Analysis of the signal fall-off in spectral domain optical coherence tomography systems

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ABSTRACT

The influence of the individual spectrometer components on the depth dependent sensitivity fall-off (roll-off) in spectral-domain optical coherence tomography (SD-OCT) is investigated. We present a method for the characterization of the roll-off in SD-OCT systems via modulation transfer function (MTF) analysis. The MTF of different image sensors was measured in a newly developed setup, which uses the interference of two coherent light beams. Different contributions, i.e. diffraction, aberrations and sampling effects, to the MTF of a spectrometer of commercially available SD-OCT systems is calculated and is compared with roll-off measurements. The difference was below $-2\,dB$ at 90 % of the maximum measurement depth.

Keywords: optical coherence tomography, modulation transfer function, image detector, roll-off

1. INTRODUCTION

In spectrometer-based OCT systems the signal sensitivity depends on the measurement depth.[1] This depth-dependent sensitivity fall-off, called roll-off, is inherent to every Fourier-domain OCT system, but becomes obvious in spectrometer based spectral-domain (SD) OCT. Hence, it has become an important quality measure for the performance of SD-OCT systems. Figure 1 schematically shows the setup of a typical spectrometer-based OCT system.

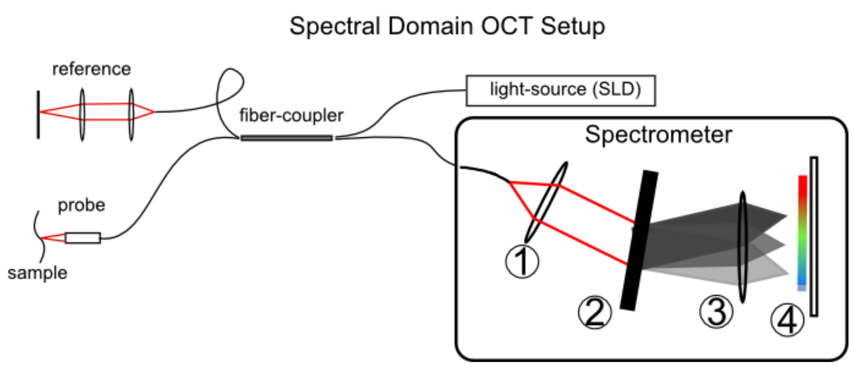

Figure 1: Schematic diagram of a typical SD-OCT system, consisting of a fiber-based Michelson interferometer with reference and sample arm, a broadband light source (SLD) and a spectrometer unit with: collimator (1), transmission grating (2), objective (3) and a line-scan detector(4)

Optical path length delays in interfering reference and radiation arm cause modulations in the signal spectra, which contain the OCT information. In the spectrometer, the light is separated into its spectral components

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by the diffraction grating and afterwards, the spectrum is imaged on the line scan detector. The maximum measurement depth of the OCT system depends on the highest spatial frequency that can be measured by the spectrometer. The SNR of an OCT system at a certain depth z_1, depends on the contrast transfer performance of the different spectrometer components at the corresponding spatial frequency f_1. So, the OCT roll-off can be described as a sensitivity loss due to the spatial frequency dependent transfer loss of signal contrast in the spectrometer unit. Hence, the roll-off in SD-OCT systems is identical to the modulation transfer function (MTF) of the complete OCT system.
The MTF is a well known measure for characterizing the imaging performance of optical and electro-optical systems. It describes the response of optical- or electro-optical systems to sinusoids of various spatial frequencies.[2] By taking advantage of the cascade properties of the MTF formalism we can separate the roll-off into MTFs allocated to single spectrometer components. This is exemplarily shown in Fig. 2.

