Geneva, Switzerland, 2021

Acqiris Solution for Swept Source (SS-OCT) Systems

"Seeing better, seeing deeper and seeing faster"

Acqiris Product Line

Acqiris develops application specific OEM solutions for system manufacturers. Acqiris signal processing software offering includes high-performance acquisition (ADC) that are designed-into a wide range of instruments and are ideal for demanding measurement applications. Acqiris offers a full range of products from 500 MS/s till 10 GS/s with resolution from 8 to 14-bit. To meet your specific requirements, most products are both available in the PCIe form factor and in a self-contained box with high-speed serial interface.
Products include proprietary technologies such as amplifiers and clock circuits to achieve unique measurement precision. Market dedicated real-time signal processing can be added to the powerful on-board FPGAs. The deep on-board memory in combination with advanced triggering and flexible data acquisition modes makes Acqiris end-to-end solutions are versatile and suitable for a wide range of applications, such as Optical Coherence Tomography or Mass Spectrometry.

Figure 1: Range of products

Swept Source Optical Coherence Tomography (SS-OCT) Instrument

An important OEM application is swept source (SS) optical coherence tomography (OCT).

Different modalities of OCT have been developed over time and the most used today are Fourier domain OCT (FD-OCT):

- **Spectral domain OCT (SD-OCT):** SD-OCT uses a broadband light source, and the detector is combined with a spectrometer.
- **Swept source OCT (SS-OCT):** Here, a tunable laser is rapidly swept in wavelength. SS-OCT is traditionally useful for applications that require high scan speeds, such as ophthalmology, cardiovascular and laryngoscopy imaging. It is also the technique of choice when deeper imaging is required, as in the case of wide-field retinal applications.

Swept source OCT offers several advantages over spectral domain OCT, including reduced fringe washout, better sensitivity with imaging depth (lower sensitivity roll-off), longer imaging range, higher detection efficiencies (because there are no spectrometer grating losses), and ability to perform dual balanced detection.

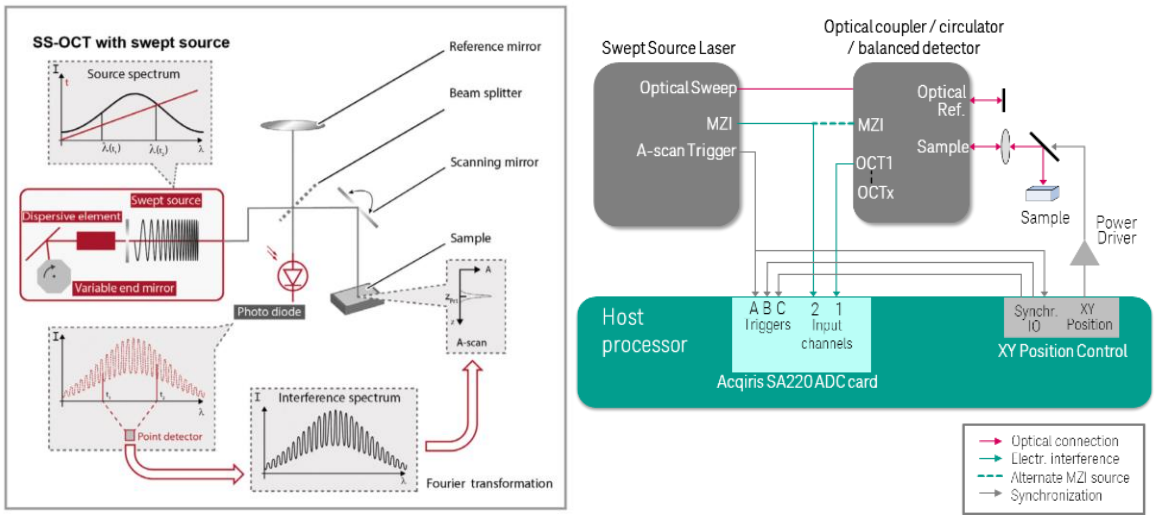


Figure 2: Simplified block diagram of the principal parts of the SS-OCT solution

Acqiris SS-OCT Solution: To maximize image clarity and quality

Leveraging many years of experience in OCT solutions and based on the new solution platform specifically developed for OEM, the 14-bit SA2 solution platform with dedicated SS-OCT processing engine offers both high resolution and high sampling rate. It also enables more real-time processing capabilities for the OCT signal. Overall performance of the SA2 enables deeper analysis, faster image reconstruction and higher image clarity.

