# Technology

## Technology and System Hardware Overview

### Technology

PulsedLight's "Time-of-flight "distance measurement technology is based on the precise measurement of the time delay between the transmission of an optical signal and its reception. Our patented, high accuracy measurement technique enables distance measurement resolution down to 1cm by the digitization and averaging of two signals; a reference signal fed from the transmitter prior to the distance measurement and a received signal reflected from the target. The time delay between these two stored signals is estimated through a signal processing approach known as correlation, which effectively provides a signature match between these two closely related signals. Our correlation algorithm accurately calculates the time delay, which is translated into distance based on the known speed-of-light. A benefit of PulsedLight's approach is the efficient averaging of low-level signals enabling the use of relatively low power optical sources, such as LEDs or VCSEL (Vertical-Cavity Surface-Emitting) lasers, for shorter-range applications and increased range capability when using high power optical sources such as pulsed laser diodes.

### System Hardware

The Single Board Sensor provides distance and velocity measurements in an ultra-small form factor. This small size is the result of PulsedLight's System-On-Chip (SoC) signal processing technology which, beyond being small, reduces the complexity and power consumption of supporting circuitry. The system consists of three key functionalities:
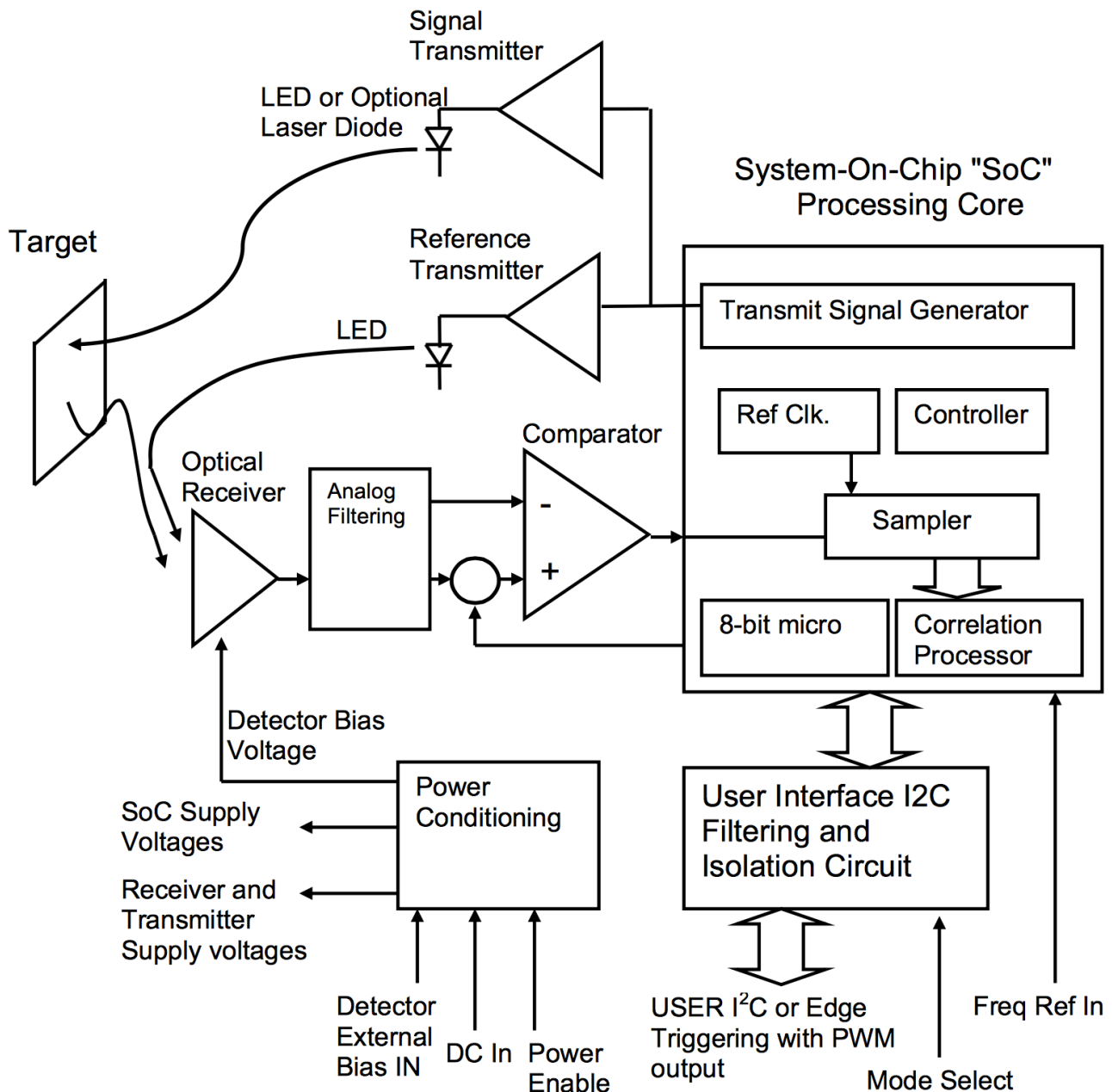
A Signal Processing Core (SPC) System-on-Chip solution encapsulating all the required functions in support of our proprietary range finding system architecture.

