is obtained which is rotated by 90° compared to the incident, linearly polarized light. If the sample changes the polarization state of the incident light, the backscattered light is changed, e.g. to elliptically polarized light. After traversing through the QWP a second time, this ellipticity is changed again but its composition stays the same so that the intensity measured in each sensor, for s- and for p-polarized components, reflects the polarization and birefringence properties of the sample.

Based on the intensity and phase differences in the interference patterns detected by both sensors, net polarization changes as a function of depth in the sample are determined with the typical spatial resolution of an SD-OCT system. As a parameter to display the cumulative polarization effect, the phase retardation, optical axis and degree-of-polarization uniformity (short: DOPU) are available. Details are provided in the OCT Software Manual (chapter 3.10. Polarization Sensitive Mode).

3.1.4. Nomenclature in OCT imaging

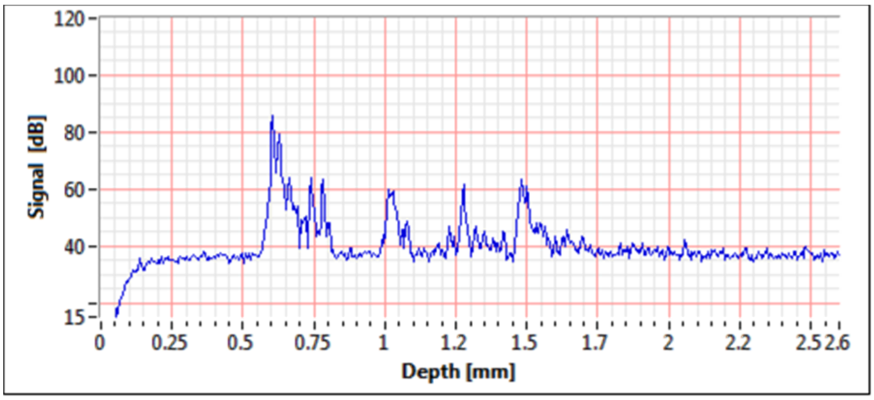

Figure 19 A-Scan Data Set

As described before, the SD-OCT engine creates a depth profile from the interference of photons reflected off layers of the sample with photons reflected in the reference arm. This depth profile is referred to as A-scan. Figure 19 shows a tomato's A-scan data. The ordinate of this graph represents the modulation amplitude based on the number of measured electrons per camera pixel. Other scales do not change the measurement.

The imaging application can make use of up to two scanning directions. When scanning one direction while collecting multiple A-scans, a 2-dimensional cross-sectional image is created. This is referred to as a B-scan. Here, the depth information is typically displayed from top to bottom, while the scan axis is from left to right. Figure 20 shows a B-scan data set.

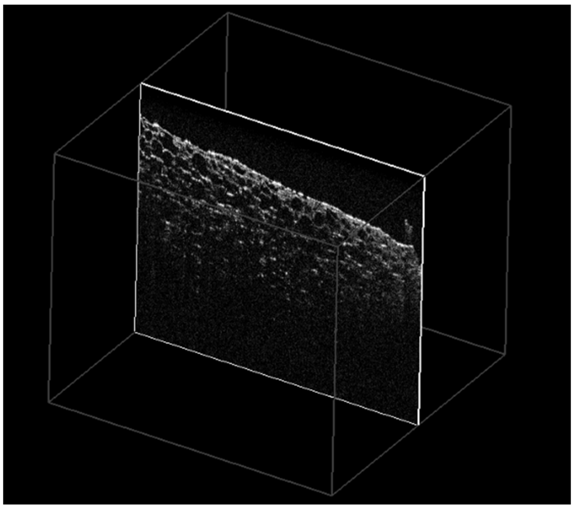

Figure 20 B-Scan Data Set

When scanning both galvanometer mirrors, a volume can be acquired. This can be imaged by movable sections through the volume or by 3D rendering. Please refer to the OCT Software Manual for all features available.

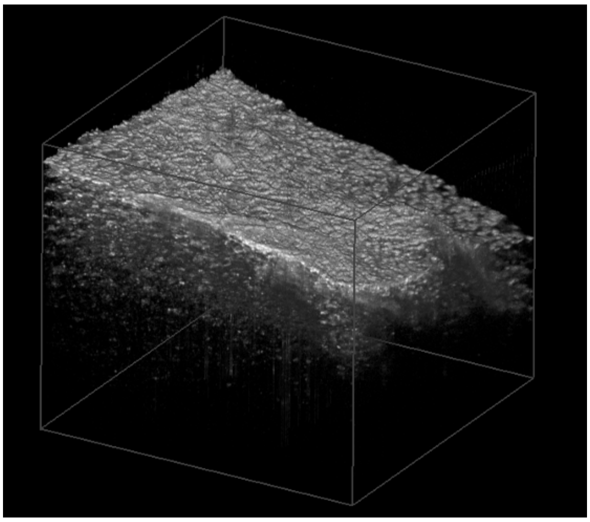

Figure 21 Rendered Volumetric Data Set

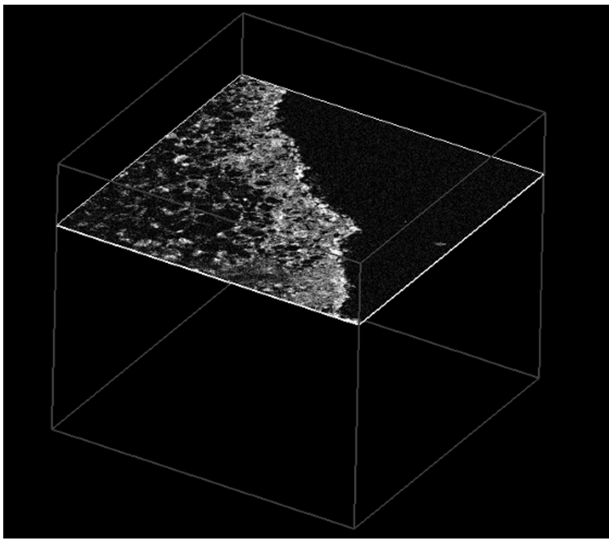

Figure 22 En-Face View or C-Scan

When displaying a plane with both scan directions as axes, an en-face image is created. Here, the viewing plane is parallel to the image plane of the color camera in the scanner. This plane is referred to as C-scan.

3.2. OCT Base Unit Components

The base unit is delivered together with a pre-installed PC or laptop, depending on the base unit type.

A scanner as well as the OCT-STAND are not included in the base unit and must be ordered separately.

When ordered together with a scanner, the system will be pre-assembled at Thorlabs and the PC settings will already be calibrated and optimized for the usage of the delivered OCT scanner.

3.2.1. Base Unit

The base unit is the main component of an SD-OCT system. This unit sends light to the application, communicates with the PC through a USB connection, synchronizes with the camera of the spectrometer and delivers the measurement data to the PC. The base unit contains a broadband super luminescent diode (SLD), which is directed through a fiber optical coupler to the “Probe” port at the backside of the device. The back-scattered and reflected light from the application is returned through the fiber optic coupler or circulator, which directs the light to a spectrometer (as described in Figure 16 or Figure 17). Other components in the base unit include a high-speed linear imaging sensor, analog and digital timing circuitry, analog controls for the application, and data acquisition hardware.

Figure 23 Base Unit (TEL210)

The central wavelength of the system depends on the SLD. The use of near-IR broadband sources balances the desire for low scattering losses with the need to operate within the wavelength range that will provide higher penetration depth into the sample. Near-IR broadband sources are a perfect compromise between sufficient transparency and a significantly reduced scattering coefficient.

3.2.2. PC with Graphical User Interface

The OCT base unit is delivered with application software made for the imaging scanners provided by Thorlabs. All required data analysis as well as 2D and 3D display can be performed within the software package. The data can be saved, analyzed and exported for further use.

Detailed operating instructions for the OCT software are provided in the OCT Software User’s Manual.

3.2.3. SDK

A software development kit (SDK) is provided with the system. The SDK gives access to all software routines used to control the units and to process the acquired data. It allows a quick start for application-specific software development. The SDK is implemented in two programming languages: C and LabVIEW®. For professional and advanced users, the C interface guarantees a seamless integration into their own object oriented software. For easy access to the functionality, we also provide a LabVIEW® Interface. The LabVIEW® interface has the same functionality as the C interface and maintains the same high processing speed achieved with the C interface.

Hardware control through the SDK ranges from low-level functions such as setting the galvo scanners to a desired position, to very powerful functions such as initiating full 3D measurements. The programmer can:

- Define either a standard scanner provided by Thorlabs or create a software representation of a custom-built device.
- Define simple or complex scan patterns.
- Acquire simple A-Scans, B-Scans or complete volumetric measurements.

Processing of acquired OCT data ranges from simple A-Scan processing to advanced routines for Doppler speed measurements. The programmer can:

- Take the standard processing steps necessary to convert a spectrum measurement into an A-Scan
- Set the color scheme, brightness and contrast of images
- Calculate the speed of particles in the sample via Doppler OCT
- Import and export the different file formats data types

The function library also contains the source code for the LabVIEW® software applications supplied with the instrument and other example programs. Often, these can be used as a starting point for software development projects.

The SDK can be installed from the USB flash drive which ships with the system.

A complete documentation of the SDK with a description of all functions can be found in PDF format in the SpectralRadar SDK program group after installation of the SDK.

3.2.4. Imaging Scanner (Accessory)

Thorlabs SD-OCT systems use a common-path OCT setup in which the interferometer is located within the imaging scanner. This integration of the interferometer eliminates the problems associated with chromatic or polarization mode dispersion that are introduced by differences between individual fibers in the sample and reference arms.

Various Lens Kits are available for these scanners.

For further detail, please refer to the specific manual of the scanner.

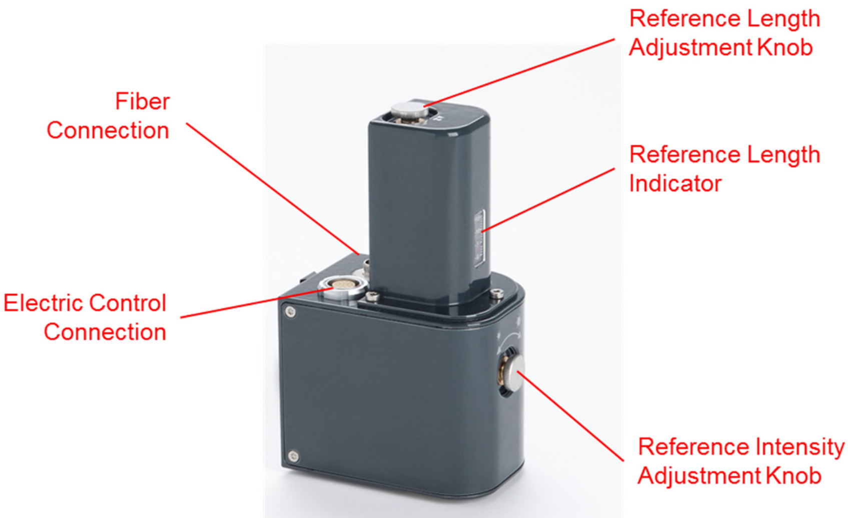

Figure 24 OCTG Standard OCT Scanner

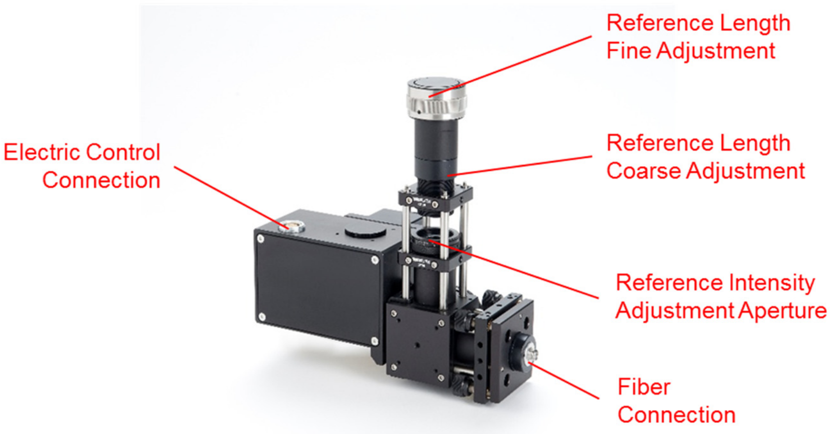

Figure 25 OCTP User-Customizable OCT Scanner

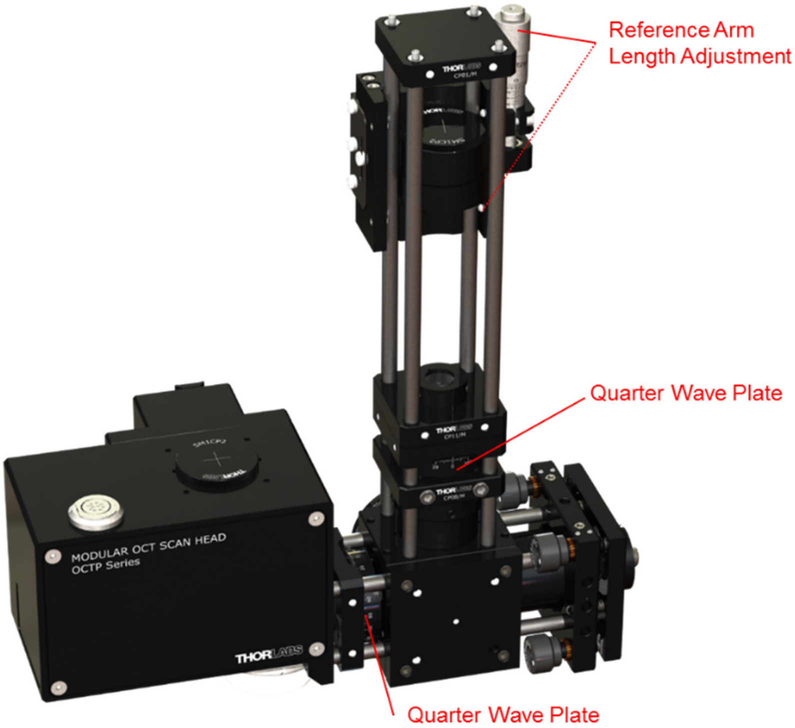

Figure 26 OCTP-PS User-Customizable PS OCT Scanner

Figure 27 OCTH Handheld Scanner

3.2.5. OCT-STAND (Accessory)

The Thorlabs OCTG and OCTP scanners can be mounted to an OCT-STAND. For this OCT-STAND, the rotation-and-translation stage OCT-XYR1 is available.