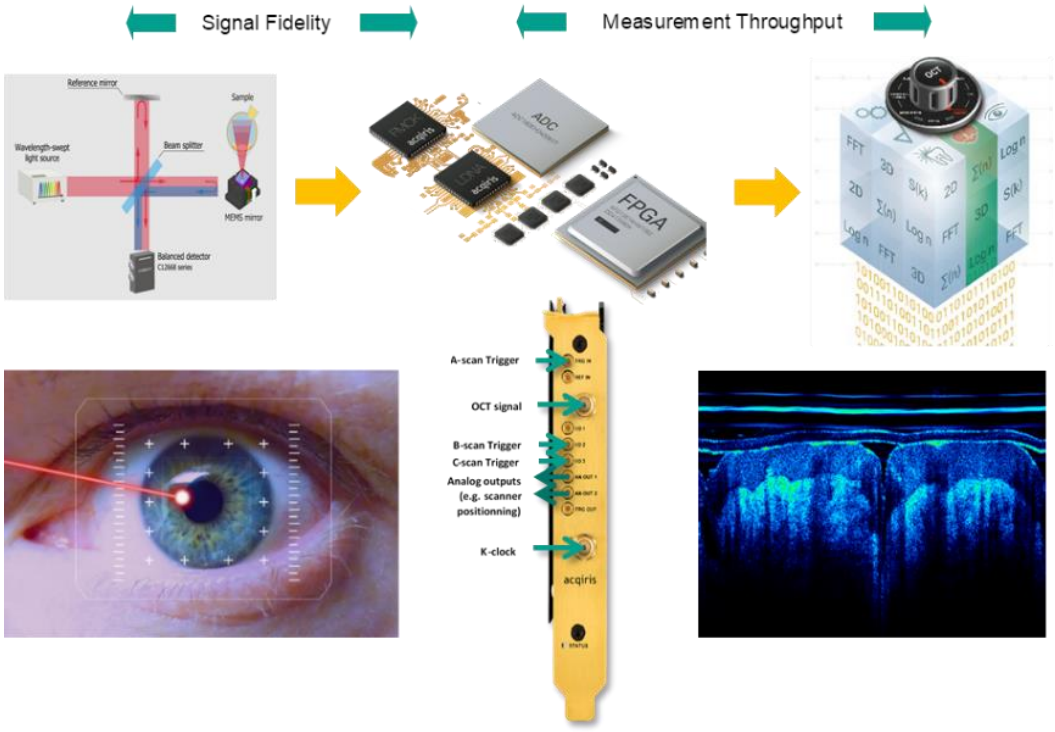


Figure 3: Acqiris Measurement Value Chain

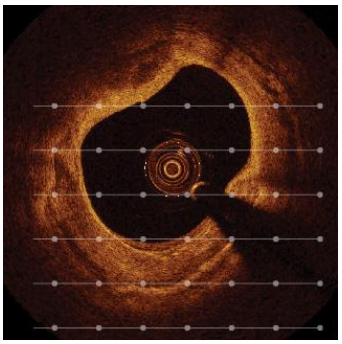
Acqiris aim to build a strong and long-term partnership with OEM system manufacturers and to allow them to focus on system IPs and innovation. Acqiris has experts in the SS-OCT application domain to offer efficient solution fitted to the specific customer requirements and experience with a large range of SS-OCT applications both in the research and in the instrument/quantification market:

- **SS-OCT medical applications**: ophthalmology, cardiovascular, gastroenterology, endoscopy, dermatology, dentistry, surgery, etc...
- **SS-OCT industrial applications**: Non-Destructive Testing and Evaluation (NDT/NDE), for obtaining digital information on their 3-D geometries and properties, inspection and quality control of the production process, scan of components before welding, characterization of multilayered structure's layer-built condition and thickness, etc...
- **LIDAR SS-OCT applications:** Industrial non-invasive inspection, robotics, 3D mapping and modeling, object detection and tracking, etc...