An optical transmitter and receiver tied to the SPC emit and receive a proprietary optical signal pattern generated by the SPC.

Power Conditioning and I2C signal filtering and buffering.

*Please refer to "LIDAR-Lite Block Diagram" section for a full overview of the system architecture.*

# LIDAR-Lite Block Diagram

# Signal Processing Core (SPC)

The key component within the system is our SPC chip which implements PulsedLight's signal processing algorithms and primary system architecture. The SPC contains four major subsystems; 1. An 8-bit microcontroller provides system control and communications. It contains an I2C slave peripheral. 2. A 500 MHz sampling clock and an associated sampler capture the logic state of the external comparator and convert the data into a slower speed 125 MHz four bit word which is sent to a correlation processor. 3. A correlation processor stores the incoming signal and performs a correlation operation against a stored signal reference with optical burst reception and stores the result in the correlation memory with data points every 2 ns. 4. A transmit signal generator produces an encoded signal waveform with an overall duration of 500 ns that consists of a varying interval pattern of ones and zeroes. These outgoing signal pulses occur at a 20 KHz repetition rate and become either the reference signal or outgoing signal pulse depending on the state of the transmitter.

# Optical Transmitter and Receiver

The optical transmitter and receiver have been designed around the requirements of our signal-processing algorithm. The transmitter produces optical pulse bursts using signal patterns generated by the SPC. When an optical reference signal is desired, a separate reference transmitter is enabled and driven with the signal pattern using a reference fed to the optical receiver. The reference transmitter has been designed to match the delay and signal shape produced by the higher power signal transmitter. The signal transmitter can drive a variety of optical sources ranging from high speed LEDs, higher power VCSEL laser or much higher power pulsed laser diodes. For the LIDAR-Lite module, the signal transmit driver drives a T1-3/4 plastic packaged laser diode with a three-amp peak, 50% average duty cycle modulation over a burst duration of 500 ns. The driver has a capability to drive sources at up to 6 A using an external DC power supply.

| Parameter | Transmitter specification |
| --- | --- |
| Bandwidth | 50 MHz, on-off modulation, arbitrary pattern |
| Burst Time/rate | 500 ns/20KHz |

| | |
|---|---|
| Typology | High side current source (programmable), low-side differential current steering |
| Reference Channel | 1 A peak (nominal setting) |
| Signal Channel | 3 A peak (nominal setting) |
| Transmit Power | Control 16 steps each Channel |
| Rise/fall | 4 ns |

The receiver incorporates a state-of-the-art low-noise preamplifier that is coupled to either a PIN photodiode or, optionally, an avalanche photodiode (APD). When using the higher performance APD, an external regulated high voltage bias voltage is needed. The APD is used to increased system sensitivity allowing either increased operating range or reduced measurement times. Before reaching the high-speed digital comparator, specialized analog filtering shapes the return signal originating from the output of the preamplifier.

