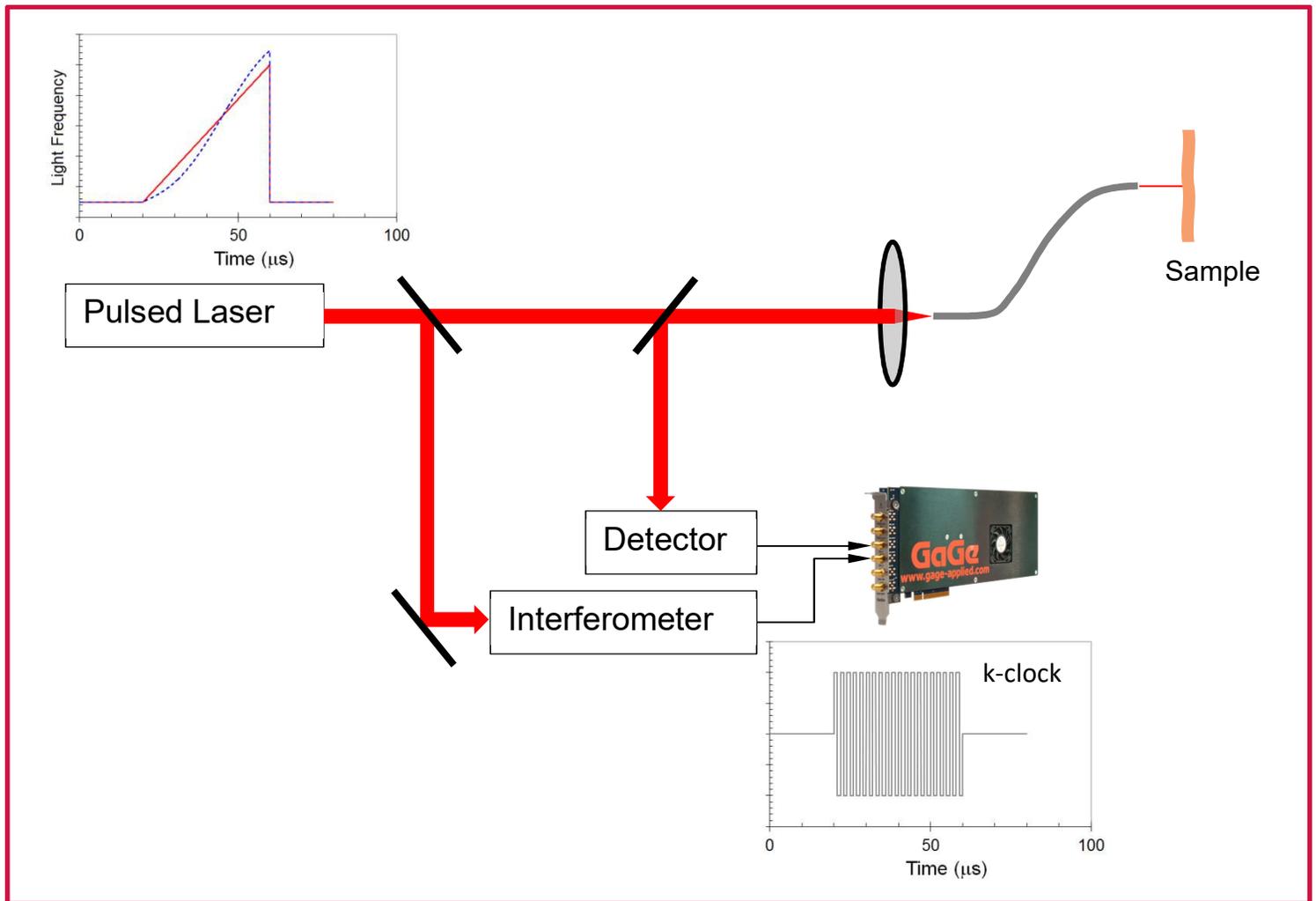


## eXpert OCT Firmware

Optical Coherence Tomography (OCT) is an innovative medical diagnostic technique that is addressing an increasing number of applications. A schematic block diagram of an idealized Swept Source OCT system is shown in Figure 1.



**Figure 1: Idealized OCT system using Gage EON Express digitizer**

The system allows for the rapid acquisition of the optical spectra of light reflected off of a remote sample. The optical source for the experiment is a high-speed pulsed laser that is capable of generating optical chirps, in which the optical frequency increases in a linear fashion throughout the duration of the laser pulse.

The ideal chirp pulse is illustrated as the red curve in the top left inset in Figure 1. In this example, the optical pulse occurs between 20 microseconds and 60 microseconds after Time=0. The red curve in the graph shows that the optical frequency increases linearly during the pulse.