Selecting a signal processing solution for SS-OCT instrument

Many decision factors need to be considered when selecting the appropriate signal processing solution for a SS-OCT project. Solution and service decision criteria embodies technological, financial and risks management. We cover these critical aspects in the following pages:

1. Benefit from unique added values in sensitivity and depth range
2. Achieve faster scan rates
3. Limit the risks with your new product introduction
4. Get flexibility for integration/synchronization into your instrument
5. Reduce the total financial cost through your project lifecycle



1. Acqiris unique added values in SS-OCT key parameters performance

Below a list of key OCT parameters and the related Acqiris SS-OCT solution advantages that are important when designing a new instrument.

Central Wavelength λ_c [nm] and Spectral Bandwidth $\Delta\lambda$ [nm]

The central/center wavelength is laser dependent and contributes to the actual imaging depth and resolution of the system. For imaging samples that have higher optical scattering properties, such as in industrial applications, the longer wavelength systems are recommended. The longer center wavelength is less/not affected by scattering, and therefore, the light is able to penetrate deeper into the sample. Acqiris partners with laser manufacturers to cover a broad range of wavelength requirements.

Axial Resolution

The axial resolution δz depends on the center wavelength λ_0 and the bandwidth (swept range) of the laser source $\Delta\lambda$. The simplified following formula can be used to make some estimation:

$$\delta z \approx \frac{2ln2}{\pi}\frac{\lambda_0^2}{n\Delta\lambda_{3dB}} \approx 0.44\frac{\lambda_0^2}{n\Delta\lambda_{3dB}}$$

n is the refractive index. For water n = 1.33 (close enough for ophthalmology measurement). $\Delta\lambda$ is the FWHM measured at -3dB. The light passes a couple of optical components, which influence the spectrum further. In all cases, the lower the central wavelength and the larger the spectral bandwidth then the better the axial resolution.

For SS-OCT system, the post-processing of the data is key to ensure a proper linearization in k-space and numerical dispersion compensation, as these parameters influence the perceived axial resolution.

Also, an increase in axial resolution always leads to a decrease in imaging range if sweep rate and acquisition rate of the ADC card are kept constant. Therefore, the chosen sweep range is a compromise between axial resolution and maximum imaging/depth range zmax.

Depth/Imaging Range (zmax)

The depth range depends on:

- Acqiris SS-OCT solution sampling rate and front-end performance
- The focal range / depth of focus
- The sample: air, water, tissue, etc... and its related absorption and scattering
- The roll-off of the signal

The maximum and minimum imaging depth zmax, that can be achieved by the swept source OCT system based on the Nyquist criterion is:

$$z_{max} = M\delta z = \frac{\lambda_0^2}{4\delta_s \lambda}$$

M is the selected number of samples and δs is the spectral sampling interval which is obtained as Δλ/N Where N is the number of spectral samples in the range Δλ. It is assumed that the interferogram is sampled with spectral sampling interval δsk into M spectral channels linearly spaced in k.

Acqiris offers complete SS-OCT solutions that have high sampling rate (with high bit-resolution) to maximize zmax imaging/depth range.

The maximum analysis depth is programmable by selecting the effective sampling rate of the SS-OCT solution. Key advantages of this approach are:

- Independency from k-clock frequency
- Programmable through variable sampling rate (internal clock from 250 MHz up to 1 GHz).