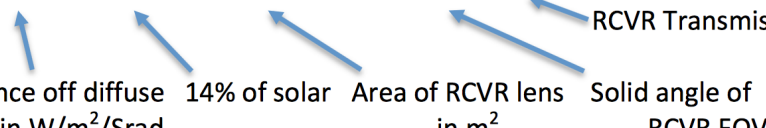| Parameter | Receiver specification |
|---|---|
| Bandwidth | 50 MHz |
| Detector | PIN diode, 500µm by 500µm , 1.5 pF, 1.8 mm diameter lens |
| Virtual Detector size | 1 mm – roughly 2X magnification of the package lens |
| Detector Bias Voltage | 8 V DC nominal. External |
| Preamp Noise Floor | 1 pA/Hz-2 |
| Transimpedance Gain | 40 K ohm |
| Noise Equivalent Power | 12 nW rms |

# Background Light

LIDAR-Lite has been designed to operate effectively under a variety of indoor and bright outdoor solar background lighting conditions. The internal optical absorption filter in combination with the detector spectral response provides a transmission band from 800 nm to 1000 nm. Outdoors, this Spectral window allows roughly 14% of the total solar Irradiance

to pass to the detector. Assuming a solar constant of roughly 1 KW per meter², and a full receiver field of view of two degrees, we get the following calculated DC solar current and detector shot noise:

$$((1000 W/m^2)\,(1/\pi))(.14)(1.1e\text{-}4m^2)(2\pi\,(1\text{-}\cos\,(\alpha/2))\,(.9)$$  ... where $\alpha$ is the Receiver FOV in degrees (2 degrees)
RCVR Transmission

Solar radiance off diffuse reflections in $W/m^2/Srad$   14% of solar   Area of RCVR lens in $m^2$   Solid angle of RCVR FOV

- **Bright solar optical background** = 6 µW - **Solar DC current** = (6e-6 W)(.6 A/W) = 3.6e-6 A - **Shot noise** = ((3.6e-6 A)(2)(1.6e-19)(1/Hz))1/2 = 1 pA/Hz1/2

Under the bright solar conditions and highly reflective diffuse background calculated above, the equivalent receiver input noise floor of 1 pA/Hz would increase by a factor of 1.4 resulting in a slight reduction in maximum range. A 20 nm spectral width narrow band optical filter is available as a factory option and results in a 10 fold reduction in solar DC current or a (10)1/2 = 3 fold decrease in the resulting noise. The narrowband filter is of most benefit in applications where specular, "mirror like" reflective surfaces, are present.

# Power Conditioning

Multiple voltage references are required by various functions on the LIDAR-Lite board. The standard PIN detector requires a DC bias voltage of roughly 8 V generated by an internal voltage multiplier. The use of optional APD detector requires a temperature dependent bias from 100 V up to 240 V depending on the selected detector. This voltage bias is varied based on the temperature compensation coefficient and is applied through the external detector bias input pin. A factory modification is required to allow external application of detector voltages above 30 V DC. A 3.7 V power supply is used by the receiver circuitry and is enabled by the SPC. Transmitter circuitry typically uses the 5 V nominal supply voltage. By default the power supply pin is coupled to the 5 V input through an isolation inductor. An enable pin allows the internal 3.3 V regulator to be disabled allowing very low power consumption under shutdown conditions.

# Operational Overview

Operation of LIDAR-Lite can be separated into two phases; initialization and triggered acquisitions as initiated by the user.

During initialization the microcontroller goes through a self-test sequence followed by initialization of the internal control registers with default values. Internal control registers can be customized by the user through the I2C interface after initialization. After the internal control registers are initialized the processor goes into sleep state reducing overall power consumption to under 10 mA. Initiation of a user command, through external trigger or I2C command, awakes a processor allowing subsequent operation.

The input of a command through the I2C interfaces may initiate an acquisition or an operation to monitor or modify system parameters. In the event of an acquisition request, the system must first power up and initialize the external functions such as the SPC and transmit/receive circuitry. Acquisition begins with the transmission of a reference burst followed by a signal burst. These signal bursts occur over intervals of roughly 50- 100µs depending on the length of the selected correlation record. These signal bursts are repeated until the maximum number of acquisitions have been reached, as defined in the default or user settings or a sufficient number of acquisitions have been performed to achieve a maximum signal strength level. At the completion of the required number of acquisition cycles, the correlation results are processed to calculate the effective time delay of the reference and return within the correlation records. The total acquisition time for the reference and signal acquisitions is typically between 5 and 20ms depending on the desired number of integrated pulses and the length of the correlation record. The acquisition time plus the required 1 msec to download measurement parameters establish a roughly 100Hz maximum measurement rate.

# Mode Control Pin

A bi-directional control and status pin provides a means to trigger acquisitions and return the measured distance via Pulse Width Modulation [PWM] without having to use the I2C interface.