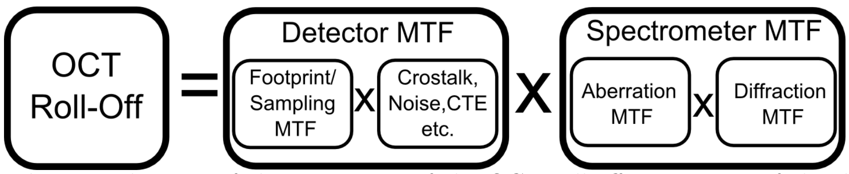


Figure 2: Simplified schematic drawing of the separation of the OCT roll-off into MTFs of the different spectrometer components.

For the characterization of a SD-OCT systems roll-off, the MTF of the image detector is of high importance. To measure it we used an experimental setup which projects sinusoidal interference gratings with different frequencies on the image detectors under test. The results of the MTF measurements were combined with calculations of MTFs due to diffraction, aberration and sampling to calculate an overall roll-off, which was then compared with roll-off measurements of the corresponding OCT device.
The characterization of SD-OCT systems via MTF analysis gives a detailed insight to the contribution of the spectrometer components to sensitivity degrading effects and shows possibilities for improvements in a SD-OCT systems design. In this work the roll-off of the commercially available THORLABS SD-OCT systems *Callisto*, *Ganymede*, *Hyperion* and *Telesto* is analyzed.

2. THEORY

2.1 MTF of image sensors

The MTF in image detectors is fundamentally determined by the detector footprint and sampling effects.[2] The loss of signal contrast due to the detector footprint is based on the fact that the pixels are extended. Due to the rectangular shape of the detector pixels, the image detection performs spatial averaging of the observed irradiation pattern, which results in a *rect* function as impulse response. Hence, the *detector Footprint MTF* of a line-scan detector with rectangular pixel aperture can be described as $MTF_{Footprint} = sinc(\xi, w)$, where ξ is the spatial frequency and w the pixel pitch.[2]
Furthermore, it has to be considered that the position of the image irradiation pattern, with respect to the pixel positions on the detector, affects the detected signal contrast. This effect is considered by the *Sampling MTF* which represents the average value of the possible MTFs that results from the variation of the irradiation pattern with respect to the pixel positions. For line-scan detectors with rectangular pixel aperture and a fill factor of one, the sampling MTF results as $MTF_{Sampling} = sinc(\xi, w)$.[2,3]
In summary, the fundamental *Detector MTF* that can be described as:

$$MTF_{Detector} = sinc^2(\xi w) \tag{1}$$

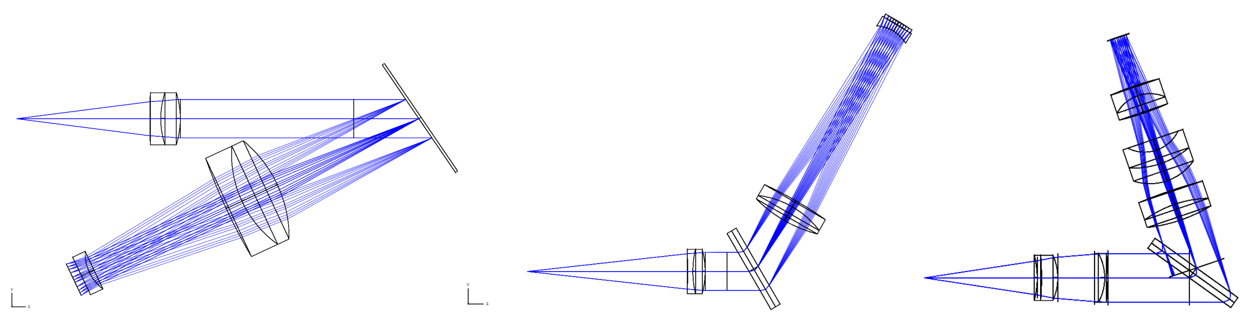
The Nyquist frequency of the above-described line scan detector is set by $f_{Nyq} = \frac{1}{2w}$. According to eq. 1 the theoretical sensitivity loss of the described detector at Nyquist frequency is about $\approx -7.8\,dB$.