Lateral Resolution

The lateral resolution is dependent on the scan lens. Various scan lens can offer a wide range of numerical aperture (NA) / beam diameter / lateral resolutions. The equation is:

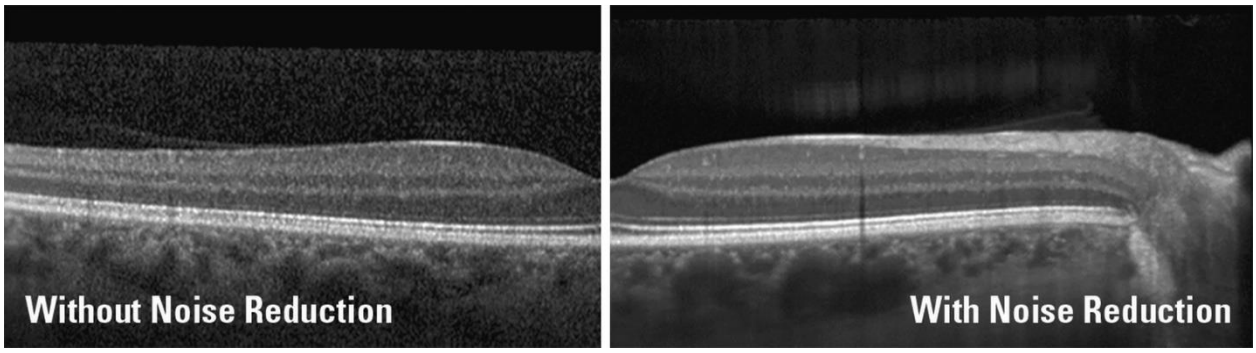
$$\delta_x = 0.37 \frac{\lambda_0}{NA}$$

Sensitivity and SNR (Signal to Noise ratio)

Sensitivity is a useful figure of merit to characterize or compare the performance of an OCT system. Sensitivity refers to the ability of the system to detect the faintest amount of back-reflection from the sample under observation. The deeper you go with spectral domain imaging, there is more noise. SS-OCT has superior sensitivity compared with SD-OCT because there are no spectrometer losses.

SNR depends on the incident optical power and the efficiency of the photon detection. For SS-OCT, the spectral resolution is determined by the instantaneous line width of the SS laser. Acqiris flat analog bandwidth response and ideal -3dB slope ensure that the SNR is not reduced by the ADC card.

Single OCT images can be averaged in real-time to decrease noise and enhance contrast. This is obviously only possible if the image rate is faster than the potential movement of the sample, something easy to implement thanks to high sampling rates and onboard averaging processing.



k-clock remapping

In any SS-OCT system, the OCT fringe resulting from the interferometry process between a reference arm and the sample arm is re-sampled by a k-clock either directly provided by the laser swept-source or generated by a discrete Mach-Zehnder Interferometer (MZI).

SS-OCT lasers are sometimes non-ideal (non-linear sweep) and consequently both OCT and k-clocks are containing the same frequency/phase shift. The potential non-linearity must be taken into account to improve both resolution and sensitivity. The resampling or remapping process, to correct for phase shift, can be done in two ways:

- **direct ADC clocking**: the ADC capturing the OCT interference is clocked directly with a clock signal. This clock-signal period contains the information of the laser source frequency sweep.
- **k-clock resampling**: The ADC capturing the OCT interference is clocked at constant sampling period. The digitized OCT interference is digitally non-linearly resampled in a way to compensate the non-linearities computed on the k-clock acquired with a second ADC channel.

Both OCT and k-clock signals are sampled from an internal clock. These data records are related to an external A-scan trigger event that can be positioned up to proprietary picosecond TTI (Trigger Time Interpolator) with accuracy of 15ps RMS.

Acqiris solution is based on resampling k-clock with a stable internal clock which provides more flexibility, consistency and reliability without requiring to generate a “dummy” k-clock out of the source sweep. Also this approach provides noticeably significant better performance for SS-OCT system with >=200 KHz A-scan rates.

Besides, the digital resampling technique presents additional capabilities, such as the compensation of the optical path difference between k-clock and OCT-signal and the programmable maximum analysis depth. For each new A-scan trigger, the k-clock data samples are used to extract a new calibration vector that is used to resample the OCT signal in the k-space domain to provide the remapped OCT vector.