The pin driver in the processor has an internal current source pull-up of roughly 50uA with the driver output coupled to the user pin through a protection diode allowing only sourcing

current into the pin. A low-going transition on the mode control pin will trigger a single measurement, and the pin will be actively pulled high with a pulse width proportional to distance. A 1K to 10K ohm termination resistance will solidly pull the pin low to trigger an acquisition state while allowing the pin to still be pulled high during the PWM output pulse. The pulse width follows a 10usec/cm relationship to the measured distance or 1msec per meter.

A simple triggering method using a standard microcontroller interface uses a 1K ohm resistor in series with an output pin to pull the mode pin low initiating a measurement with a second port pin used to monitor the low-to-high output pulse width. If the pin is held low, the acquisition process will repeat indefinitely producing a variable frequency output proportional to distance.
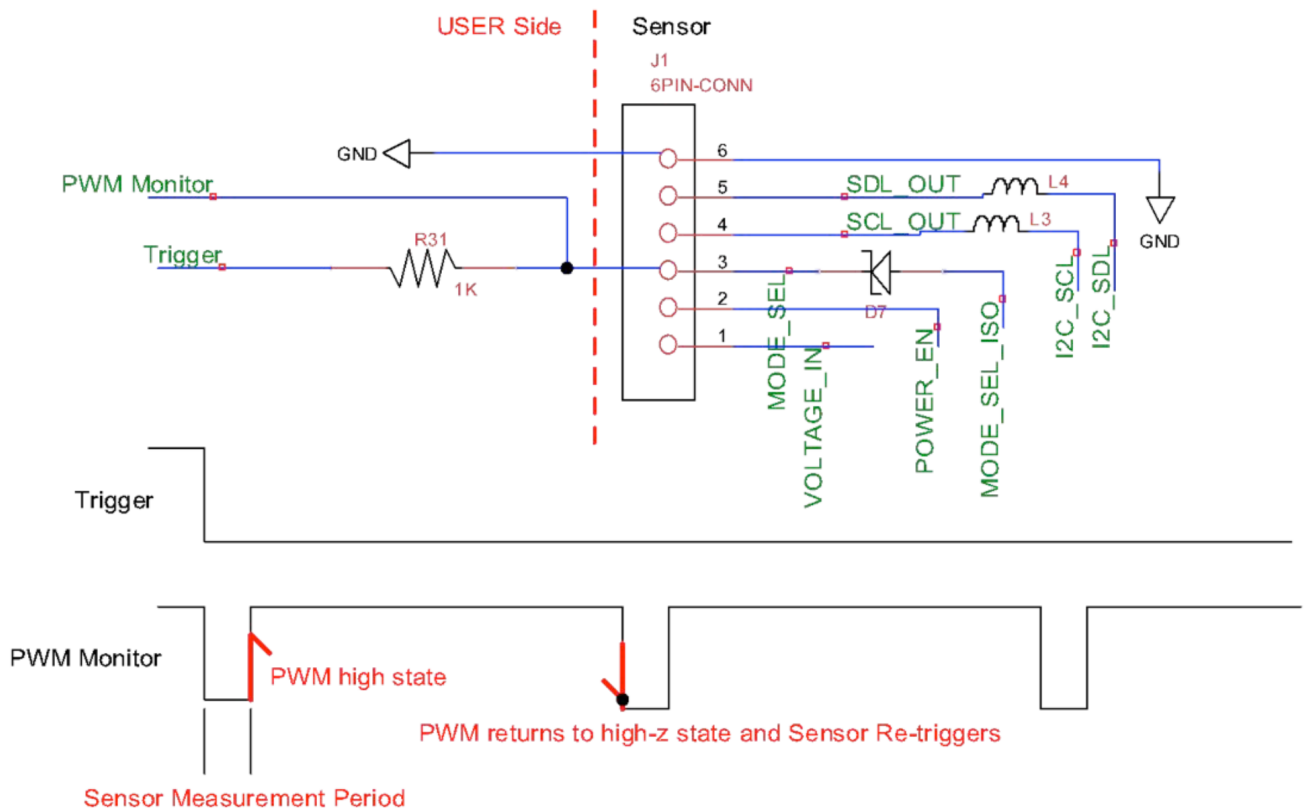


# Acquisition Settings

Signal acquisition parameters can be easily changed to trade-off system performance parameters. If a high measurement rate is required, then the maximum signal integration time can be reduced to decrease measurement times at the expense of somewhat reduced

sensitivity and maximum range. Optical transmit power can be increased by the setting loaded into the Laser Power Register. High pulse power may need to be compensated with an increased spacing between pulse bursts to maintain an acceptable laser duty cycle based on thermal derating requirements. If the length of the correlation record is increased to allow for longer range measurements, increased processing time will decrease the measurement rate.