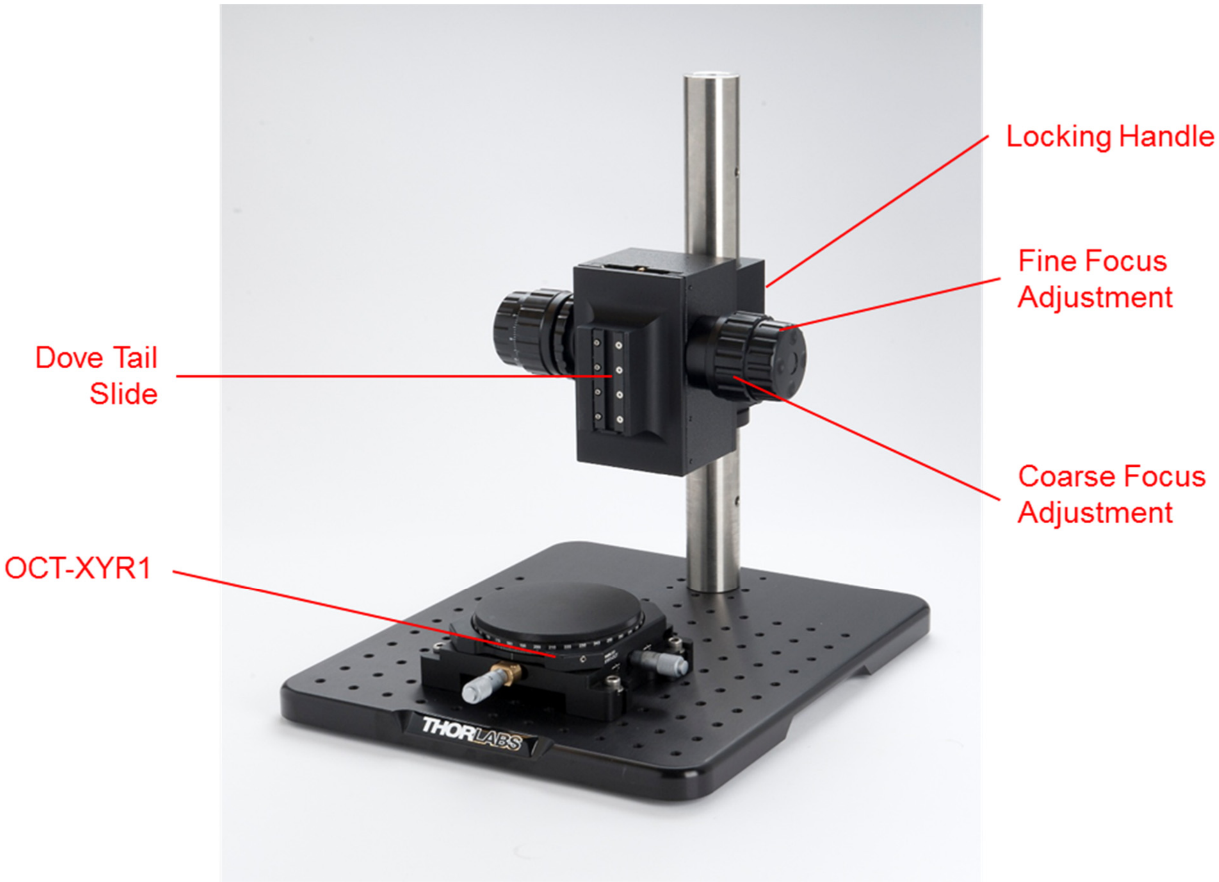

Figure 28 OCT-STAND with OCT-XYR1

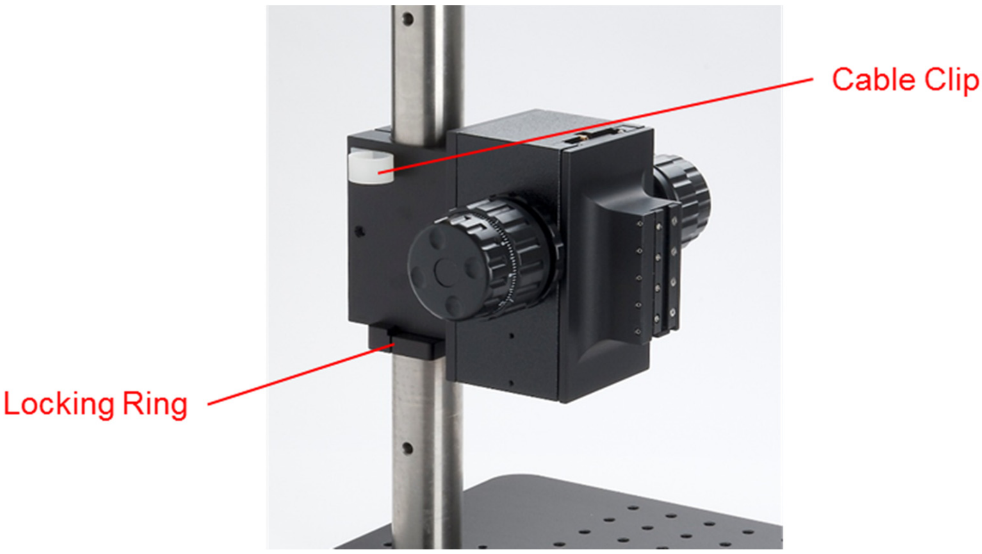

Figure 29 OCT-STAND Adjuster

Figure 30 OCT-XYR1 Sample Rotation Stage

For further details on the OCT-STAND and the OCT-XYR1 please refer to the Thorlabs web site.

Chapter 4 System Operation

4.1. Starting the System

Follow these steps for proper initialization of the system:

1) Start the base unit by placing the POWER switch to the "**I**" Position. Verify that the "POWER ON" indicator turns green. Wait for 30 seconds until the PC has recognized the hardware.

2) Start the Thorlabs OCT software (see software user's manual for details). The system will be switched on via remote control from the computer. After starting the software, the green "SYS OK" LED on the base unit will illuminate.

3) After loading the program, the software performs a warm up and initial calibration procedure. During the warm up, the internal light source is off and the system performs a dark current measurement. Next, the light source is switched on ("SLD ON" LED will illuminate) and stabilized with respect to temperature and the related performance parameters. The warm up takes approximately 10 seconds to complete.

4.2. Basic Adjustments

When receiving a complete SD-OCT system from Thorlabs, the reference length is adjusted so that OCT imaging in air is possible simply by adjusting the focus to the region of interest. If the reference arm length no longer matches the sample arm length, the following procedure will aid you to a good basic adjustment. For OCT imaging through refractive media, e.g. water or glass, please refer to chapter 4.3.2.

4.2.1. Adjusting the Focus

For a coarse adjustment of the focus, place a suitable sample, e.g. the IR viewing card delivered with the system, underneath the scanner. Using the OCT software, a fraction of the card can be seen in the sample monitor. Now, adjust the height of the imaging scanner with respect to the card by adjusting the focus block of the OCT-STAND (see Figure 28) to obtain a sharp image.

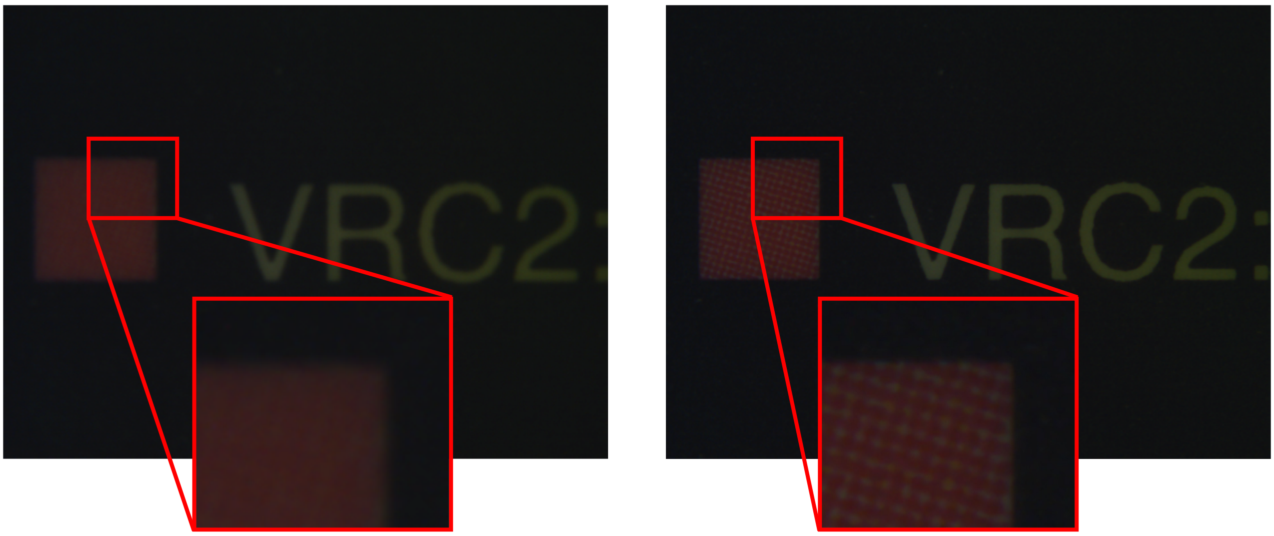

Figure 31 Basic Focus Adjustment

4.2.2. Adjusting the Reference Intensity

For optimum imaging quality it is necessary to ensure that the reference intensity is set into the correct range. The reference intensity is displayed by the OCT software, as shown below. For optimizing the reference intensity pull out the reference intensity adjustment knob (see Figure 24).

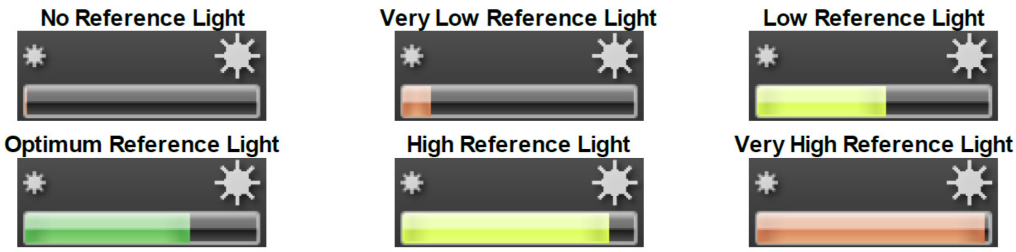

Figure 32 Reference Intensity Indication Bar in ThorImage®OCT

Start a B-scan acquisition. If the reference intensity bar is low, turn the knob **clockwise** to optimize the reference intensity. When optimization is achieved, the reference intensity bar becomes green.
In case the reference intensity bar is too high, turn the knob **counter-clockwise.**

4.2.3. Adjusting the Reference Length

The following steps will guide you to a basic adjustment of the reference length:

- Start B-scan acquisition. When significantly misadjusted, you will get an incorrect OCT image or no image of your sample, irrespective of the focus position.
- Pull out the reference length adjustment knob from the locked position at the imaging scanner (as shown in Figure 24). Turn it **counter-clockwise**, until the force needed for turning significantly increases.
- Now, slowly turn the reference length adjustment knob **clockwise** until you see the signal from the sample coming into the displayed B-scan from the bottom.
- Click the auto-adjust button (see Software Manual) to adjust the dynamic range of your B-scan.
- When using the IR card for adjustment, your B-scan image should look as shown in Figure 33.

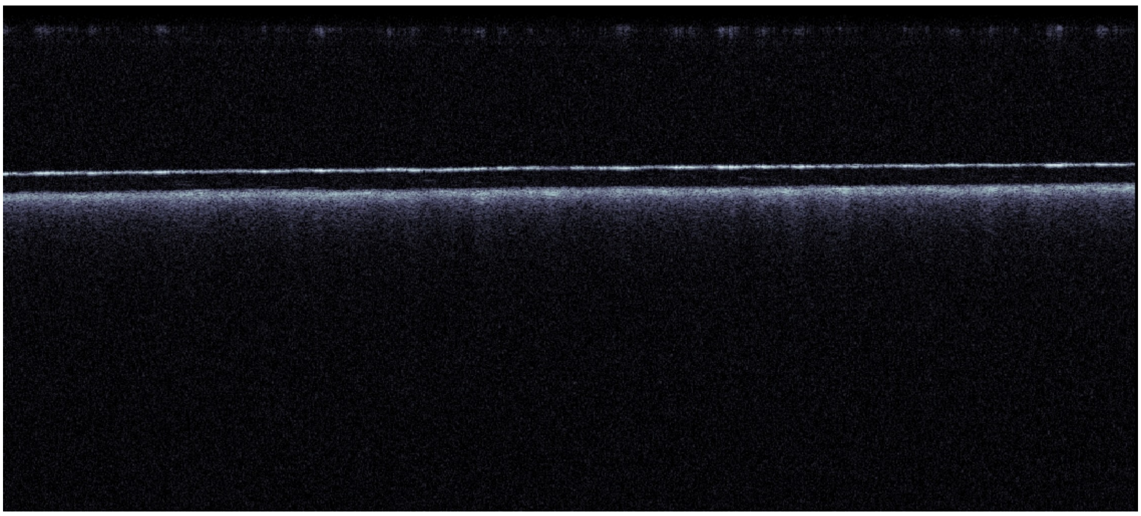

Figure 33 B-Scan of an IR Viewing Card

After basic alignment, you need to adjust the focus position inside your sample by use of the fine focus adjuster (see Figure 28) of the OCT-Stand. Then, the final position of the OCT image in the B-scan or volume can be set using the reference length adjustment knob, which will move the image up and down until you achieve the desired location.

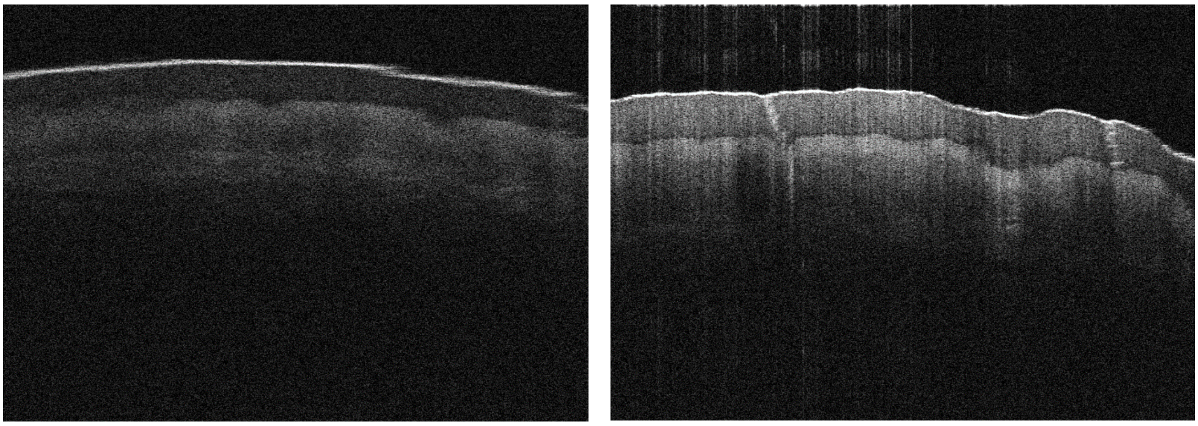

Figure 34 B-Scan of a Fingertip Out of Focus and In Focus

In Figure 34, two images of a fingertip are shown: the left is out of focus and the right is in focus.
The focus can usually be identified by one of more of the following features:

- Sharp (thin) features in lateral direction
- Autocorrelation terms (see chapter 5.3)
- Higher contrast (i.e. a strong signal). Note, that the focus does not always have to be on the top surface of your sample, but needs to be adjusted to the layer of interest in your sample.

4.3. Advanced Adjustments

4.3.1. Focus and Choice of Objective Lens

In OCT, an objective lens is used to focus the light beam on and into the sample and also to collect the backscattered light. The focused nature of the beam means that the lateral extension of the beam is different along the depth axis. Since OCT records signals along this depth axis, the collected signal corresponds to different lateral extensions of the beam and therefore the resolution is different along the depth axis. The best resolution can be obtained from the axial focus plane; the further away from the focal plane the light is backscattered from, the more blurred out the signal will appear.