Phase Stability

The phase stability is an important performance criterion in several SS-OCT applications which are phase sensitive[1]. It is also required before applying any background subtraction scheme in the time domain to efficiently remove any fixed pattern noise resulting from the SS-OCT system imperfections.

In SS-OCT unreproducible laser sweeps, trigger jitter and k-clock jitter degrade phase stability. With Acqiris products, no needs to be concerned by the k-clock imperfection, unlike the direct clocking

[1] All Doppler-based imaging techniques aimed at displaying the blood flow throughout the tissue under analysis are retrieving the fluid velocity by detecting the phase-shift between successive A-lines

approach. SA2 product family also offers unique real-time internal trigger time interpolator enabling a high trigger resolution and a precise and accurate phase measurement.

The SS laser is usually providing a A-scan trigger signal that is marking the beginning of the wavelength sweep. The jitter between the time of occurrence of this signal and the effective sweep of the laser is known to be significant. Hence some SS laser manufacturers have included a wavelength trigger which is optically derived from the wavelength sweep. This trigger is providing a minimum of jitter but is usually located near the middle of the sweep and therefore requesting pre-trigger capability. Acqiris offers up to 100% pre-trigger to cover any specific requirement needs.

Phase washout and Doppler effect

This concerns motion artifacts if the sample moves during the A-scan acquisition. The solution is then higher A-scan rate. Acqiris SS-OCT engine allows the fastest A-scan rate up to 1MHz and beyond.

A-Scan/Sweep rate

The speed of an OCT system depends on several factors. For SS-OCT the speed of the swept source laser is often the limiting speed while Acqiris can support the fastest swept sources of today and tomorrow.

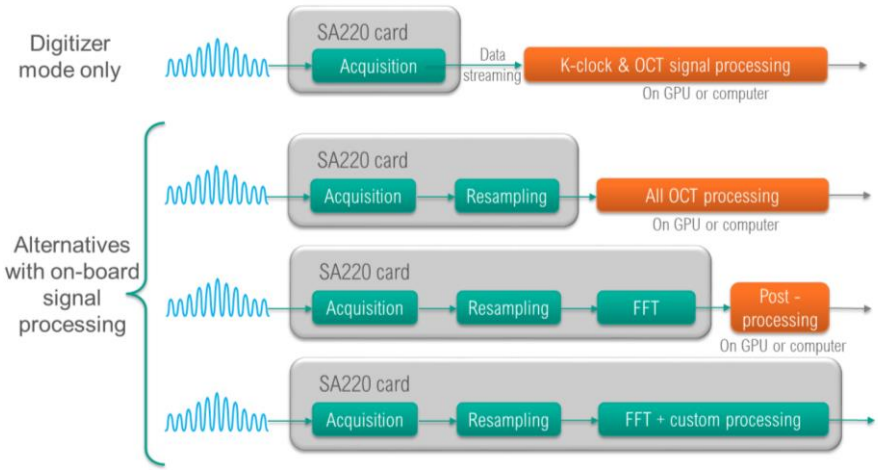


Figure 4: Acqiris supports flexible solutions for signal processing to answer the needs of different applications

Acqiris provides SS-OCT DAQ cards that can cover from 500MS/s to 8GS/s sampling rate to:

- either to double the maximum analysis depth with same A-scan rate
- or to double the image speed (double A-scan rate), keeping the same analysis depth.

The successive A-scan acquisitions can run continuously without missing any A-scan trigger, up to (today) 1 MHz. SA2 product family features simultaneous acquisition and readout: output data are streamed to the computer while the next A-scan data are acquired and processed, enabling high scanning speed.

Acqiris products provide also optional synchronization inputs for the B-scan and C-scan triggers. These additional synchronizations guarantee that there is no loss time during a full 3D image acquisition. As 3-D images are very long to acquire, the sustained scan rate is crucial for minimizing unwanted samples movement.