Key control registers impacting acquisitions:

# Internal register space

| Register | Description |
|---|---|
| control_reg [2] | Maximum acquisition count sets the maximum number of acquisition cycles with a maximum value of 255. In most cases an acquisition of 128 is adequate. |
| control_reg [3] | Correlation record length establishes the portion of correlation memory allocated to the return signal. The value is broken in to upper and lower nibbles where the lower indicates the starting location and the upper nibble the end point. The nibble value multiplied by 64 is its location in memory. A value of 0xf indicates the end of the record with a value of 1024. |
| control_reg [4] | Acquisition mode control establish the enabled acquisition functions such as velocity measurement, lower power consumption states and inhibiting the reference. |

# External register space

| Register | Desciption |
|---|---|
| control_reg [0x43] | Laser power control. |
| control_reg [0x4b] | Range Processing Criteria for two echoes. Max signal, Max/Min Range. |
| control_reg [0x65] | Power management – Sleep states. |

# Signal Acquisition Process

After loading new acquisition parameters or retaining default values, a command is sent to the SPC to initiate a signal acquisition. The steps of the acquisition are as follows: 1. Power is applied to the receiver preamp and, after a prescribed delay, the DC offset at the threshold detector is adjusted to set the effective slicing level or threshold in the middle of the noise distribution. The adjustment process is based on the measurement of the one/zero duty cycle at the comparator output. When the signal offset is nulled, the duty cycle of the noise pattern approaches an average of 50%. In more sophisticated applications the threshold can be offset as part of an algorithm to measure the approximate rms value of the noise supporting diagnostics or as part of a voltage control feedback signal supporting an avalanche photo detector biasing. 2. Prior to starting signal acquisition, the correlation memory is cleared and the transmitter is activated to generate a burst signal pattern that is stored in a signature memory that is used as key element in the correlation process. 3. Signal acquisition begins with the activation of the reference portion of the transmitter, followed by the feeding of the signal pattern necessary to generate the optical reference signal which then passes directly to the receiver photo detector. After amplification and zero-crossing detection, this record is stored in the signal memory. 4. The stored reference signal record is then correlation processed using the transmit pattern stored in the signature memory as a template which is then added to any correlation data previously processed and residing the reference portion of the correlation memory. 5. Next the signal transmit portion of the transmitter is enabled and the outgoing optical signal goes out to a target and the signal return is amplified, detected and stored in signal memory. 6. As in step 4, the stored signal record is correlation processed and then added to any correlation data previously processed and residing in the signal portion of the correlation memory. 7. As the signal and reference acquisitions are repeated, the peak correlation values in the correlation record increase and would ultimately overflow the 12-bit word size. To prevent this overflow condition, the correlation process is terminated for either the signal or reference records when a peak signal within the record exceeds a preset maximum value slightly under overflow. Once both the reference and signal records have reached their maximum values or that maximum acquisition count has been exceeded the acquisition process is terminated. 8. After the signal acquisition process is complete, a low-pass and DC restoring filtering process typically

cleans-up the waveform to improve the final measurement accuracy at low signal conditions and short range. This function can be disabled by resetting the filter enable bit in control register 4 for improved accuracy and resolution at longer ranges.

# Correlation Record

Distance measurements are based on the storage and processing of reference and signal correlation records.