2.2 MTF of the spectrometer unit

The imaging performance of an OCT systems spectrometer unit is basically limited by diffraction and aberrations. The diffraction limit of the spectrometer optics is proportional to F/# and the wavelength λ. Furthermore, the MTF of a spectrometer system is a function of λ, because every wavelength enters the objective lens under a certain angle. Here, the MTF's of the spectrometer units were modeled with ZEMAX for one wavelength in the center of the signal spectrum.

For instance, figure 3 schematically shows three spectrometer designs representing different states of development of the THORLABS *Callisto* OCT. Additionally, the plot in figure 4 shows the calculated sensitivity loss due to diffraction and aberrations at the Nyquist frequency of the detector.

It is clear, that with growing grating efficiency and complexity of the optics, the impact of aberrations can be minimized. Hence, in the spectrometer design process one always has to find a trade off between technical effort and acceptable sensitivity loss.



(a) (b) (c)

Figure 3: Schematic drawings of spectrometer unit designs of the THORLABS *Callisto* SD-OCT for the versions of 2007 (a), 2009 (b) and the current version (2011) (c)

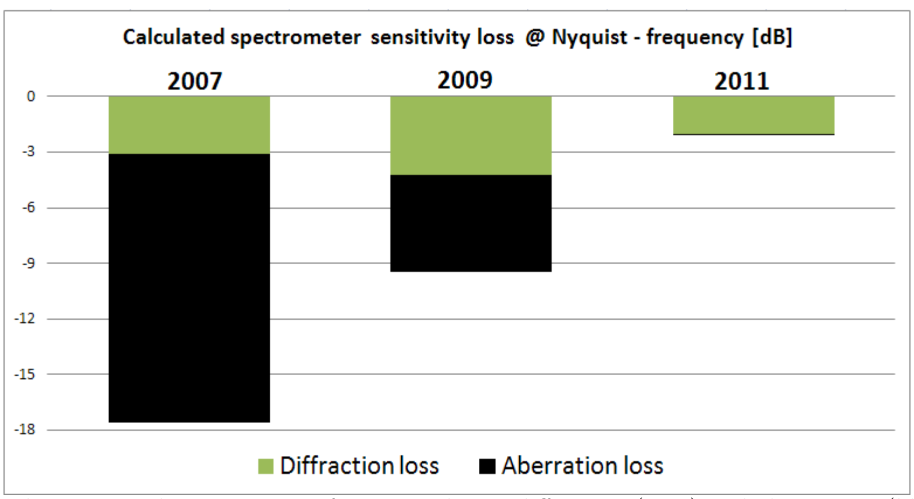


Figure 4: Calculated sensitivity loss at Nyquist frequency due to diffraction (gray) and aberrations (black) for the 2007, the 2009 and the 2011 version of the THORLABS *Callisto* spectrometer unit.

3. EXPERIMENTAL SET-UP FOR MTF MEASUREMENT OF IMAGE SENSORS

3.1 Design and operation

The measurement of the MTF of line-scan detectors was based on the work of Marchywka et al.[4]

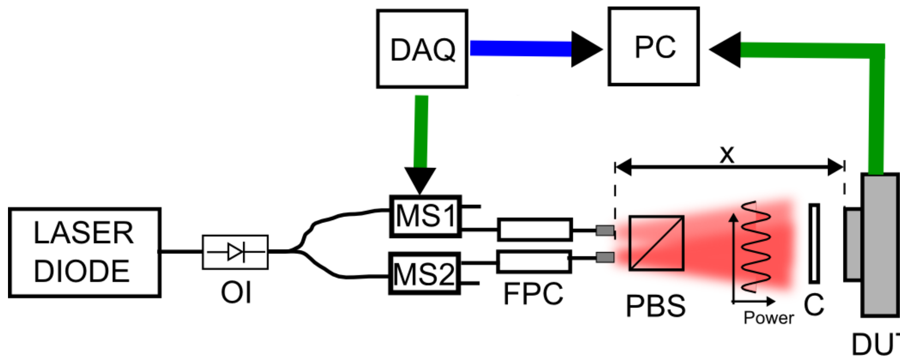


Figure 5: Schematic diagram of the setup with the components: OI: optical isolator, MS1/MS2: MEMS switches, FPC: fiber-based polarization controllers, PBS: polarizing beam splitter, C: cylindrical lens, DAQ: data acquisition card, DUT: device under test, PC: Computer for data evaluation