The light pulse is focused through a lens and is relayed through an optical fiber to impinge upon a sample. Light returned by the sample travels through the fiber to a detector whose electrical output is connected to the Channel 1 input of a GaGe EON Express CompuScope digitizer.

Not shown in Figure 1 is the triggering scheme, which is that the laser's optical pulse also simultaneously creates an electric pulse that is relayed to the External Trigger input of the EON CompuScopes. The external trigger event, therefore, is coincident with the laser excitation pulse and the instant Time=0.

If there is indeed a linear relationship between the laser light frequency and time (starting from Time=20  $\mu$ s) during the output pulse, then the electrical waveform created by the optical detector should be proportional to the frequency spectrum of the light returned by the sample, such that different times in the waveform corresponding to different optical frequencies in a linear fashion. It is this rapid acquisition of frequency spectra in the time domain that is the key power to the OCT technique.

If we assume a strictly linear time-frequency relationship in the optical pulse, then the digitizer that acquires the optical detector signal does not need any special functionality. As we shall see, however, this is not the case if the time-frequency relationship becomes significantly nonlinear, which is the case for most actual pulsed lasers in practice.

Compensation for laser pulse non-linearity is achieved in an innovative fashion. The optical excitation pulse is passed through an optical splitter and a resulting reference beam enters an interferometer. This interferometer will produce an optical fringe and a corresponding electrical output pulse whenever the optical frequency changes by a fixed increment,  $\Delta f$ .

For an ideal linear chirp, therefore, the interferometer will output a uniform burst of clock pulses throughout the duration of the optical pulse. This interferometer output for a linear chirp is shown as the lower right inset of Figure 1 and is referred to in OCT as the k-clock.

Consider now the case of a non-linear time-frequency relationship in the optical pulse. An example is given as the blue dashed curve in the top left inset of Figure 1. In this case, the frequency of the k-clock signal coming from the interferometer will not be uniform throughout the duration of the optical pulse but would vary in proportion to the slope of the blue dashed curve.

If the k-clock signal were used as an external clock source for the digitizer, however, then the digitizer would create a new waveform sample every time it received a pulse from the interferometer. Since each pulse corresponds to a change in the optical frequency

by  $\Delta f$ , therefore, usage of this external clocking scheme recovers the linear relationship between sample number within the processed waveform (which is no longer directly proportional to time) and optical frequency. In this way, the k-clocking scheme compensates for the non-linear time-frequency relationship of the laser pulse and produces correct optical spectra despite the nonlinearity.

While externally clocking the digitizer with the k-clock solves the non-linearity problem in principle, it presents practical problems. The variance in the external clocking frequency throughout the duration of the optical pulse is generally small enough that it can be handled by most ADC chips. The big problem, however, is that the k-clock signal illustrated in the lower right inset of Figure 1 is completely inactive for a significant fraction of the waveform acquisition duration (specifically, for Time<20  $\mu$ s and Time>60  $\mu$ s).

Typically, high-speed ADC chips provide a clocking frequency range of about one order of magnitude and cannot handle clocking signals that go inactive. Such inactivity can lead to complete corruption of ADC sample values or incorrect sample ordering. Even if such severe distortion does not occur, missed clocks or extra clocks can lead to inconsistent sample positions. Figure 1 shows that the k-clock signal is inactive even during occurrence of the trigger event (at Time=0), whose latching usually requires an active clock signal.

Some digitizer manufacturers have addressed the problem of an inactive external k-clocking signal by creating an internal "bogus clock" signal to which the ADC chip is switched when the external k-clock becomes inactive (which corresponds to a clocking frequency of 0). While this approach may resolve ADC sample distortion problem, an inconsistent number of clock pulses may be transferred to the ADC chip during the clocking signal transition, which may lead to inconsistent sample positioning or jitter. While appealing because it allows for direct usage of the interferometer signal as an external clocking source, this approach unfortunately suffers from the problems of flexibility and robustness in practice.

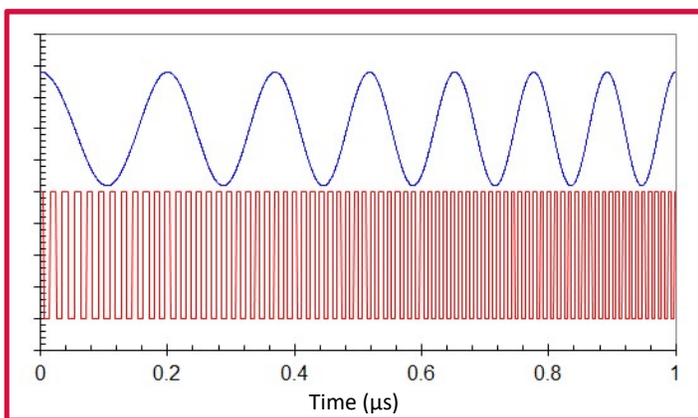
The approach taken by GaGe with the PCIe Express EON CompuScope is to simultaneously digitize the interferometer signal with the returned optical signal.