The length of the axial focus depends on the optics of the OCT system, especially on the choice of the objective lens. For samples with a small axial focus length, an objective lens with a high numerical aperture can be chosen. This will grant a small lateral and axial focus, hence allowing a more in-depth analysis of the sample but also restricting the axial depth that can be investigated. For samples with a deep region of interest, it is helpful to choose an objective with a low numerical aperture, thus being able to collect signals from a large focus band. However, low numerical aperture objective lenses will decrease the lateral resolution of the image.

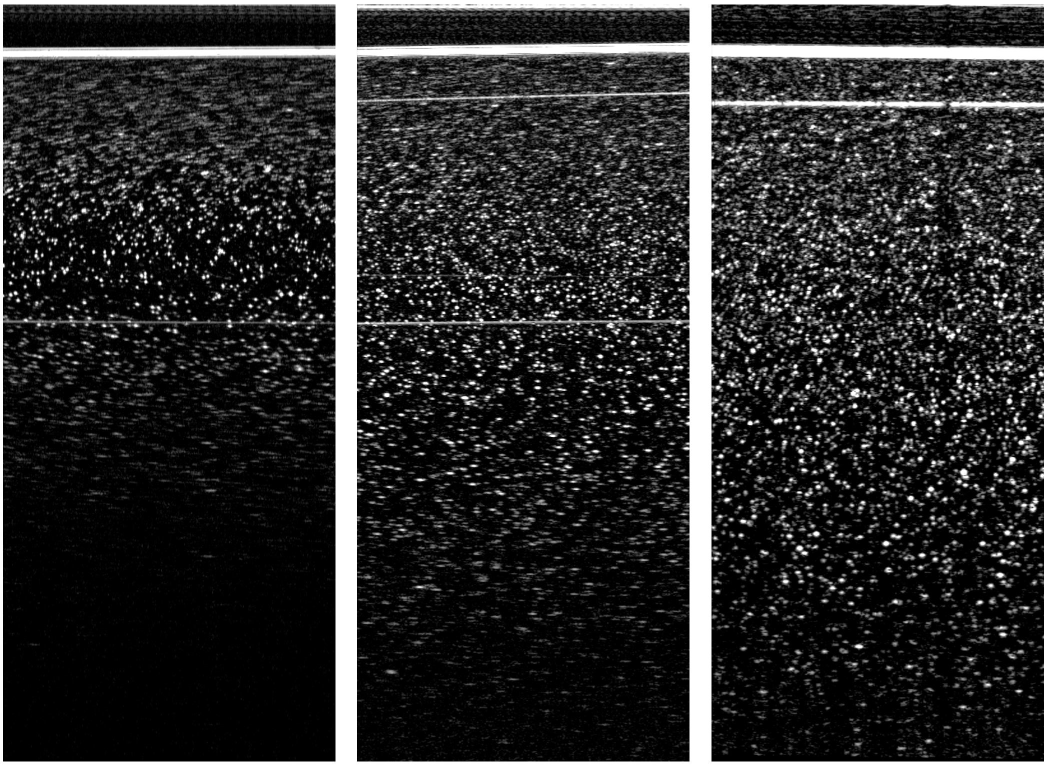

Figure 35 OCT B-Scans of Scattering Particles taken with LSM02, LSM03, and LSM04

Thorlabs offers three scan lens kits for different purposes. Figure 35 shows the difference in lateral resolution and depth of focus for the OCT-LK02 (high resolution imaging), OCT-LK3 (general purpose), and OCT-LK4 (long depth of focus). Note the change in signal strength and lateral resolution over depth caused by an increasing focus band.

Please contact Thorlabs for more information on how to incorporate different objective lenses in your OCT system.

4.3.2. Imaging through Refractive Media

To acquire OCT images, the optical path lengths of the sample arm and reference arm have to be matched. When imaging through refractive media,

- The optical path length of the sample arm is increased, which has to be compensated in the reference arm (for more details see chapter 5.8).
- The amount of dispersion changes, which can be compensated using the ThorImage®OCT software.

Every time the amount of refractive media is changed, this procedure has to be repeated in order to achieve a good image quality.

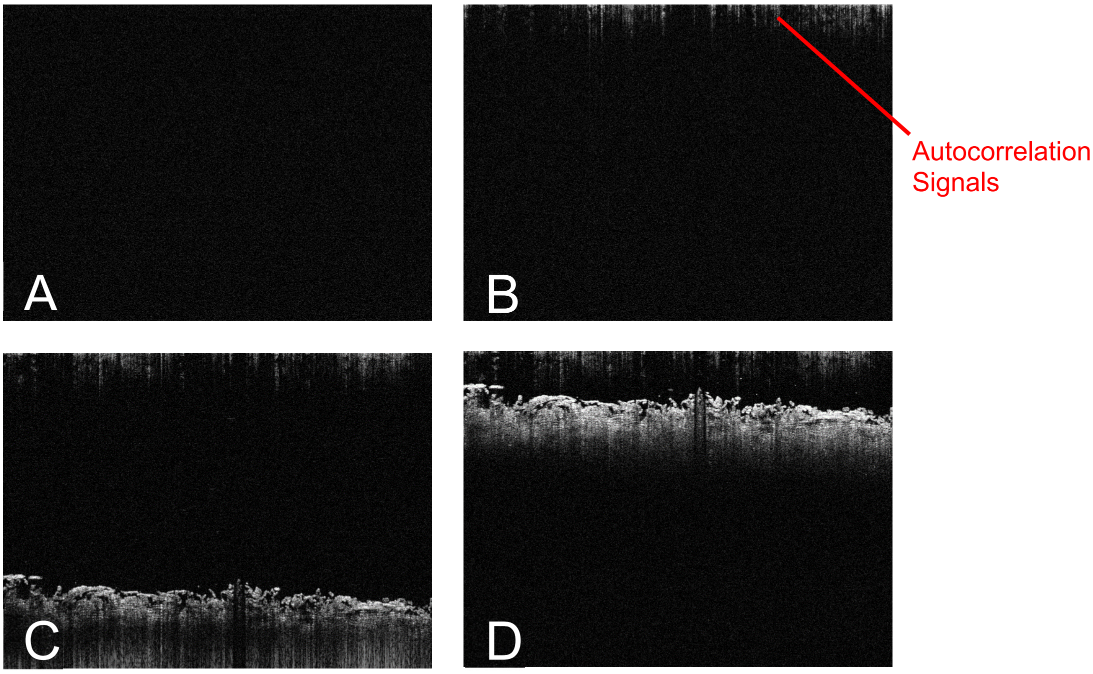

Figure 36 Step by Step Adjustments when Imaging through Refractive Media

Instead of adjusting focus and reference arm length at the same time, it is often helpful to first find the focus and then adjust the reference arm length. Figure 36 shows this procedure step by step, starting with a sample that is out of focus and with a misaligned reference arm, so that no sample can be seen in the B-scan (Figure 36A). After finding the focus, autocorrelation terms will appear in the upper part of the image even without any reflecting surface in the field of view of the B-scan. When these artifact signals are the strongest stop focusing and adjust the reference arm length so that the image appears in the top half of the window.

Furthermore, the refractive media will introduce dispersion effects, i.e. washing out due to a dependence of the phase velocity on the wavelength. This can be compensated using the ThorImage®OCT software (for more details, see the software manual). Note that the amount of dispersion depends on the thickness of the refractive media. Hence, the dispersion compensation has to be changed every time the thickness of the refractive media changes.

Note: If you are able to identify autocorrelation signals but are not able to move the OCT image into the observable window, the optical path length of the sample arm is likely increased to an extent that cannot be adjusted by the reference arm anymore. Thorlabs offers a special reference arm adapter to further increase the reference arm length, please contact Thorlabs for more information.

4.3.3. **Optimizing the Sensitivity**

In Frequency-Domain OCT systems, a fall-off of the sensitivity is observed at larger measurement depths. This is especially obvious in SD-OCT systems where this so-called roll-off starts to affect measurements already at around 30% of the maximum measurement depth. For example, the contrast of the structure in Figure 36D is much better than in C, even though the only difference is the measurement depth. Keep the region of interest in the top half of the window to use the most sensitive region of the instrument.

For some measurements it is not possible to keep the region of interest in the top half of the window, e.g. because there's additional material on top of the region of interest that would flip back into the image and overlay with the region of interest. In those situations, it might be helpful to flip the whole image of the sample (see chapter 5.6). Note that you can use the software to flip the image back to its original position, however, this is purely cosmetic and does not increase the sensitivity (for more details see the OCT software manual).

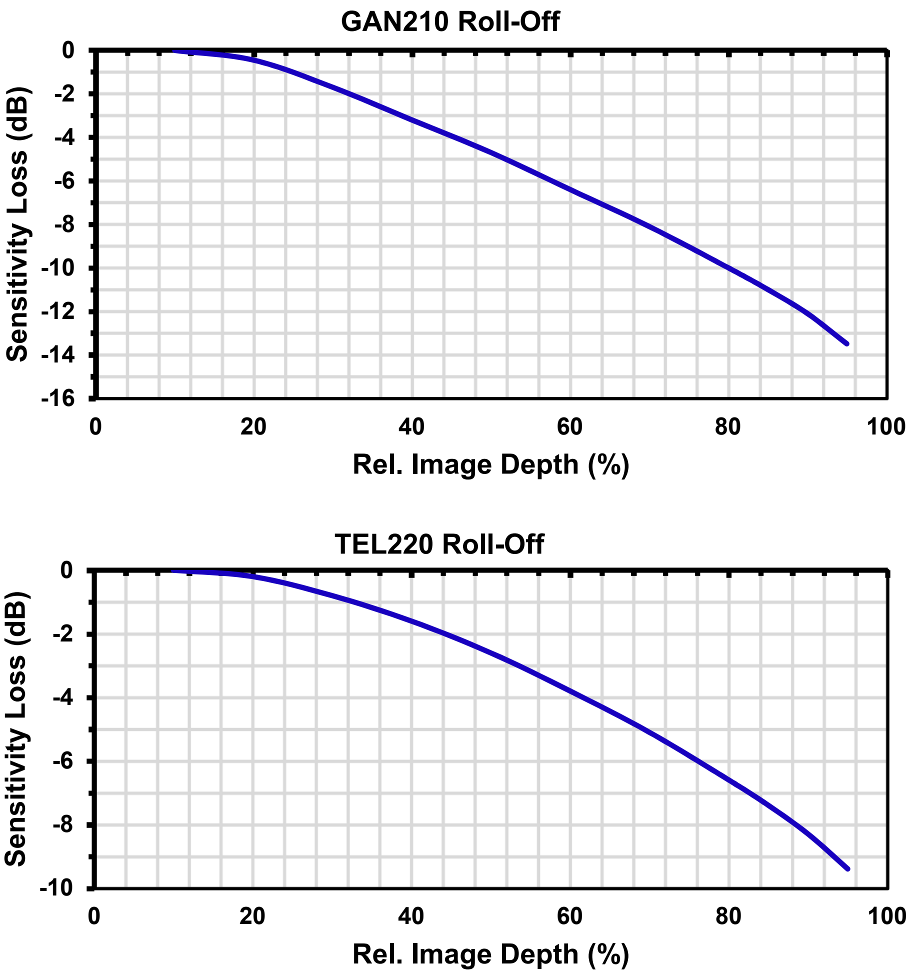

Figure 37 Measured Sensitivity Roll-Off (GAN210 & TEL220)

Figure 37 summarizes the roll-off measured for two typical base units; the GAN210 and the TEL220. The depth of each graph is normalized to the maximal measurement depth.

4.3.4. **Reflecting Surfaces and Interfaces**

Reflecting surfaces and interfaces might lead to a saturation of the detector and in turn lead to artifacts described in more detail in chapter 5.1. The influence of the artifacts can be decreased by tilting the probe or the sample. By doing that, the reflections from the sample are directed back at a different angle than the incident beam and are not collected by the objective lens.

4.3.5. **Rough Surfaces**

Rough interfaces between two layers with different refractive indices will lead to reduced sensitivity. The reason is that the sample light is scattered at the interface and directed into various directions. Here, it is often helpful to use an immersion gel and a flat surface (e.g. a glass slide) to reduce scattering.

Thorlabs offers sample z-spacers that provide a glass plate at a fixed distance to reduce scattering effects and to keep the sample in focus, please contact Thorlabs for more information.

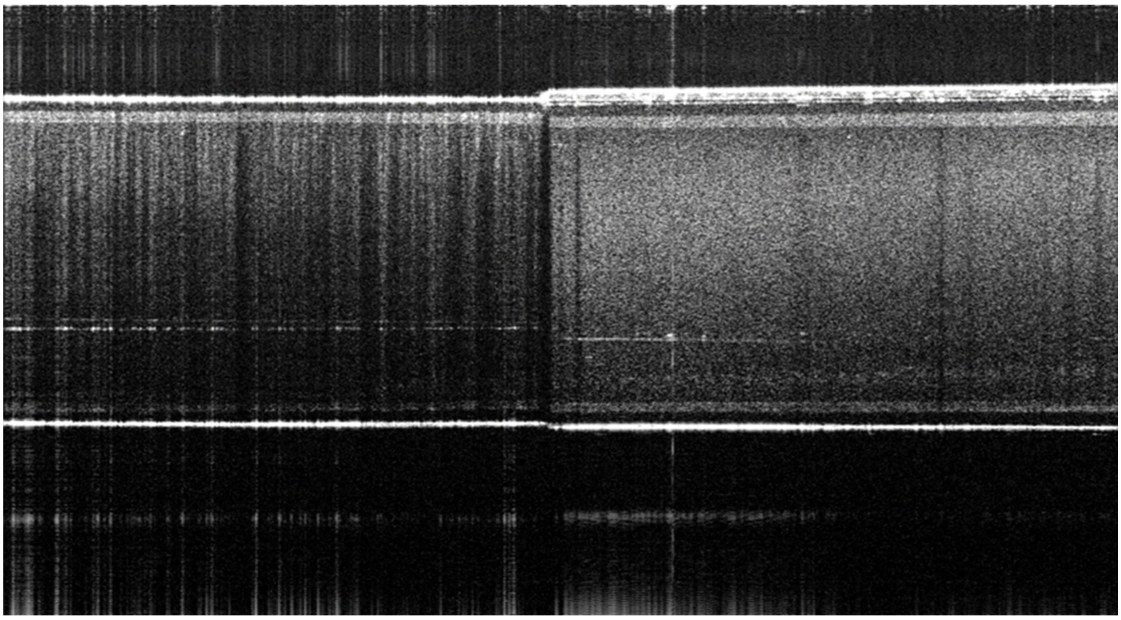

Figure 38 Plastic with Matte Surface, Partially Covered with Clear Adhesive Tape

Figure 38 shows a B-scan of a plastic substrate with a matte surface. The right part of the surface was covered with a strip of adhesive tape to make the rough surface smoother. Due to this smooth surface, the OCT image is much more consistent and the contrast in deeper layers is much better compared to the plain matte surface that is shown on the left. This is the same effect that can be seen when looking through a transparent material with a matte surface. As an example, frosted glass becomes more transparent with water.