The high scanning speed and fast image restitution are guaranteed continuously and not only for a limited period. This is achieved by:

- Real time OCT processing on FPGA and simultaneous SS-OCT signal acquisition and image data readout. SA2 product family sustained data throughput to PC at > 6 GB/s
- Continuous acquisitions of B-scans without missing any trigger/data

Acqiris offers flexibility and modularity to cover all needs and maximize scan rates:

- Possibility to read either the raw data after the re-sampling, the raw data before the re-sampling (ADC raw data), the complex data after FFT, the Linear or Log magnitude and the phase and magnitude simultaneously. Reading phase and magnitude simultaneously allow to support phase sensitive applications.
- Capability to enable / disable windowing and to enable / disable averaging (to reduce SNR)
- System abnormalities/unwanted effects, such as dispersion compensation, can be managed in the FPGA for optimum performance.

Finally, both “Up and Down sweep” and “Up-sweep only” SS-laser mode are supported by Acqiris.

Artifacts

Artifacts are related to the interference between the sample light and the reference light.
There are two contributions:

- Autocorrelation signal: The sample light interferes with itself
- DC signal: The reference light interferes with itself

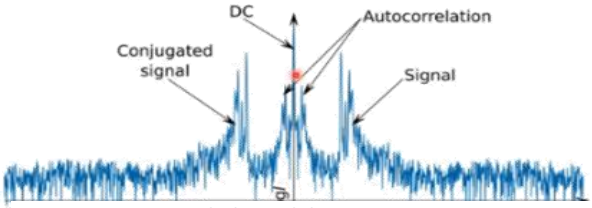


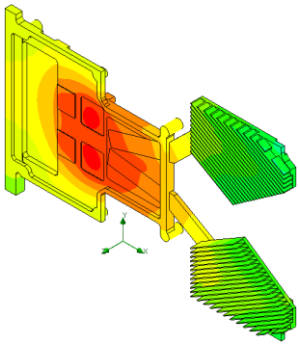
Figure 5: In SS-OCT, balanced detection removes autocorrelation and DC terms

Acqiris SS-OCT solution allows to acquire together both the OCT and the k-clock signal with the same clock. Both waveforms are then sampled by an internal low-jitter and stable fast clock synthesized on the ADC card. This minimizes artifacts compare to clocking directly the ADC with a non-uniform frequency is not ideal from a conversion stability/reproducibility perspective.

2. Limit the risks with your new product introduction

Acqiris provides unique services to easier evaluation and integration into the OCT instrument:

- Easy to use dedicated evaluation and API (Application Programming Interface) tools and user interface GUI for live display and visualization
- Dedicated IO sequencing to control and synchronize the customer system
- Integration support, knowledge of customer applications/challenges
- High quality/reliability, i.e. lifetime with state of the art cooling system



3. Flexibility and reduced time for integration/synchronization into your instrument

SS-OCT technologies and manufacturer’s product line are evolving quickly. Acqiris existing solution with a track record facilitates the design of your OCT system easier and shorten the time-to-market:

- No compromise: fitting your actual requirements, and including only what you need
- Light-source independent: SA2 family card is compatible with the main laser sources on the market.

- Dedicated SS-OCT firmware with real-time processing of the k-clock and OCT signal drastically reduced the need for an additional processing card
- Compensating the system abnormalities/unwanted effects in the FPGA for optimum performances
- Compensating the differences between the k-clock and OCT optical path, with a programmable delay.

Acqiris delivers not only a standalone signal acquisition card but a key piece of the SS-OCT instrument with all the required and customizable synchronization capabilities. Acqiris furthermore provides unique functions and options to enhance the customer SS-OCT performance and time to measurement with adjustable FIR (Finite Impulse Response) filter to match measurement system requirements.