The cameras under test were illuminated by two coherent beams which were derived from a single-mode laser diode source (Laser Diode: THORLABS LPS-830-FC; Controlling unit: THORLABS ITC502). At the illumination output two FC-PC ferrules were aligned in parallel to each other in a well known distance of 3,5 mm. Both fibers emitted divergent light cones which interfered with each other, so that a sinusoidal interference pattern occurred on the detector which was placed in the beams. The spatial frequency of the interference pattern depends on the distance of the camera to the open fiber ends (see distance x in Fig. 5).

From the measured fringe patterns the modulation contrast was calculated by

$$M(n) = \frac{I(n) - (I_1(n) + I_2(n))}{2 \cdot \sqrt{I_1(n) \cdot I_2(n)}} \tag{2}$$

Here $I_1(n)$ and $I_2(n)$ are the irradiances of each illumination arm on the sensor. After the acquisition of the interference signal $I(n)$ and its components $I_1(n)$ and $I_2(n)$, a black image is subtracted from the other image data. The signal contrast was detected by calculating the power spectrum of M(n) via Fourier transform. From analyzing the power spectrum we determined the modulation frequency f_S and the contrast of the signal.

4. RESULTS

4.1 MTF of image detectors

The specifications of the line-scan cameras and -sensors that were measured are listed in table 1. Figure 6 shows the MTF's of the line-scan detectors in dB against the spatial frequency normalized to the Nyquist frequency of the image detectors. Additionally, the theoretical MTF of an ideal detector according to Eq. 1 is shown.

The LIS1024 CMOS sensor, the BALSER Runner and BASLER Sprint follow the theoretical expectations and have a maximum loss of signal contrast at Nyquist frequency varying from $\approx -9\,dB$ (LIS1024 CMOS sensor) to $\approx -10,5\,dB$ (BASLER Runner and Sprint). The maximum sensitivity loss of the GOODRICH SU-LDH camera was measured to be less than $-6\,dB$, which is less than theoretically expected. Possible explanations can be a detector fill factor of less than one or a non-uniform spatial sensitivity of each pixel.[2]

Table 1: Image detectors: devices under test

Line-scan camera (Maunfacturer)	Pixels per line	Pixel Size $h \times w$ (w=pitch)	Fill factor
PVS CMOS LIS1024 (PVS INC.)	1024	$125\,\mu m \times 7,8\,\mu m$	1
BASLER Runner (BASLER AG)	2048	$10\,\mu m \times 10\,\mu m$	1
BASLER Sprint (BASLER AG)	2048	$10\,\mu m \times 10\,\mu m$	1
GOODRICH SU-LDH (GOODRICH)	1024	$500\,\mu m \times 25\,\mu m$	1