4.4. Shutting Down the System

The following steps should be followed when shutting down the system:

1) Save any important data.

2) Close the Thorlabs software.

3) Shut down the PC.

4) Turn the power switch on the base unit to “**0**”.

4.5. Example Images

Frequency Domain OCT can be used for a wide range of real-time monitoring applications in biological and clinical fields as well as in manufacturing and materials science. This technology is ideal for in-line industrial imaging applications ranging from laminated packaging films to 3D visualization of mechanical parts.

Skin Imaging

SD-OCT provides real-time high resolution surface and sub-surface imaging of human skin, making this system ideal for many dermal and sub-dermal applications, including burn-depth monitoring, wound healing, and cancer detection.

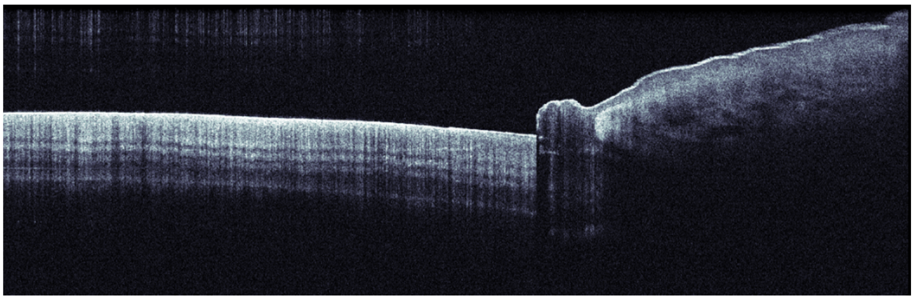

Figure 39 B-Scan of a Nailfold

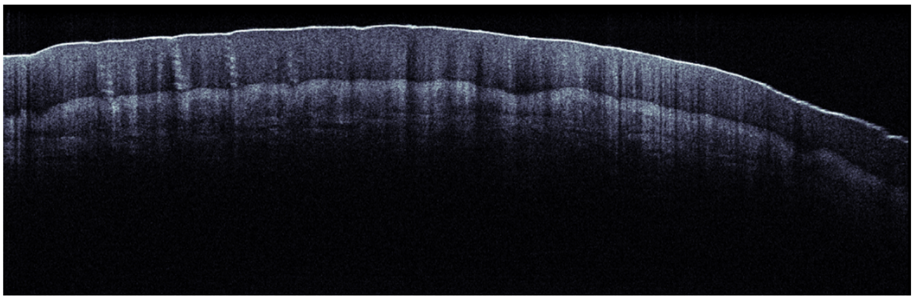

Figure 40 B-Scan of a Fingertip

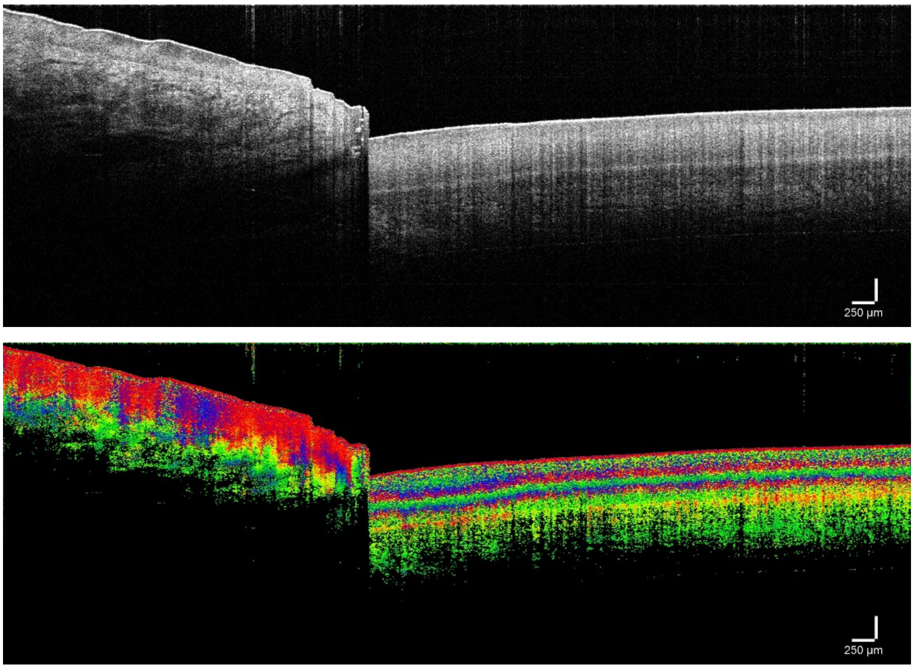

Figure 41 B-Scan of Skin and Nailfold. Top – Intensity-Based OCT image, Bottom – Optic Axis Polarization-Sensitive OCT image

Material Imaging

SD-OCT can also be used for non-biological material science applications. Such systems are ideal for monitoring surface topography and layered structures.

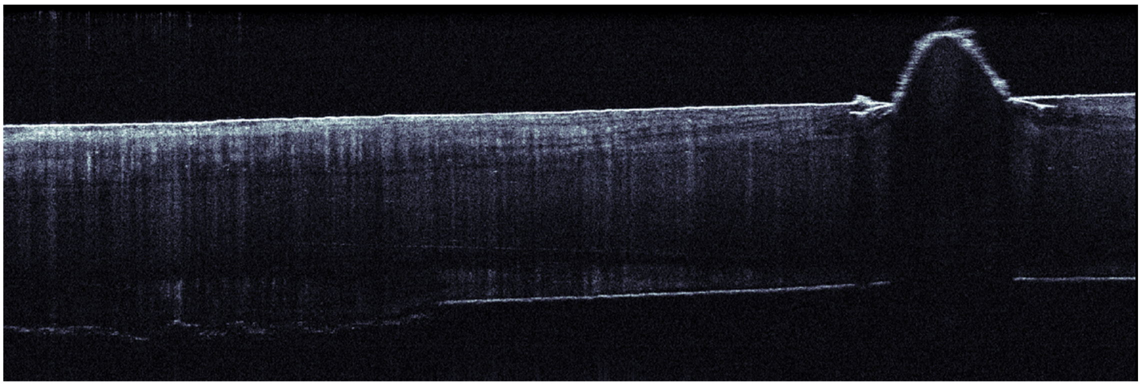

Figure 42 B-Scan of a Semi-Transparent Molded Plastic Cap

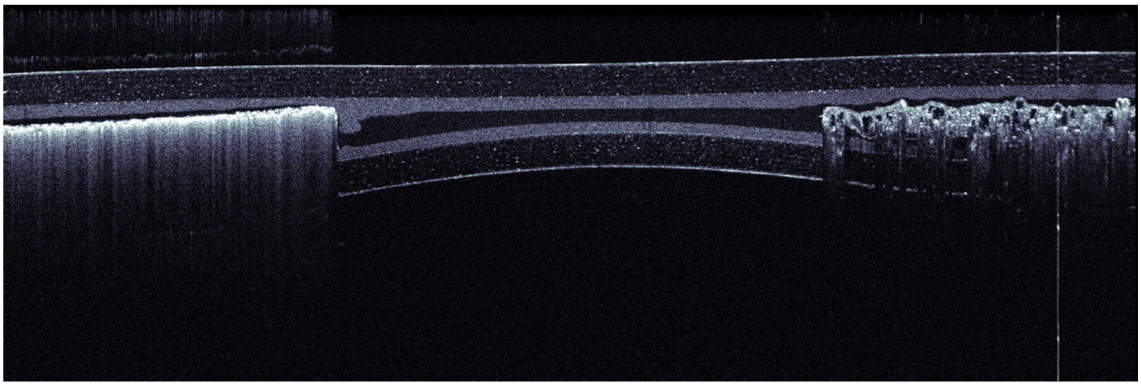

Figure 43 B-Scan of a Laminated IR Card

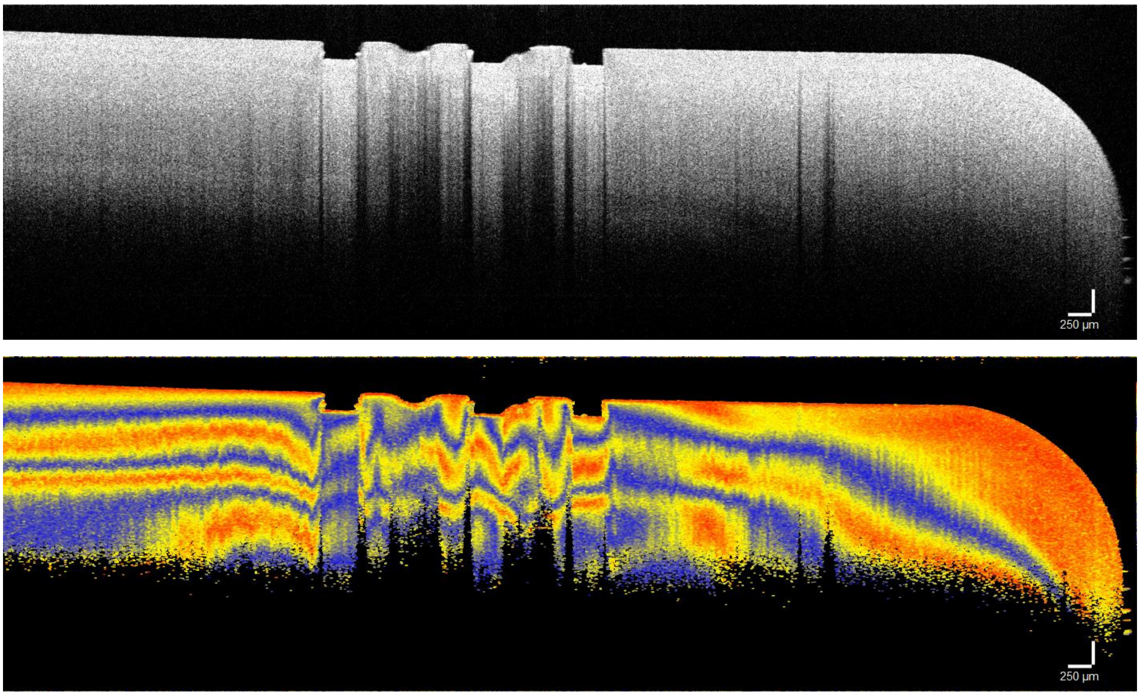

Figure 44 B-Scan of plastic. Top – Intensity-Based OCT Image, Bottom – Retardation Polarization-Sensitive OCT Image

Biological Imaging

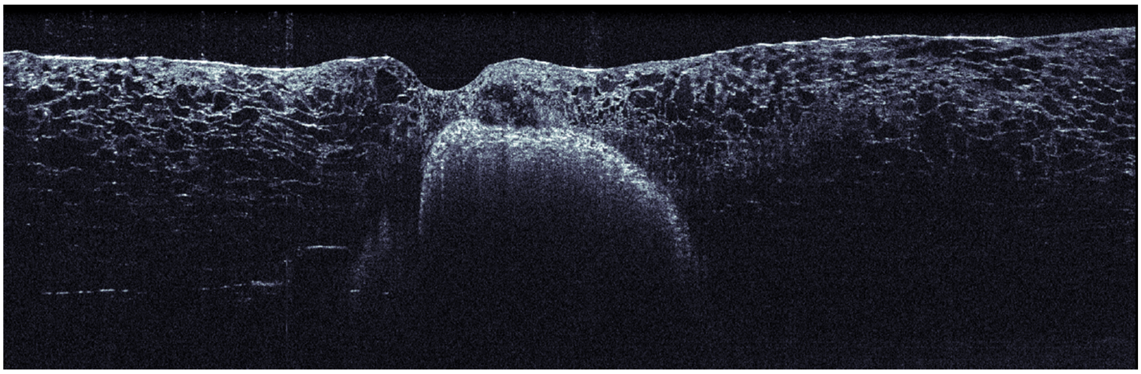

Figure 45 B-Scan of a Section of a Grape

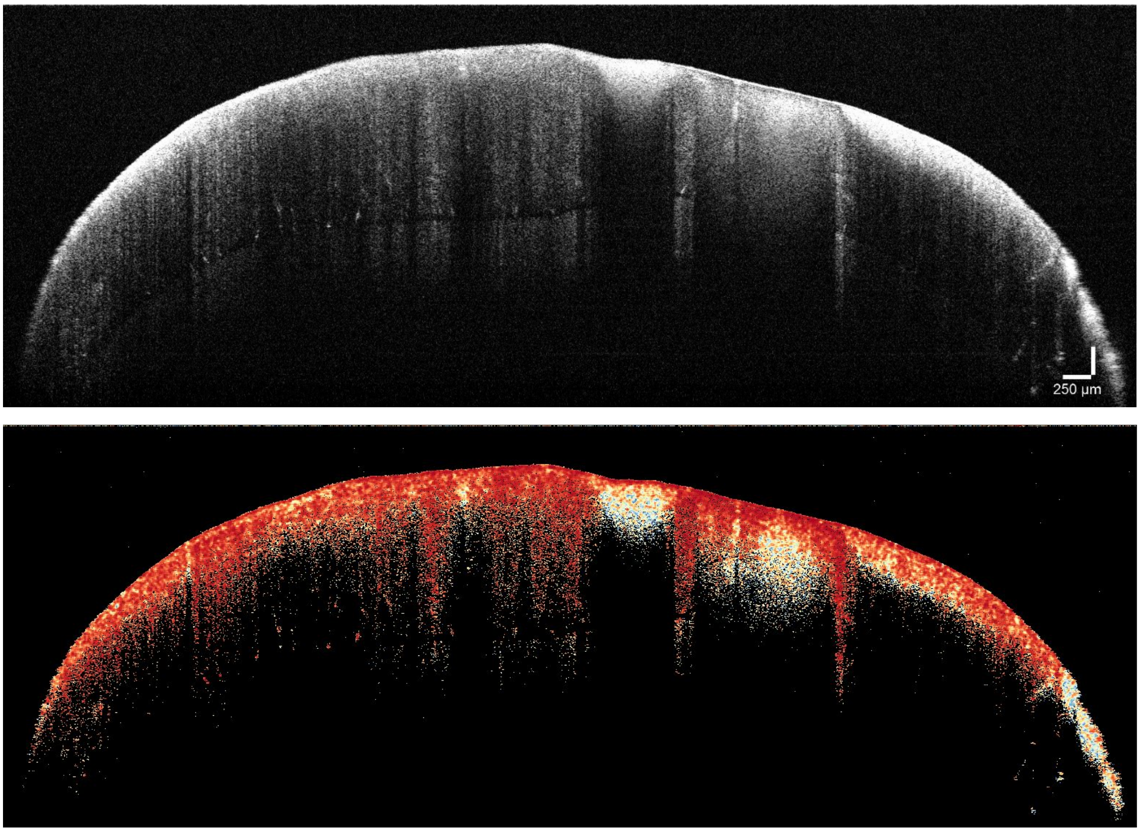

Figure 46 B-Scan of carious tooth. Top – Intensity-Based OCT image, Bottom - Degree Of Polarization Uniformity (DOPU)-Based OCT image

Chapter 5 Imaging Artifacts

5.1. Saturation and Non-Linearity

The OCT A-scan data is created by frequency analysis of the spectral data generated by the spectrometer. Intense reflection from the sample can saturate the sensor of the spectrometer or illuminate very close to saturation. This effect broadens the signal and leads to a nonlinear response. For example, a sinusoidal optical signal is interpreted as partially rectangular. Consequently, additional harmonic frequencies of the root signal appear.