Idealized signals acquired at the EON's 300 MS/s sampling rate are shown as Figure 2, which illustrates the red interferometer signal as a square wave of varying frequency, as expected for a non-linear optical chirp.

The blue input signal was purposely created so that its frequency varies in proportion to the frequency of the k-clock signal. The blue and red signals breathe together. Accordingly, if the blue signal were to be acquired with the red external clocking signal, then the breathing would disappear and the blue signal should become a sine wave of uniform frequency.

Figure 3 shows a magnified view of Figure 2 and also illustrates the technique used by GaGe to do OCT processing.

If the red k-clock signal that was acquired on Channel 2 had been used to externally clock the EON CompuScope, then every time a rising edge occurred in the k-clock signal, the ADC would acquire a new sample on Channel 1. The eXpert OCT firmware simulates this hardware action of external clocking in the digital domain and might be called *virtual external clocking*.



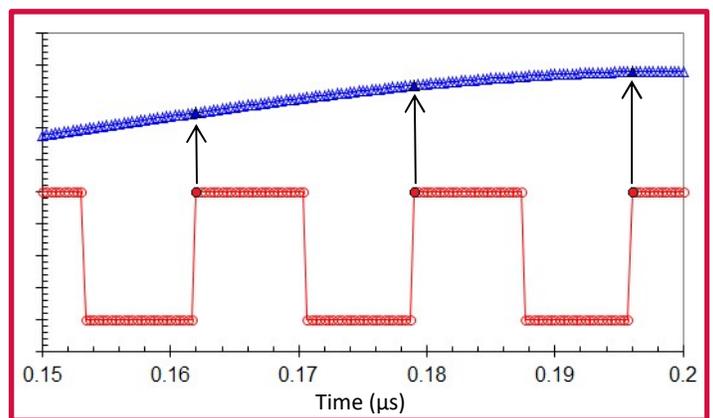
**Figure 2: Idealized OCT Signals:**

**The blue signal indicates an idealized OCT optical detector signal, which is connected to Channel 1 of the Eon CompuScope. The red signal shows the corresponding interferometer output (the k-clock), which is connected to Channel 2 of the EON CompuScope. Time=0 represents the trigger event.**

The virtual external clocking technique is very simple and is illustrated in Figure 3. The firmware first identifies the samples that occur right after rising edges of the k-clock signal, which occur when the signal crosses the threshold level that is indicated by a horizontal dashed red line. These post-rising edge samples are indicated by closed red circles in Figure 3.

With the positions of closed red circles identified, the points that were acquired on Channel 1 and that are simultaneous with these positions are identified. This identification is illustrated by vertical arrows in Figure 3 and the target points are shown as closed blue triangles. It is the extraction of these closed blue triangular points performed by the eXpert OCT firmware that implements the virtual external clocking.

One shortcoming of this digital OCT analysis method is that it may erroneously locate the rising edges of the clock by as much as one sample point in the worst case. The high 3 GS/s sampling rate of the EON CompuScope, however, makes this error only 1/3 nanosecond. Furthermore, the Gage eXpert OCT firmware also includes provisions for linear interpolation between samples, which allows for localization of the rising edge to within 100 picoseconds.