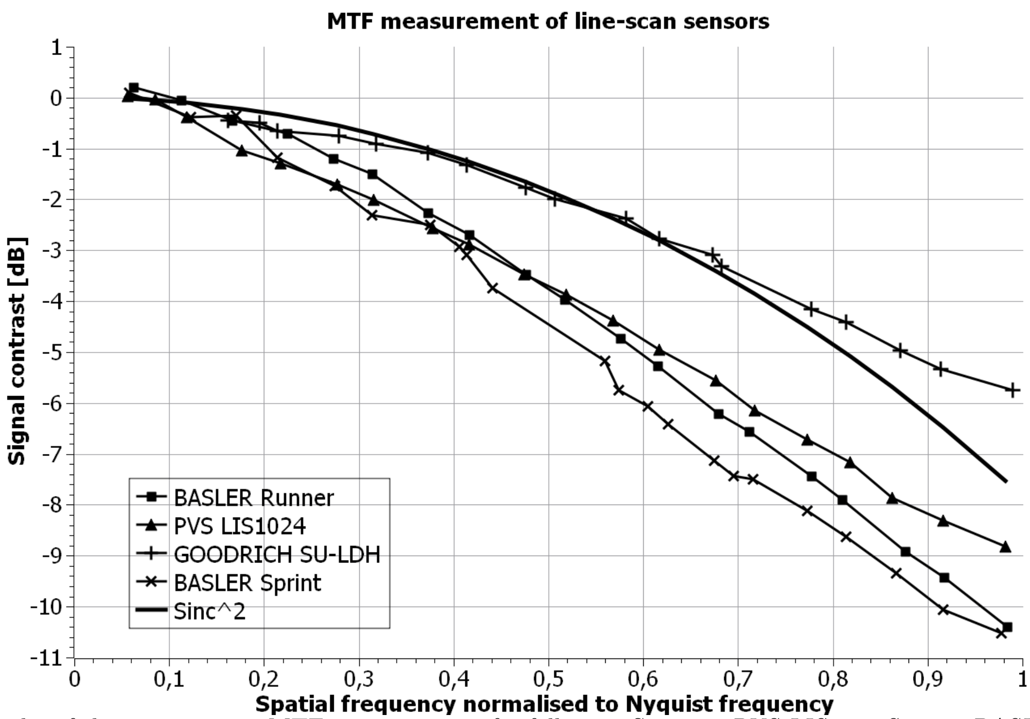


Figure 6: Results of the image sensor MTF measurements for following Sensors: *PVS LIS1024 Sensor*, *BASLER Runner* camera, *BASLER Sprint* camera, *GOODRICH SU-LDH* camera, theoretical detector MTF according to eq. 1

4.2 Roll-off analysis of SD-OCT systems

The results from the detector-MTF measurements as well as the calculations of the spectrometer-MTF were combined to an overall MTF of the OCT system, which was compared to the roll-off measurements of the corresponding THORLABS SD-OCT systems.
For example, Figure 7 shows the roll-off analysis of the current version of the *Ganymede* OCT. Here, the single MTF plots of the different spectrometer components are multiplied with each other and are compared with a roll-off measurement (lowest plot) of the corresponding OCT device. All plots are normalized in the x-axis to the Nyquist frequency of the image detector and are scaled from 10 % to 90 % of the OCT measurement range.

The roll-off was measured to be $-12.1\,dB$. The maximum sensitivity loss due to diffraction is less than $-1.5\,dB$ whereas impact of aberrations on the systems sensitivity is negligible. The image detector causes a