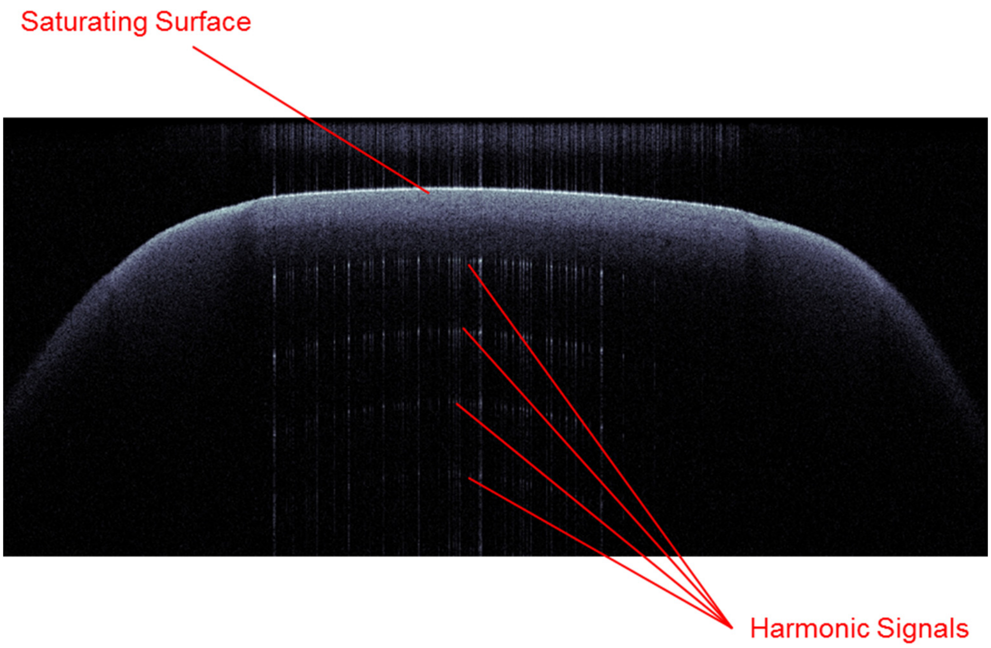

Figure 47 High Surface Reflection Causing Saturation and Nonlinear Response of the Spectrometer

A typical example of this effect is shown in Figure 47. Saturation can be reduced or avoided by:

- Changing focus position
- Tilting the sample with respect to the A-scan axis
- Introduction of a wedge into the optical path (first reflex reflecting outside of NA) and immersion (see Figure 48)

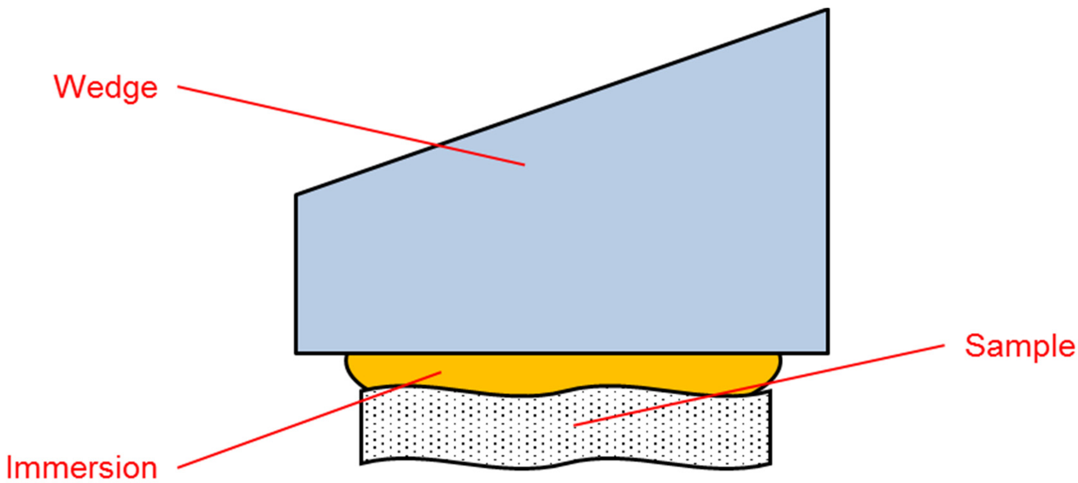

Figure 48 Avoiding Strong Surface Reflection by Use of an Immersed Wedge

When operating with a wedge, the image will be tilted in the direction of the wedge angle. When scanning in the orthogonal direction, no tilt occurs.

5.2. Wrong Reference Intensity Setting

The OCT image is created by interferometry as shown in Figure 17. For good image acquisition, the intensity of the reference light needs to be well above noise level and well below saturation. In the OCT software, a colored bar indicates if the reference intensity is set properly. For adjustment of the reference intensity, please refer to chapter 3.2.4.

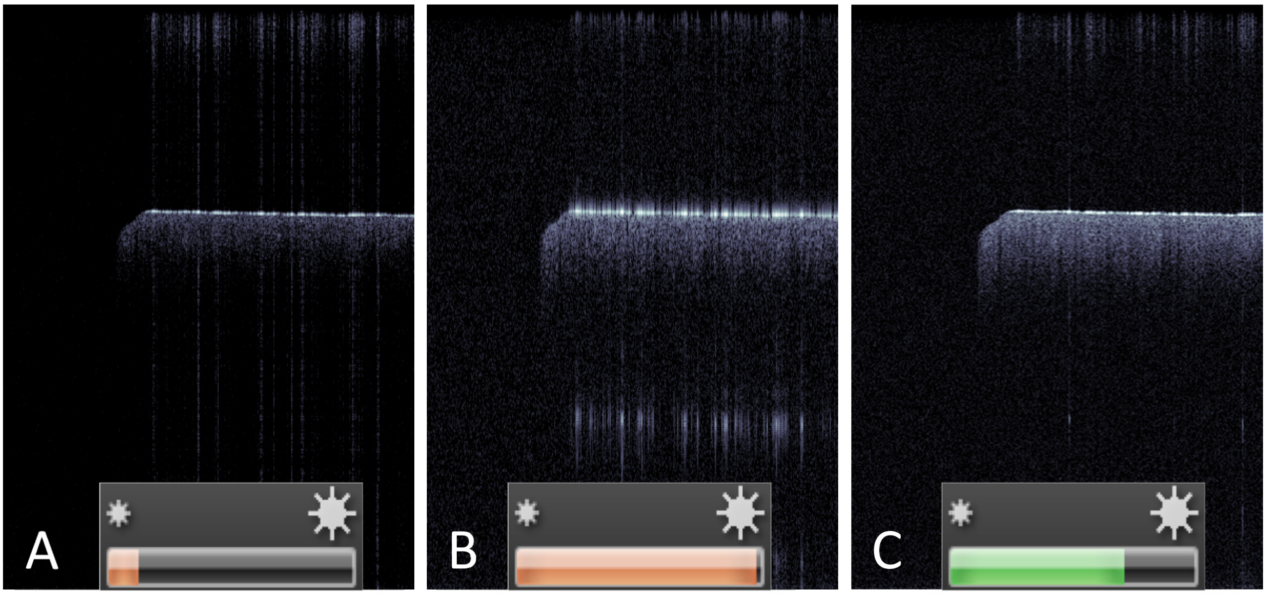

Figure 49 OCT Image Acquired with Low (A), High (B), and Good (C) Reference Intensity Settings

With low reference intensity (see picture Figure 49A), the image becomes very noisy and autocorrelation is strong compared to the signal intended (frequent issue when doing thickness measurement of reflecting films). High reference intensity (see picture Figure 49B), causes saturation and loss of information.

5.3. Autocorrelation

The fundamental principle of SD-OCT is a frequency analysis of an interference signal entering the spectrometer. In the usual case, this interference signal is created by photons returned from the sample interfering with photons returned from the reference arm.

In case a sample has at least one highly reflecting surface, the reflections off this surface can interfere with other photons returned from the sample. The OCT engine cannot distinguish between interference created in respect to the reference arm and interference created within the sample. Figure 50 shows the B-scan of a sample (laminated foils).

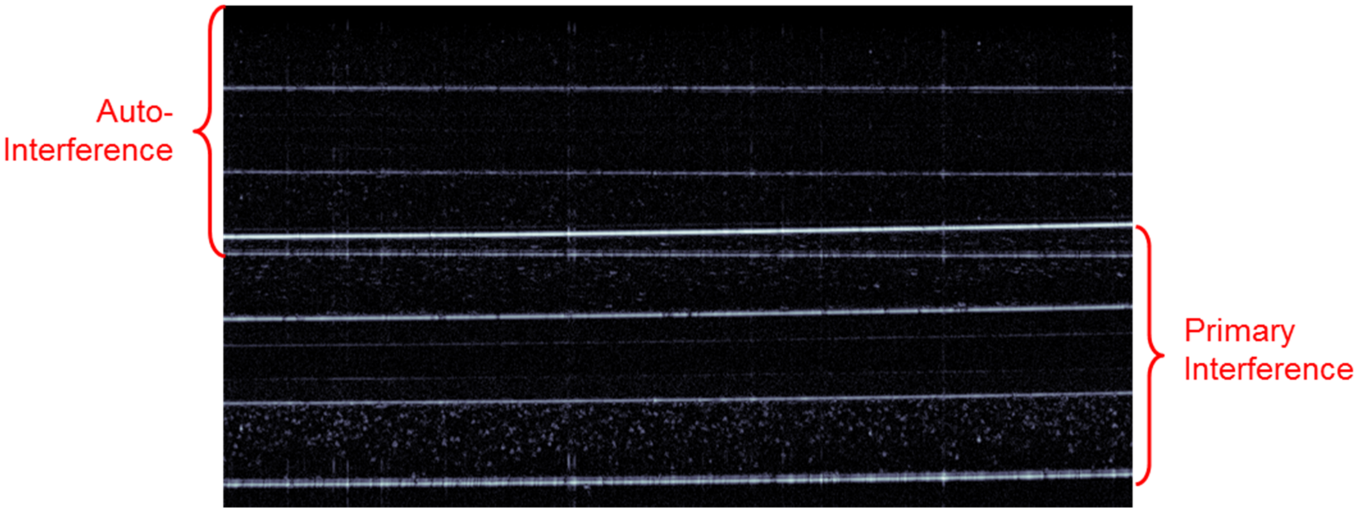

Figure 50 Autocorrelation from a Surface Reflective Sample in a B-Scan

When blocking the reference arm – by turning the reference arm intensity knob counter-clockwise - the signal caused by autocorrelation remains in the B-scan, while the primary interference signal disappears. This is shown in Figure 51.

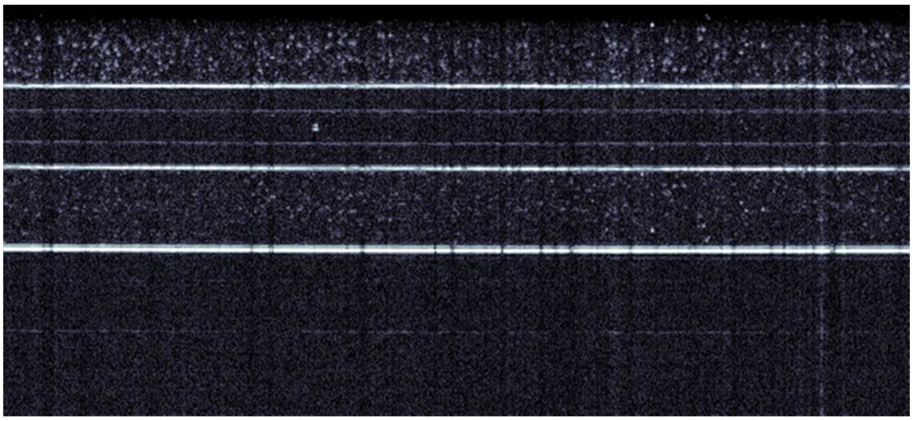

Figure 51 Autocorrelation with the Reference Arm of the Imaging Scanner Blocked

For thickness measurement of foils or related features, the autocorrelation can be a wanted feature. For avoiding this effect, proper index matching (see Figure 48) or tilting of the sample is suggested.

5.4. Multiple Scattering

When imaging highly scattering material, a large portion of the photons returned to the detection system have been scattered multiple times from travelling into the sample until exiting. Since OCT visualizes the relative travelled path lengths of photons, signals from multiple scattered photons are shown deeper in the image than physically present.

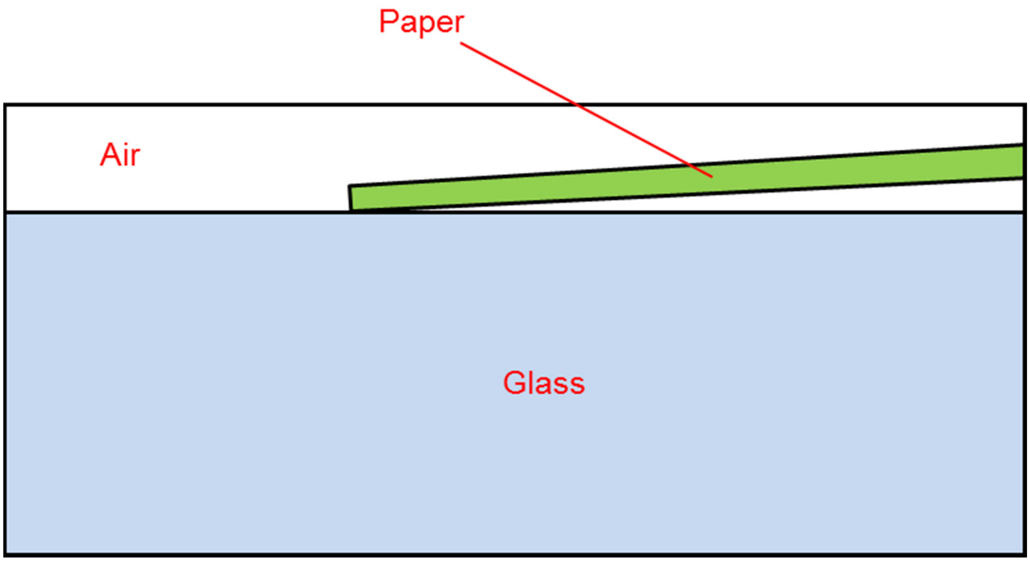

Figure 52 Schematic of a Setup to Show the Influence of Multiple Scattering

Multiple scattering is intense in paper. For illustration of this artifact, a setup as depicted in Figure 52 is imaged. Here, a piece of paper is placed over a glass substrate.