**Figure 3: Illustration of eXpert OCT Processing:**

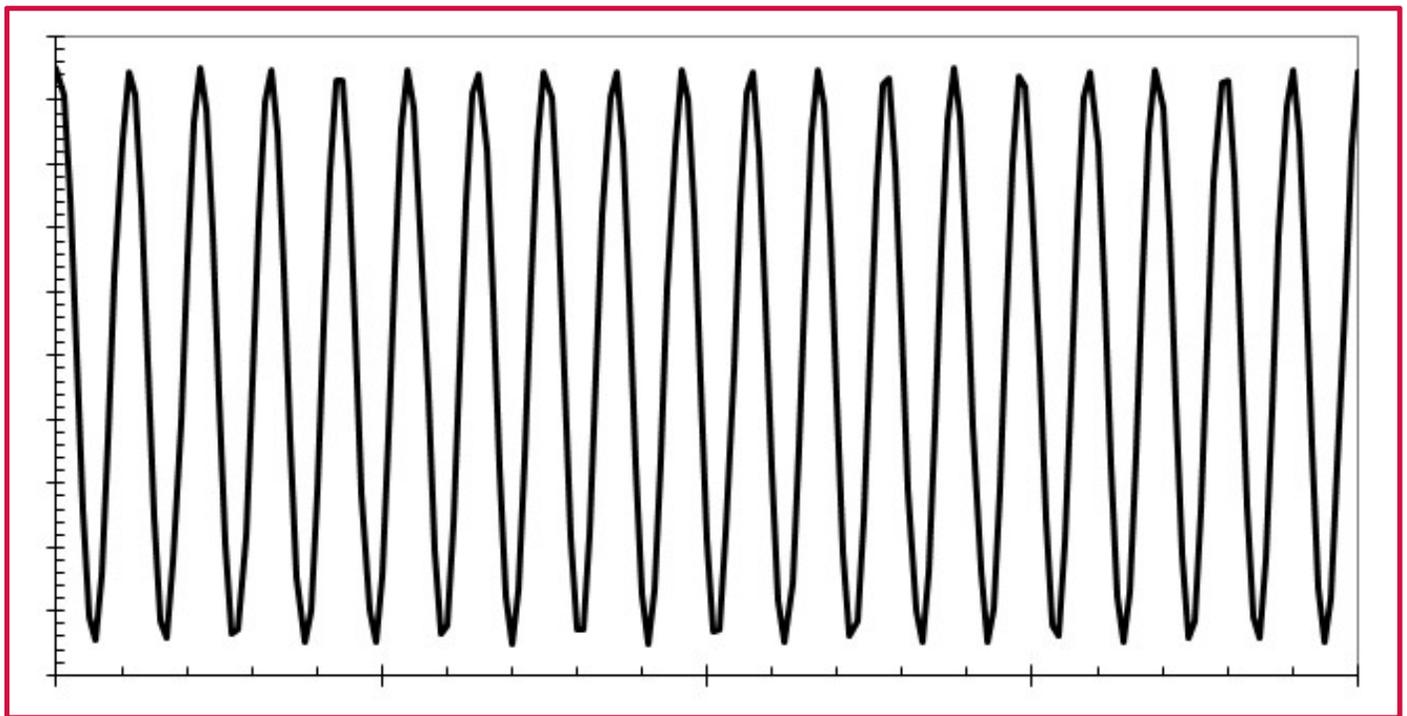
**The graph is nothing more than a magnification of Figure 2 just below Time=0.2  $\mu$ s. Unlike in Figure 2, however, sample points are indicated by open points. Closed points and vertical arrows illustrate the OCT processing technique, which is described in the text.**

Of course, the inactivity of the k-clock does not present an operational problem because it is not used to externally clock the digitizer's ADC and so the associated electrical problems do not arise. The eXpert firmware allows for rejection of rising edges for pulses that are below certain amplitude. The firmware also returns the raw data sample number so that the user can manually manage clock pulses that occur on the border between k-clock activity and inactivity.

The efficacy of eXpert OCT Processing is proven in Figure 4. The data imported to the processing algorithm are the Channel 1 data partially shown in Figure 2. Over its entire duration, the frequency of the k-clock signal increases by a factor of more than two - from 50 MHz to well over 100 MHz. In strict proportion, the signal frequency increases from 5 MHz to well over 10 MHz near the end of the waveform.

When the waveform data are processed by the OCT processing firmware, Figure 4 shows that all frequency variation in the sine wave frequency has vanished. This test shows the power of the expert OCT processing firmware to perform virtual externally clocking, which allows for the synchronous sampling of data while avoiding the pitfalls of clocking a digitizer with an intermittent external clocking signal.

The eXpert OCT Firmware requires the GaGe C/C# SDK that provides a ready-made compiled OCT sample program that illustrates how to configure and use the OCT feature and documentation for configuring the OCT in C.



**Figure 4: Results of eXpert OCT Processing:**

**The results of OCT processing of the data in Figure 2 using the method illustrated in Figure 3. The horizontal axis is in rising edge count.**

## ORDERING INFORMATION

eXpert FPGA Firmware	Order Part Number
<p>eXpert Optical Coherence Tomography (OCT)</p> <p><b>NOTE:</b> The eXpert OCT Firmware requires the GaGe C/C# SDK and is compatible for use with the following GaGe Digitizer Model Series sold separately:</p> <ul style="list-style-type: none"><li>• EON Express</li><li>• RazorMax Express</li></ul> <p>Please refer to the separate GaGe product datasheets for these digitizer models for their full specification details and ordering information.</p>	250-181-006

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