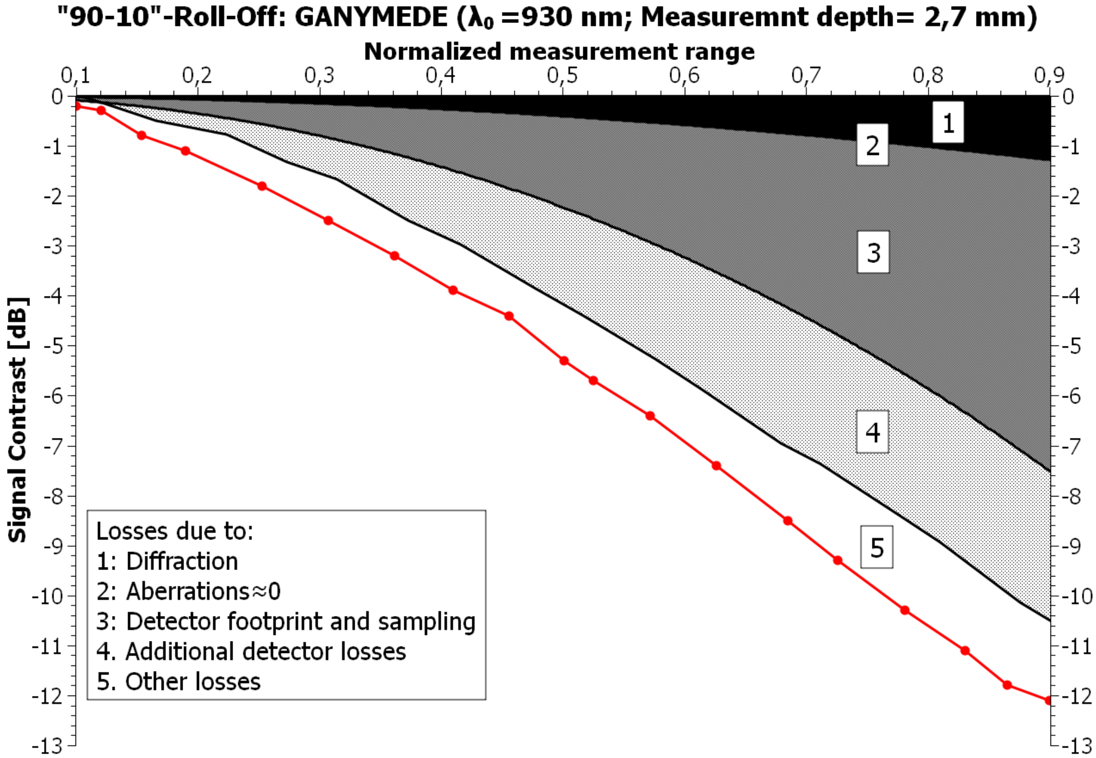


Figure 7: OCT roll-off simulation consisting of the measured detector MTF- and calculated spectrometer MTF plots.

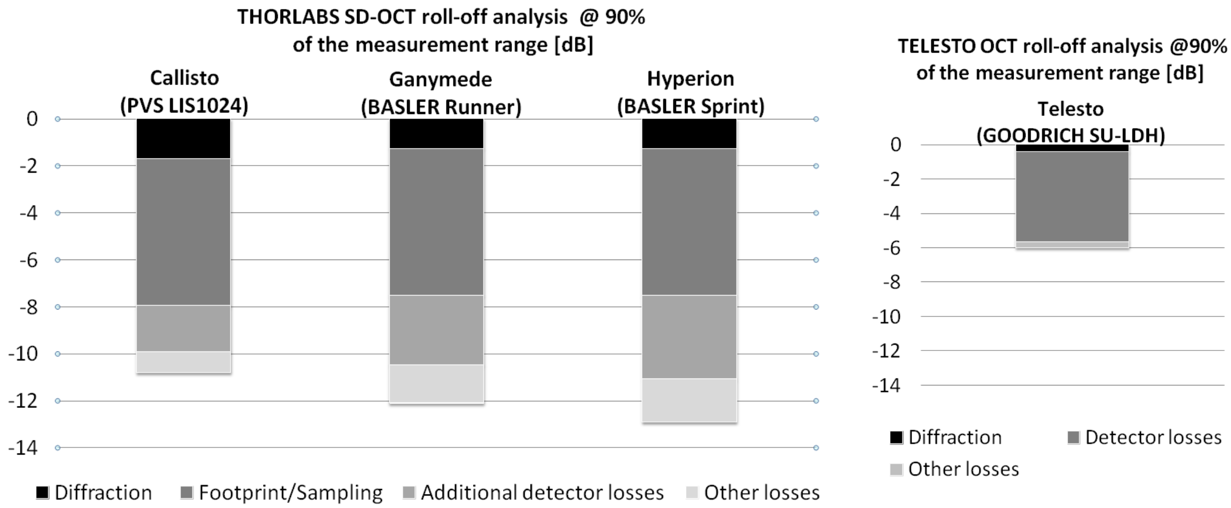
maximum sensitivity loss of $-9.25\,dB$ hereof $-6.25\,dB$ can be allocated to detector footprint and sampling. The discrepancy between the calculated overall MTF and the roll-off measurement (Figure 7: *Other losses*) is less than $-2\,dB$. This shows that the roll-off performance of the *Ganymede* OCT system is less than 6 dB from the fundamental limit of sampling and footprint MTF.