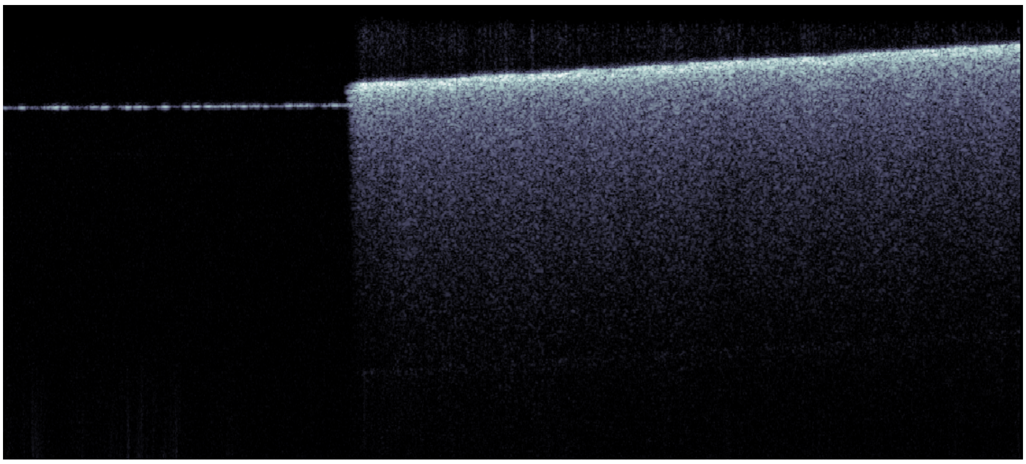

Figure 53 OCT Image Showing Multiple Scattering

In the OCT image (see Figure 53), one can clearly see that the paper appears to be very thick. This apparent thickness is induced by the relatively long travel of photons that are scattered multiple times before finding their way back into the detecting aperture.

5.5. Phase Wrapping and Fringe Washout

The A-scan data created by the SD-OCT system is produced from spectral information of an optical interference. Depending on the system setting, a certain integration time is applied for acquisition of each A-scan. Certain movement of the sample or parts of it can well be detected by comparing the phase information of adjacent A-scans. This Doppler Imaging mode is provided by the OCT Software (please refer to the OCT Software Manual for details). Sample movements of more than ¼ of the detected wavelength λ (from A-scan to A-scan) lead to misleading results. The maximum detectable speed (in direction of the A-scan axis) is

$$v_{\max} = f \cdot \frac{\lambda}{4}$$

For an A-scan rate of f = 1.25 kHz at 930nm, the maximum detectable speed v (in the direction of the A-scan axis) is 290μm/s. When the direction of the movement occurs at an angle with respect to the A-scan axis, faster speeds can be imaged.

For larger movements within the integration time of the detector, a complete washout of the interference will occur.

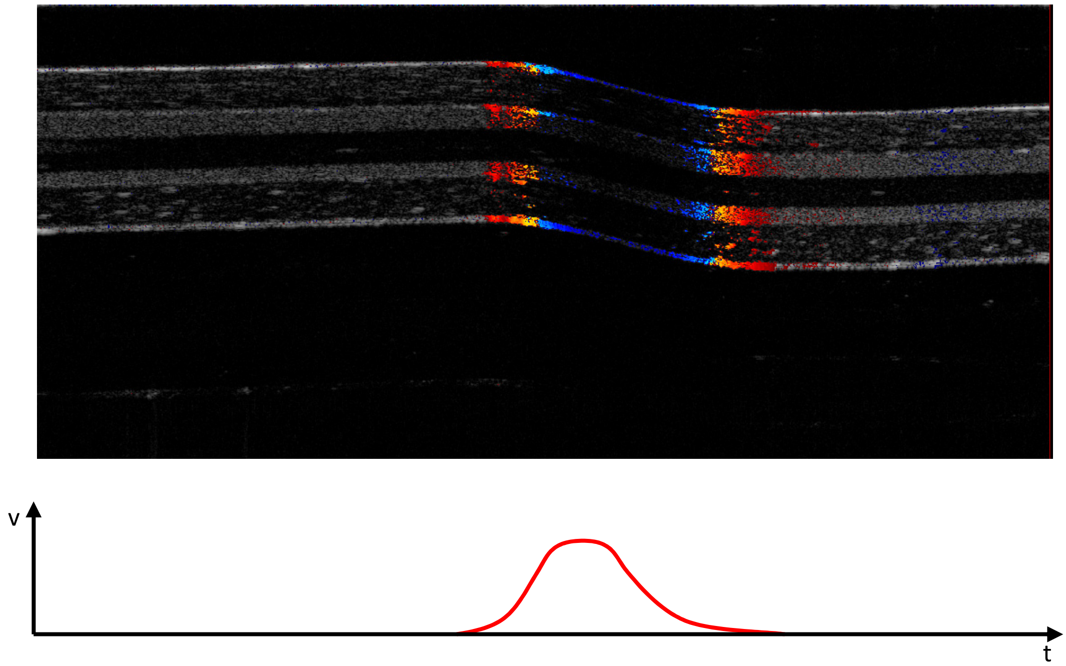

Figure 54 Sample Image Showing Fringe Washout and Phase Wrapping

To illustrate these effects, a sample has been moved quickly while slowly acquiring a B-scan. Figure 54 shows the result. The intensity data is shown in black and white, while the Doppler information is displayed red to blue. When the movement starts, the Doppler information is displayed red, which means that the sample moves down. Now at increasing speed, the Doppler information turns blue. This means that the phases of the signal have wrapped and an inverse speed is shown. In the middle of the movement where the speed is at its maximum, almost no OCT data is displayed (fringe washout).

5.6. Flipped Image

Without the introduction of additional techniques not provided by the standard SD-OCT system, there is no distinguishing between photons that traveled a distance Δd shorter or longer from the beam splitter to the sample compared to the reference arm length. When adjusting the reference length to be too long, the image appears flipped.

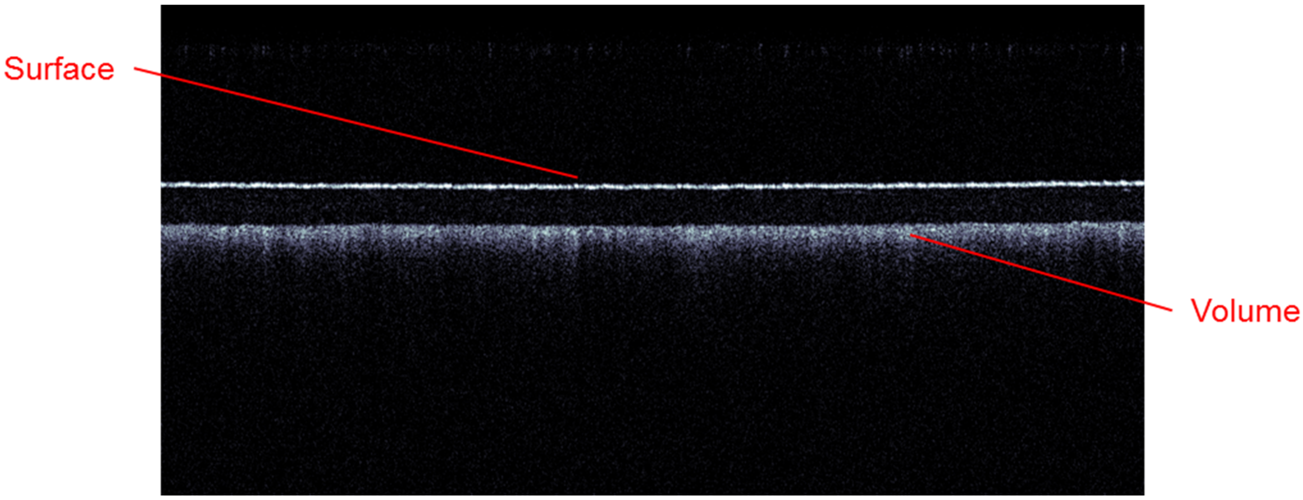

Figure 55 Right Orientation Up Reference Length Adjustment for Imaging of an IR Viewing Card

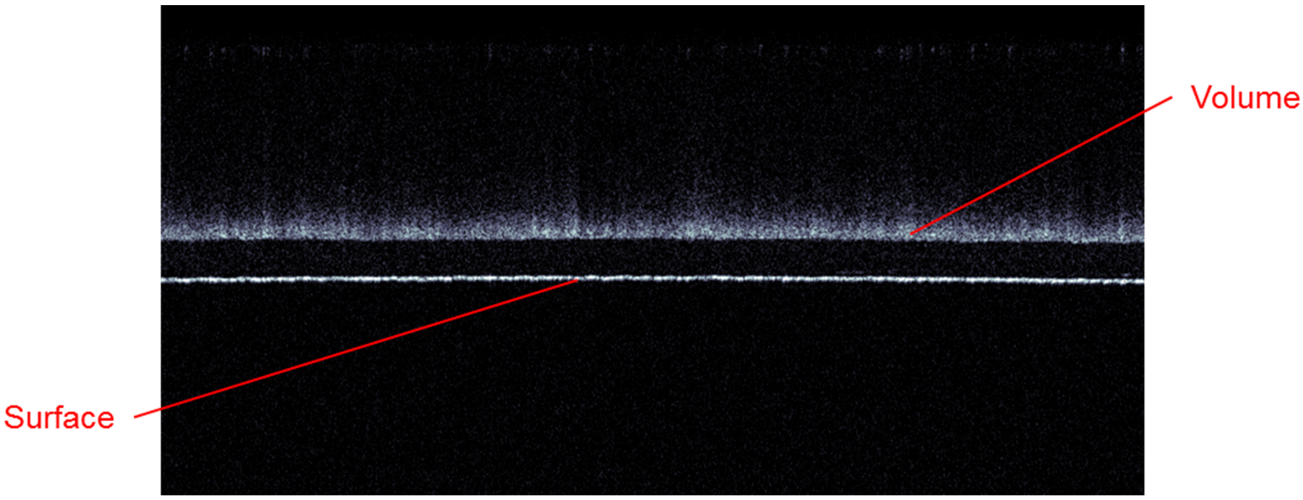

Figure 56 Upside Down Reference Length Adjustment Showing a Flipped Image

Figure 55 and Figure 56 show the different adjustments of the reference length when imaging the IR viewing card provided with the system.

5.7. Shadowing

Since the SD-OCT imaging uses light for detection of depth information, one can only see information from regions in the sample, where photons are transmitted to and allowed back into the sampling aperture. Reflections, strong scattering and absorption lead to shadows in the depth distribution of the data acquired.

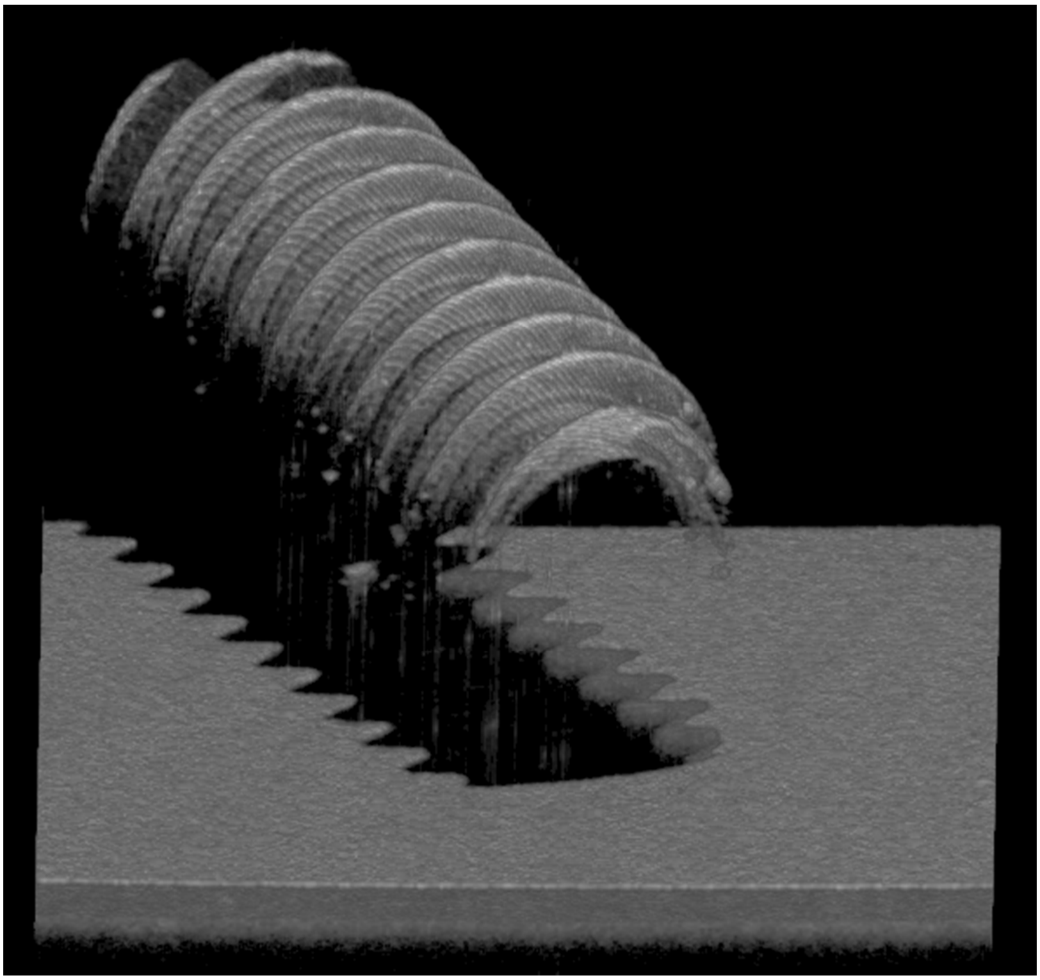

Figure 57 Rendered Volume of a Screw on an IR Viewing Card Displaying the Shadowing Effect

5.8. Image Distortion by Refractive Media

OCT images display path length differences in between reference arm length and sample arm length (distance from the beam splitter to the scattering or reflecting object). These path lengths are optical path lengths, calculated from the physical path length multiplied by the group refractive index.

In the images below a schematic sample setup and the resulting OCT image are shown.

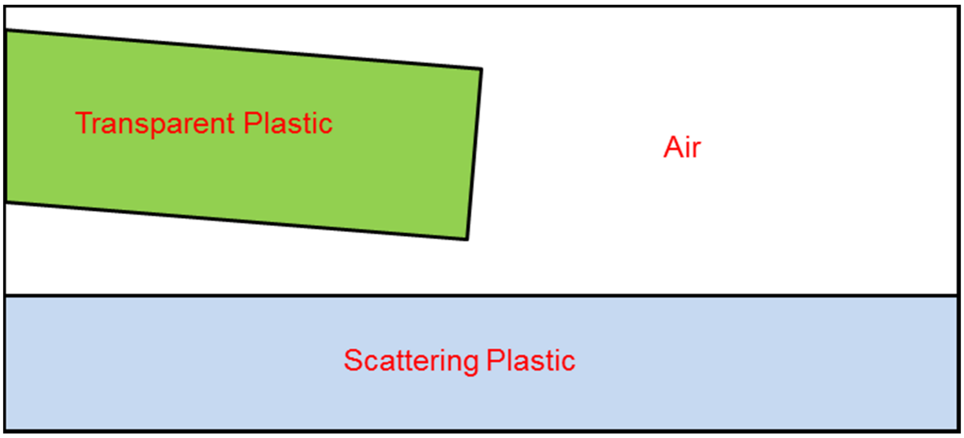

Figure 58 Schematic of a Setup to Show Distorsion from Refracting Media

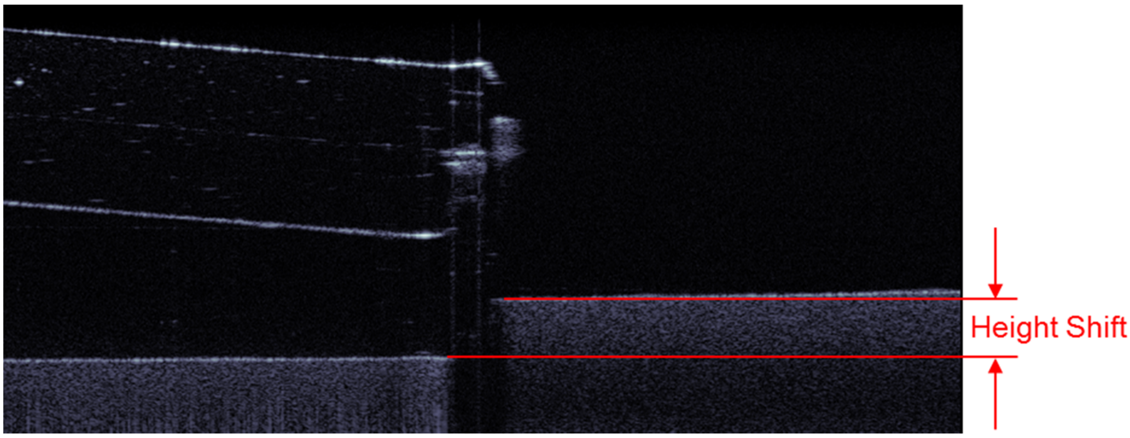

Figure 59 Height Shift of OCT Image Through Refractive Media

5.8.1. The Group Refraction Index

The principle of optical coherence tomography is the detection of optical path length differences between the two arms of an interferometer. The optical paths within these arms are defined by the mechanical path lengths and the refractive indices of the materials.