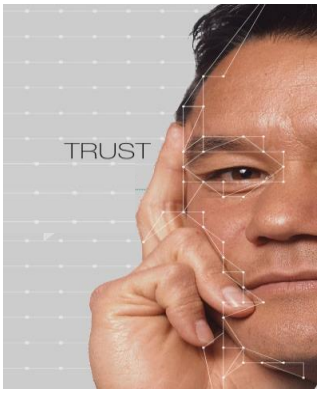
Acqiris realizes that a standard product might not fit your specific system requirements. We have a Customization team to enabling fitted specifications to the customer dedicated instrument and covering the image quality and data throughput needed.

4. Reduce the total financial cost through your project lifecycle

Acqiris offers:
- Extensive qualification tests including EMC/Safety certifications, because we recognize how challenging FDA/CFDA can be
- High reliability, stability, robustness and 5-year warranty
- Reduced power consumption and size to address new volume applications

Acqiris offers solutions adapted to the customer innovation plans targeting an increase of its market share. This allows a full control of development budget throughout the full project's life cycle, from the earliest stages of system development until the end product obsolescence.

- Guaranteed long term availability and full visibility about product lifecycle
- Benefit from accumulated volumes across markets and customers
- Pricing according to the customer volume's and expected added value. Acqiris recognizes and knows by experience what is necessary for clinical products that needs FDA (US Food and Drug Administration and/or CFDA (China Food and Drug Administration) approvals and therefore understands that volume applications are price sensitive
- Software is re-usable and upgradable
- Firmware (FPGA code) on-the-fly switchable, and also remotely upgradable
- Project delays



Strong communication and partnering with your R&D Team ensures that you participate to our R&D product roadmap, specifying means to get innovations in your system. When we engage in an OEM agreement, we guarantee that the solution we develop fits your actual needs and is driven by innovation.

5. Recommended Solutions for SS-OCT Applications

Key specification	SA220P	SA240P	SA248P	SA220E
Max. sampling rate	1 - 2 GS/s	4 GS/s	8 GS/s	2 GS/s
ADC resolution	14-bit	14-bit	14-bit	14-bit
Form factor	PCIe card	PCIe card	PCIe card	Serial module
Number of channel	2	2	1	2
Bandwidth	DC - 1.2 GHz	DC – 2 GHz	DC - 2.5 GHz	DC - 1.2 GHz
Full scale range	500 mV 2.5 V	500 mV 1 V	1 V	500 mV 2.5 V
Interface	PCIe Gen 3	PCIe Gen 3	PCIe Gen 3	USB-C ThunderBolt 3
Data throughput	6.5 GB/s	6.5 GB/s	6.5 GB/s	2 GB/s

Figure 6: For more information, please visit the products page: https://acqiris.com/#section-products

Some public references

2014: Acqiris DP310: Impact of device geometry on the imaging characteristics of an intravascular photoacoustic catheter **https://www.osapublishing.org/ao/abstract.cfm?uri=ao-53-34-8131**

2018: Acqiris U5303A : A Novel Mach-Zehnder Interferometer Using Eccentric-Core Fiber Design for Optical Coherence Tomography **https://www.mdpi.com/1424-8220/18/5/1540/htm**

2020: Acqiris SA220P: High-speed imaging and biometry of human accommodation dynamics with SS-OCT **https://iovs.arvojournals.org/article.aspx?articleid=2769935**

Acqiris History

Originally founded in 1998, Acqiris joined Agilent in 2006 and continued to operate as the electronic measurement portfolio of Keysight Technologies (2014). On August 1, 2017, Keysight OEM PCIe-based group became a new company and returned to its original name. The same team of dedicated specialists continues developing Swiss Made, high quality signal acquisition products with customizable FPGA real-time processing, bringing technical excellence to your OEM applications.

For more information visit **www.acqiris.com** or contact our local team.

Acqiris Americas
contact-americas@acqiris.com
Acqiris Asia-Pacific
contact-asia-pacific@acqiris.com
Acqiris Europe
contact-emea@acqiris.com
Acqiris Japan
contact-japan@acqiris.com
Support
support@acqiris.com
Acqiris SA | Ch. des Aulx 12 | CH-1228 Plan-les-Ouates | Geneva/Switzerland