The OCT roll-off values are most significant at the maximum measurement depth. Therefore, only the results at 90% of the measurement depth of the other THORLABS SD-OCT systems are presented. Figure 8a shows the roll-off analysis of the current versions of the THORLABS *Callisto*, *Ganymede* and *Hyperion*. The plots display the sensitivity losses at 90% of the measurement range due to *diffraction*, *aberrations*, *detector footprint/sampling* and *additional detector losses*. The lower end of each bar marks the measured OCT roll-off. The gab between the roll-off simulation and the roll-off measurement is indicated as *other losses*.

The roll-off analysis shows that *Callisto*, *Ganymede* and *Hyperion* have a quite similar roll-off behavior. For all three systems the impact of diffraction is less that $-2\,dB$ whereas aberrations are negligible. Sensitivity losses due to the detector are the main component in the OCT roll-off and go from $-8.2\,dB$ (Calliso) to $-9.8\,dB$ (Hyperion). The roll-off was measured to be $-10.8\,dB$ for the *Callisto*, $-12.1\,dB$ for the *Ganymede* and $-12.9\,dB$ for the *Hyperion*. For all three OCT devices, the discrepancy between the roll-off measurement and the simulation lies within a range of up to $-2\,dB$.

The OCT roll-off analysis of the *Telesto* is plotted in figure 8b. Here,the impact of Detector footprint and sampling on the sensitivity fall-off could not be calculated, because the exact values of the camera specifications *(Goodrich SU-LDH)* is still unknown at the time. However, the influence of diffraction was calculated to be $\approx -0,42\,dB$ and aberrations are negligible as well. The sensitivity loss of the detector was measured to be $-5.2\,dB$, whereas the roll-off of the corresponding OCT system is $-6\,dB$. The discrepancy between the simulation and the roll-off measurement is $-0.36\,dB$, which indicates that the *Telesto* OCT is almost at the fundamental limit.

The *other losses* represent all signal degrading effects which were not considered in this analysis. Possible



(a) (b)

Figure 8: Roll-off analysis of the THORLABS SD-OCT systems. Sensitivity loss in dB at 90 % of the measurement range of the *Callisto* (detector: PVS LIS1024), *Ganymede* (detector: BASLER Runner), *Hyperion* (detector: BASLER Sprint) (a) and the *Telesto* OCT (detector: GOODRICH SU-LDH)(b)

reasons could be additional aberrations of the grating, tolerances of the optical components and the alignment. In the roll-off simulation the MTF due to aberrations is calculated for a single wavelength in the center of the spectra. This leads to a discrepancy because aberrations are not constant over the field of view of the spectrometer optics. The influence of aberrations rises at the edge of the detector, but lies typically below $-5\,dB$. But, due to the limited bandwidth of the light source, the influence of aberrations at the edges of the line detector on the OCT roll-off is small.

In order to estimate the influence of manufacturing tolerances on the OCT systems performance, the roll-off characteristics of 11 different *Callisto* OCT devices were measured. The average roll-off value was $\approx -10.8\,dB$ at 90 % of the measurement range and the calculation of the standard deviation returned $\sigma \approx 1,3\,dB$. This shows that the variations due to manufacturing tolerances lie within the range of the discrepancy in the roll-off analysis. In this case the variations are even slightly higher than the *other losses.* This could be due to variations in the performance of the corresponding image detectors or to observational errors.

5. SUMMARY

An MTF analysis of the roll-off performance of SD-OCT systems was presented and compared with roll-off measurements. It was shown that the detector MTF is the main component in a SD-OCT systems roll-off. The MTF analysis provides a more detailed insight into the contribution of spectrometer components to the depth-dependent sensitivity fall-off of SD-OCT systems. Hence, the MTF analysis offers the opportunity to find a well balanced trade-off between desired OCT performance and technical effort.

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