When talking about the refractive index of an optical material, it most of the time refers to the phase velocity index. As the name indicates this is a factor for the velocity of the phase when travelling through the material in relation to the vacuum speed of light. The standard abbreviation of the phase refractive index is n .

The group velocity of a wave is the velocity with which the overall shape of the wave's amplitudes — known as the modulation or envelope of the wave — propagates through space. This velocity usually is different from the speed of the phases of the single wavelengths. This velocity is calculated by using the group refractive index n_g of a material.

The relation of these two values is: $n_g = n - \lambda_0 \frac{dn}{d\lambda_0}$

In OCT systems the group refractive index defines the optical path lengths.
In the table below some materials and their phase refractive indices n_p as well as their group refractive indices n_g are given.

Material	λ = 900nm		λ = 1050nm		λ = 1310nm	
	n_p	n_g	n_p	n_g	n_p	n_g
Water 24°C	1.327	1.340	1.324	1.340	1.320	1.343
Water 37.6°C	1.324	1.341	1.321	1.339	1.316	1.339
Quartz	1.452	1.465	1.450	1.463	1.447	1.462
N-BK7	1.510	1.523	1.507	1.521	1.504	1.519
N-LAK22	1.640	1.659	1.638	1.655	1.634	1.651
N-SF11	1.760	1.798	1.754	1.786	1.748	1.775
N-SF57	1.818	1.861	1.812	1.847	1.805	1.834

In vacuum, the values for n_p as well as for n_g are 1 for all wavelengths. The difference for the performance in air is negligible for most instances.

5.8.2. Measurement Depth in OCT Systems

The spectral resolution of a frequency domain OCT system defines its possible measurement depth. This depth is the maximum detectable optical path length difference limited by the Nyquist criteria. In real materials the measurement depth of OCT systems as well as the axial resolution is reduced. The reduction of the resolution depends on the material properties between the two measured interface signals used. The reduction of the imaging depth is a result of the materials in the sample image as visualized in the graphic below:

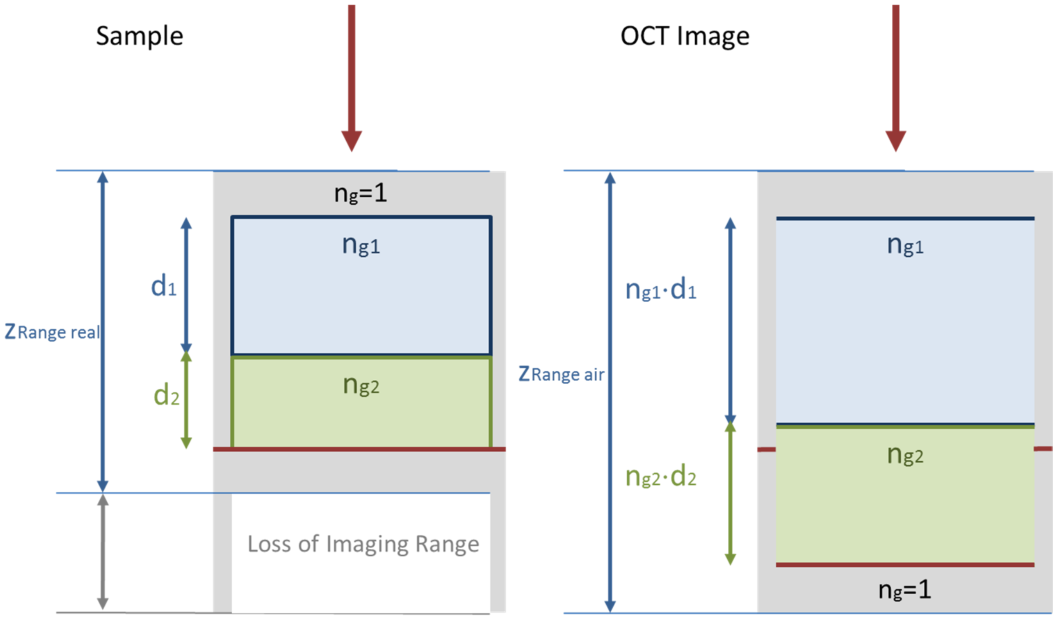

Figure 60 Measurement Depth With Refractive Media

In the image, the incoming beam from above is scanned over a structure made of two different materials named one (d_1, n_{g1}) and two (d_2, n_{g2}) stacked on a flat surface (red line). The imaging range is displayed as a light grey area. Vertical structures are barely visible.

The materials are displayed in the OCT image with an axial dimension corresponding to the optical path lengths.

In most cases, the sample is not well known. The measurement depth in air (vacuum) is known and the optical path lengths of the materials are obtained. The material properties (e.g. group refractive indices) must also be known in order to determine the real physical thickness of the materials.

The loss of imaging depth depends on the thickness and the group refractive indices of the materials displayed within the image. It is calculated as follows:

$$loss = \sum_i (n_{gi} - 1) d_i$$

5.8.3. Distortions in the Image

In complex structures, distortions occur in the OCT image which require a close look to be understood.

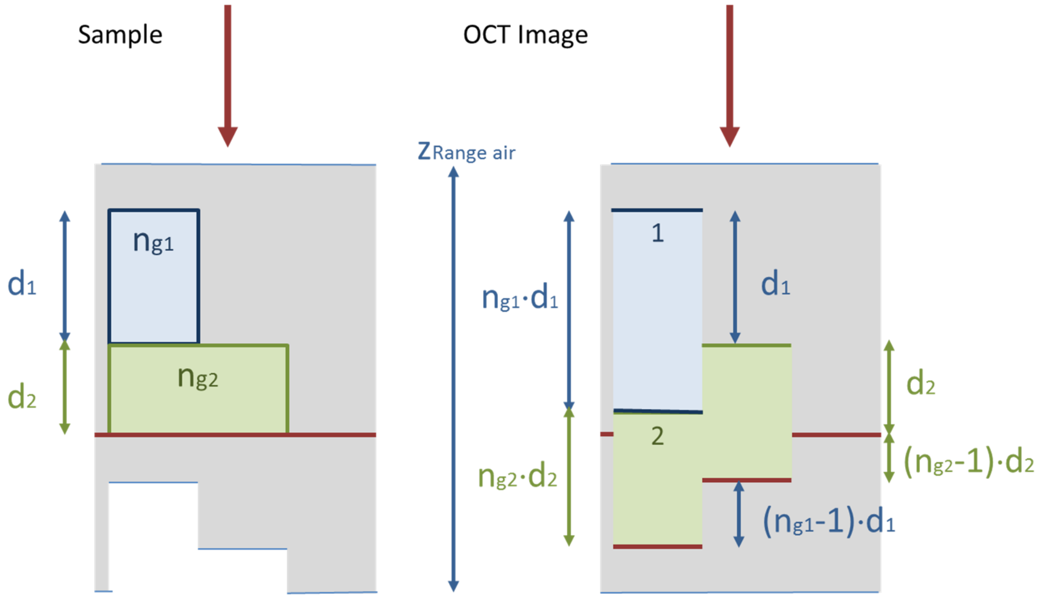

Figure 61 Different Materials in One Measurement

The loss of imaging depth depends on the amount of material through which the beam passes. As a result the measured depth in the sample changes throughout the scan.

In the setup shown in Figure 61, one can determine the properties of the materials assuming the underlying surface to be flat and horizontal in the image. In the OCT image on the right, the physical thicknesses d_i, optical path lengths $n_{gi} d_i$, as well as the resulting shifts of underlying structures $(n_{gi} - 1) d_i$ can be determined directly.

The real imaging areas are displayed in the graphic for real sample dimensions on the left.
When the physical structure becomes more complex, the resulting OCT image becomes more difficult to interpret.

Especially when the surface is not horizontal or curved, effects like shadowing, diffraction on interfaces, and multiple measured structures may occur in addition to the changes in optical path length.

As an example, a material with wedge is analyzed:

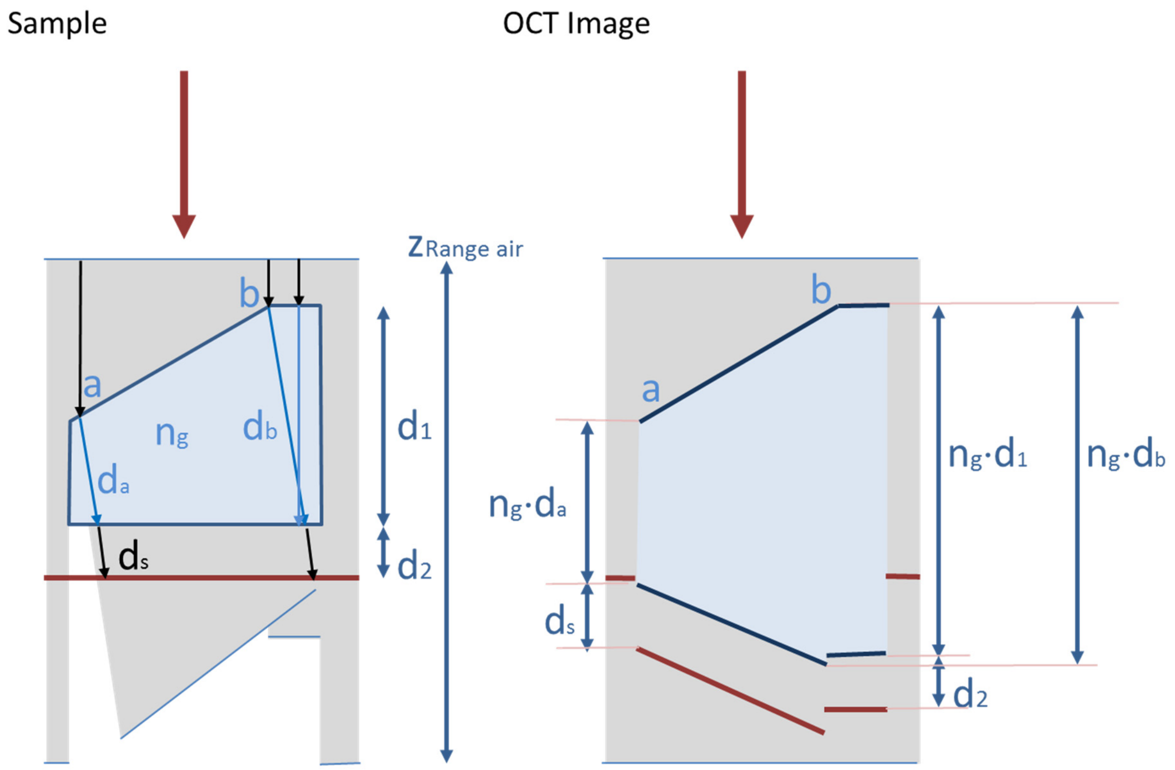

Figure 62 Complex Structure in Image

The block shows "standard" behavior on the right side where the surface is perpendicular to the incoming beam.

In the chamfered area there is diffraction and the beam travels under an angle through the block. The real angled physical path is enlarged a little (d_a and d_b), and d_s is not in-line with d_a.

These paths are displayed strictly vertical in the OCT image showing the expected optical path lengths $n_{gi} d_i$. The beam is displayed without rotation.

This difference between the real diffracted optical path and the displayed OCT image makes it difficult to perform an inverse ray tracing because all the diffractive interfaces need to be determined in 3D.
Even this determination needs to be undertaken step after step since the first interface affects the OCT image of the second interface and so on.

The most challenging part is the light grey area in the sample marking the imaged field. In the left edge of the chamfered block there is an area which is not reached by OCT light and therefore cannot be visualized at all. On the other hand there are structures that are measured twice because of the two different optical paths leading to these structures.

In very complex structures these effects become more and more difficult to handle – Just assume spherical or curved interfaces, bubbles, inhomogeneous materials, possible imaging aberrations in the sample etc.

Chapter 6 Troubleshooting

Symptom	Possible Cause	Solution
System Does Not Start	No power is supplied to the unit	Connect the power supply
	Power cord is broken	Change power cord
	Other reason	Call Thorlabs[1]
System Does Not Make Measurements	PC crashed	Restart PC
	Poor connection of USB cable	Check USB connection
	Data acquisition cable not inserted	Connect data acquisition cable
	Optical path length not matched	Adjust optical path length
	Beam is blocked	Clean fiber tip
	Other reason	Call Thorlabs[1]
No Signal in Image	Fiber not connected	Connect fiber patch cable
	Fiber tip is dirty	Clean fiber tip
	Scanner not connected	Connect Scanner
	Focus is out of imaging area	Adjust reference length, readjust focus
	Reference intensity too high or too low	Adjust reference intensity knob
	Other reason	Call Thorlabs[1]
Bad Image Quality	Under sampled, mirrored image shown	Observe the OCT image while adjusting the distance of the scanner to the sample
	Distance to the sample is too short	When decreasing the distance, the image needs to move towards the top of the OCT image
	Reference intensity too high or too low	Adjust reference intensity knob
	Other reason	Call Thorlabs[1]
Flipped Image	Reference length set incorrectly	Adjust reference length

Table 3 Troubleshooting

[1] *Please refer to Chapter 12 for Thorlabs contact information.*

6.1. Changing the Input Fuses

If for some reason you need to replace an open fuse in the base unit, you must perform the following procedure:

- Remove the AC input cable that may be connected to the unit.
- Slide open the cover of the fuse holder located at the rear panel of the base unit as shown in Figure 23.
- Remove the broken fuse(s) and install the appropriate replacement fuse(s) for the base unit. Use only IS 1 A 250 VAC Type T 5x20 mm style fuses (IEC 60127-2/III, low breaking capacity, slow blow).
- Slide the fuse cover closed.

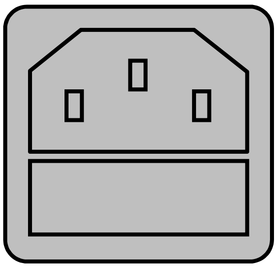

Figure 63 Fuse Cover on Base Unit Rear Panel

Chapter 7 Certifications and Compliance

7.1. Declaration of Conformity GAN2x0 Series Base Units

THORLABS
www.thorlabs.com

EU Declaration of Conformity

in accordance with EN ISO 17050-1:2010

We: Thorlabs GmbH

Of: Hans-Boeckler-Str. 6, 85221 Dachau/München, Deutschland

in accordance with the following Directive(s):

2014/35/EU	Low Voltage Directive (LVD)
2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS)

hereby declare that:

Model: ***GAN2x0***

Equipment: ***GAN200-Series OCT Base Unit***

is in conformity with the applicable requirements of the following documents:

EN 61010-1	Safety Requirements for Electrical Equipment for Measurement, Control and Laboratory Use.	2010
EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requirements	2013
EN 60825-1	Safety of laser products	2014

and which, issued under the sole responsibility of Thorlabs, is in conformity with Directive 2011/65/EU of the European Parliament and of the Council of 8th June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, for the reason stated below:

does not contain substances in excess of the maximum concentration values tolerated by weight in homogenous materials as listed in Annex II of the Directive

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications, and complies with all applicable Essential Requirements of the Directives.

Signed: *On:* 15 February 2017

CE 17

Name: Dorothee Jennrich

Position: General Manager

EDC - GAN2x0 -2017-02-15

7.2. Declaration of Conformity GAN6x0 Series Base Units

THORLABS
www.thorlabs.com

EU Declaration of Conformity

in accordance with EN ISO 17050-1:2010

We: Thorlabs GmbH

Of: Hans-Boeckler-Str. 6, 85221 Dachau/München, Deutschland

in accordance with the following Directive(s):

2014/35/EU	Low Voltage Directive (LVD)
2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS)

hereby declare that:

Model: ***GAN6x0***

Equipment: ***GAN600-Series OCT Base Unit***

is in conformity with the applicable requirements of the following documents:

EN 61010-1	Safety Requirements for Electrical Equipment for Measurement, Control and Laboratory Use.	2010
EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requirements	2013
EN 60825-1	Safety of laser products	2014

and which, issued under the sole responsibility of Thorlabs, is in conformity with Directive 2011/65/EU of the European Parliament and of the Council of 8th June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, for the reason stated below:

does not contain substances in excess of the maximum concentration values tolerated by weight in homogenous materials as listed in Annex II of the Directive

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications, and complies with all applicable Essential Requirements of the Directives.

Signed: *On:* 28 June 2018

Name: Bruno Gross

Position: General Manager

EDC - GAN6x0 -2018-06-28

CE

7.3. Declaration of Conformity TEL2x0 Series Base Units

THORLABS
www.thorlabs.com

EU Declaration of Conformity

in accordance with EN ISO 17050-1:2010

We: Thorlabs GmbH

Of: Hans-Boeckler-Str. 6, 85221 Dachau/München, Deutschland

in accordance with the following Directive(s):

2014/35/EU	Low Voltage Directive (LVD)
2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS)

hereby declare that:

Model: ***TEL2x0***

Equipment: ***TEL200-Series OCT Base Unit***

is in conformity with the applicable requirements of the following documents:

EN 61010-1	Safety Requirements for Electrical Equipment for Measurement, Control and Laboratory Use.	2010
EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requirements	2013
EN 60825-1	Safety of laser products	2014

and which, issued under the sole responsibility of Thorlabs, is in conformity with Directive 2011/65/EU of the European Parliament and of the Council of 8th June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, for the reason stated below:

does not contain substances in excess of the maximum concentration values tolerated by weight in homogenous materials as listed in Annex II of the Directive

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications, and complies with all applicable Essential Requirements of the Directives.

Signed: D. Jennrich *On:* 15 February 2017

Name: Dorothee Jennrich

Position: General Manager

EDC - TEL2x0 -2017-02-15

CE 17

7.4. Declaration of Conformity TEL2x0PS Series Base Units

THORLABS
www.thorlabs.com

EU Declaration of Conformity

in accordance with EN ISO 17050-1:2010

We: Thorlabs GmbH

Of: Hans-Boeckler-Str. 6, 85221 Dachau/München, Deutschland

in accordance with the following Directive(s):

2014/35/EU	Low Voltage Directive (LVD)
2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS)

hereby declare that:

Model: ***TEL2x0PS***

Equipment: ***TEL200PS-Series OCT Base Unit***

is in conformity with the applicable requirements of the following documents:

EN 61010-1	Safety Requirements for Electrical Equipment for Measurement, Control and Laboratory Use.	2010
EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requirements	2013
EN 60825-1	Safety of laser products	2014

and which, issued under the sole responsibility of Thorlabs, is in conformity with Directive 2011/65/EU of the European Parliament and of the Council of 8th June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, for the reason stated below:

does not contain substances in excess of the maximum concentration values tolerated by weight in homogenous materials as listed in Annex II of the Directive

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications, and complies with all applicable Essential Requirements of the Directives.

Signed: *On:* 27 September 2018

Name: Bruno Gross

Position: General Manager

CE

EDC - TEL2x0PS -2018-09-27

7.5. Declaration of Conformity TEL3x0 Series Base Units

THORLABS
www.thorlabs.com

EU Declaration of Conformity

in accordance with EN ISO 17050-1:2010

We: Thorlabs GmbH

Of: Hans-Boeckler-Str. 6, 85221 Dachau/München, Deutschland

in accordance with the following Directive(s):

2014/35/EU	Low Voltage Directive (LVD)
2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS)

hereby declare that:

Model: ***TEL3x0***

Equipment: ***TEL300-Series OCT Base Unit***

is in conformity with the applicable requirements of the following documents:

EN 61010-1	Safety Requirements for Electrical Equipment for Measurement, Control and Laboratory Use.	2010
EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requirements	2013
EN 60825-1	Safety of laser products	2014

and which, issued under the sole responsibility of Thorlabs, is in conformity with Directive 2011/65/EU of the European Parliament and of the Council of 8th June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, for the reason stated below:

does not contain substances in excess of the maximum concentration values tolerated by weight in homogenous materials as listed in Annex II of the Directive

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications, and complies with all applicable Essential Requirements of the Directives.

Signed: *On:* 15 February 2017

Name: Dorothee Jennrich

Position: General Manager

EDC - TEL3x0 -2017-02-15

CE 17

7.6. Declaration of Conformity CAL1x0 Series Base Units

THORLABS
www.thorlabs.com

EU Declaration of Conformity

in accordance with EN ISO 17050-1:2010

We: Thorlabs GmbH

Of: Hans-Boeckler-Str. 6, 85221 Dachau/München, Deutschland

in accordance with the following Directive(s):

2014/35/EU	Low Voltage Directive (LVD)
2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS)

hereby declare that:

Model: ***CAL1x0***

Equipment: ***CAL100-Series OCT Base Unit***

is in conformity with the applicable requirements of the following documents:

EN 61010-1	Safety Requirements for Electrical Equipment for Measurement, Control and Laboratory Use.	2010
EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requirements	2013
EN 60825-1	Safety of laser products	2014

and which, issued under the sole responsibility of Thorlabs, is in conformity with Directive 2011/65/EU of the European Parliament and of the Council of 8th June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, for the reason stated below:

does not contain substances in excess of the maximum concentration values tolerated by weight in homogenous materials as listed in Annex II of the Directive

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications, and complies with all applicable Essential Requirements of the Directives.

Signed: D. Jennrich *On:* 14 February 2017

Name: Dorothee Jennrich

Position: General Manager

EDC - CAL1x0 -2017-02-14

CE 17

Chapter 8 Warranty

8.1. Lasers and Imaging Systems

Thorlabs offers a one year warranty on all lasers and imaging systems, with the exceptions of laser diodes.

8.2. Non-Warranty Repairs

Products returned for repair that are not covered under warranty will incur a standard repair charge in addition to all shipping expenses. This repair charge will be quoted to the customer before the work is performed.

8.3. Warranty Exclusions

The stated warranty does not apply to products which are (a) specials, modifications, or customized items (including custom patch cables) meeting the specifications you provide; (b) ESD sensitive items whose static protection packaging has been opened; (c) items repaired, modified, or altered by any party other than Thorlabs; (d) items used in conjunction with equipment not provided by or acknowledged as compatible by Thorlabs; (e) subjected to unusual physical, thermal, or electrical stress; (f) damaged due to improper installation, misuse, abuse, or storage; (g) damaged due to accident or negligence in use, storage, transportation, or handling.

Chapter 9 Specifications

General Performance Specifications – SD-OCT Base Unit	
Supply Voltage for Base Unit*	100 V – 240 V / AC
Maximum Power Consumption	150 W
Weight Base Unit	12.5 kg
Storage/Operating Temperature	10 °C to 35 °C
Dimensions of OCT-STAND (L x W x H)	206 mm x 305 mm x 248 mm
Dimensions of Base Unit (L x W x H)	420 mm x 320 mm x 149 mm
Airborne Noise Emission	< 70 dB$_A$

Table 4 General Specifications

*base unit has universal AC input

Optical Performance Specifications – TELESTO-Series Base Unit						
Base Unit	**TEL210**	**TEL210PS**	**TEL220**	**TEL220PS**	**TEL310**	**TEL320**
Central Wavelength	1325 nm		1300 nm		1325 nm	1300 nm
Axial Scan Rate	5.5 kHz to 76 kHz				10 kHz to 146 kHz	
Max Imaging Depth Air/Water (typical)	7.0 / 5.3 mm		3.5 / 2.6 mm		7.0 / 5.3 mm	3.5 / 2.6 mm
Axial Resolution Air/Water (typical)	12 / 9.0 µm		5.5 / 4.2 µm		12 / 9.0 µm	5.5 / 4.2 µm
Lateral Resolution at Focus with OCT Scan Lens Kit	20.0 µm (OCT-LK4)		13.0 µm (OCT-LK3)		20.0 µm (OCT-LK4)	13.0 µm (OCT-LK3)
Sensitivity	96 – 111 dB (76 - 5.5 kHz)	94 – 109 dB (76 - 5.5 kHz)	96 – 111 dB (76 - 5.5 kHz)	94 – 109 dB (76 - 5.5 kHz)	93 – 109 dB (146 – 10 kHz)	93 – 109 dB (146 – 10 kHz)

Table 5 TELESTO-Series Specifications

Optical Performance Specifications – Ganymede 200 and 600 Series Base Unit				
Base Unit	**GAN210**	**GAN220**	**GAN610**	**GAN620**
Central Wavelength	930 nm	900 nm	930 nm	900 nm
Axial Scan Rate	5.5 kHz to 36 kHz		5 kHz to 248 kHz	
Maximum Imaging Depth Air/Water (typical)	2.9 mm / 2.2 mm	1.9 mm / 1.4 mm	2.7 mm / 2.0 mm	1.9 mm / 1.4 mm
Axial Resolution Air/Water (typical)	6.0 µm / 4.5 µm	3.0 µm / 2.2 µm	6.0 µm / 4.5 µm	3.0 µm / 2.2 µm
Lateral Resolution at Focus with OCT Scan Lens Kit	8.0 µm (OCT-LK3-BB)	4.0 µm (OCT-LK2-BB)	8.0 µm (OCT-LK3-BB)	4.0 µm (OCT-LK2-BB)
Sensitivity	93 dB – 101 dB (36 kHz - 5.5 kHz)	93 dB – 101 dB (36 kHz - 5.5 kHz)	84 dB – 102 dB (248 kHz - 5 kHz)	84 dB – 102 dB (248 kHz - 5 kHz)

Table 6 Ganymede Series Specifications

Optical Performance Specifications – Callisto Series Base Unit	
Base Unit	**CAL110**
Central Wavelength	930 nm
Axial Scan Rate	1.2 KHz
Maximum Imaging Depth Air/Water (typical)	1.7 mm / 1.3 mm
Axial Resolution Air/Water (typical)	7.0 µm / 5.3 µm
Lateral Resolution at Focus with OCT Scan Lens Kit	8.0 µm (OCT-LK3-BB)
Sensitivity	107 dB

Table 7 Callisto Series Specifications

Some specifications depend on the actual type of accessory used. (Selection Preferred Systems)

Chapter 10 Mechanical Drawings

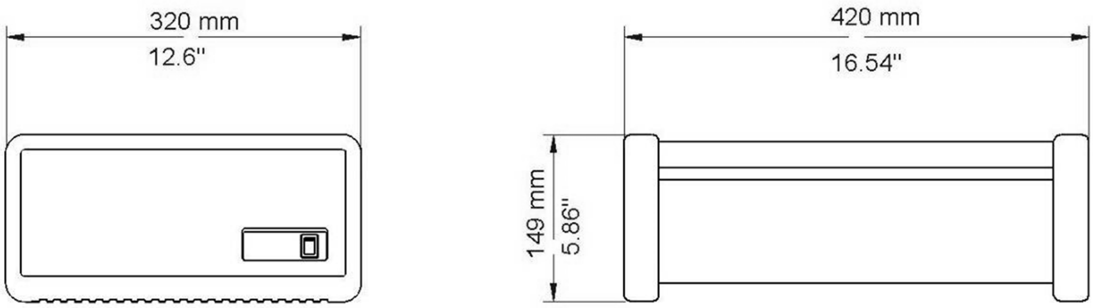

Figure 64 Base Unit Dimensions

Chapter 11 Regulatory

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return "end of life" units without incurring disposal charges.

- This offer is valid for Thorlabs electrical and electronic equipment:
- Sold after August 13, 2005
- Marked correspondingly with the crossed out "wheelie bin" logo (see right)
- Sold to a company or institute within the EC
- Currently owned by a company or institute within the EC
- Still complete, not disassembled and not contaminated

Wheelie Bin Logo

As the WEEE directive applies to self-contained operational electrical and electronic products, this end of life take back service does not refer to other Thorlabs products, such as:

- Pure OEM products, that means assemblies to be built into a unit by the user (e. g. OEM laser driver cards)
- Components
- Mechanics and optics
- Left over parts of units disassembled by the user (PCB's, housings etc.).

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

11.1. Waste Treatment is Your Own Responsibility

If you do not return an "end of life" unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

11.2. Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS directive is to reduce the content of toxic substances in electronic products in the future.

The intent of the WEEE directive is to enforce the recycling of WEEE. A controlled recycling of end of life products will thereby avoid negative impacts on the environment.

Chapter 12 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at www.thorlabs.com/contact for our most up-to-date contact information.

USA, Canada, and South America
Thorlabs, Inc.
sales@thorlabs.com
techsupport@thorlabs.com

Europe
Thorlabs GmbH
europe@thorlabs.com

France
Thorlabs SAS
sales.fr@thorlabs.com

Japan
Thorlabs Japan, Inc.
sales@thorlabs.jp

UK and Ireland
Thorlabs Ltd.
sales.uk@thorlabs.com
techsupport.uk@thorlabs.com

Scandinavia
Thorlabs Sweden AB
scandinavia@thorlabs.com

Brazil
Thorlabs Vendas de Fotônicos Ltda.
brasil@thorlabs.com

China
Thorlabs China
chinasales@thorlabs.com

THORLABS
www.thorlabs.com