The figure below shows a correlation record for a sensor without optics at short distances of 0, 4 and 8 feet. The reference record runs from 0-63 and the signal record from 64 to 130. Each sample point represents 2nsec or roughly one foot.
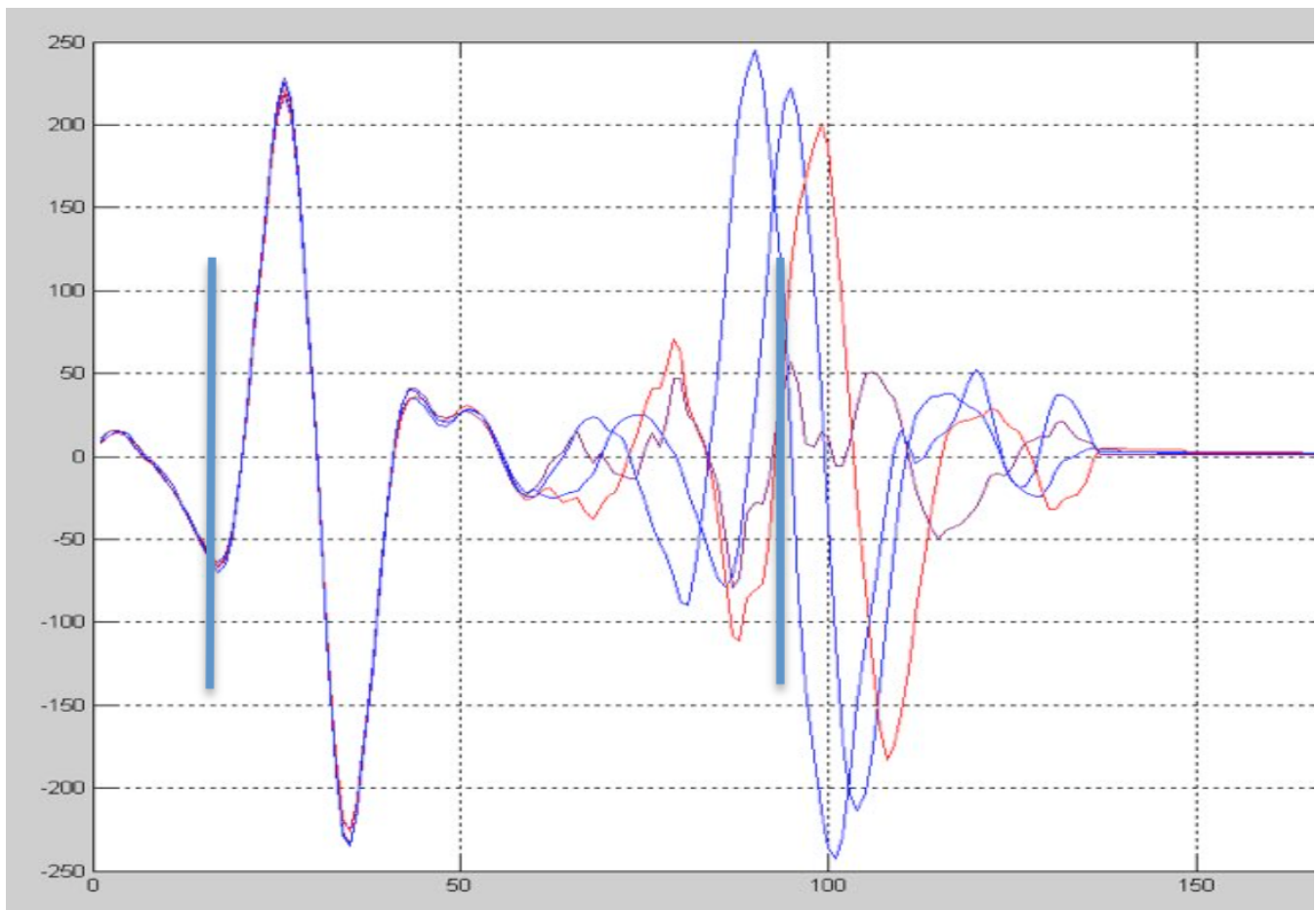


The correlation waveform has a bipolar wave shape, transitioning from a positive going portion to a roughly symmetrical negative going pulse. The point where the signal crosses zero represents the effective delay for the reference and return signals. Processing with the

SPC determines the interpolated crossing point to a 1cm resolution along with the peak signal value.

The figure below illustrates a correlation record example for a long-range system using an avalanche photodiode or APD and laser with a processing chip with a half resolution 2-foot/correlation steps and two-thousand element signal record. The target is at 660 meters and forms the same bipolar correlation wave shape as in the short-range system, but in practice the correlation waveform must be distinguished from background noise present in the correlation record. A correlation record detection threshold is established based on the background noise and if no signals are detected above this threshold, a no signal status indication is provided.
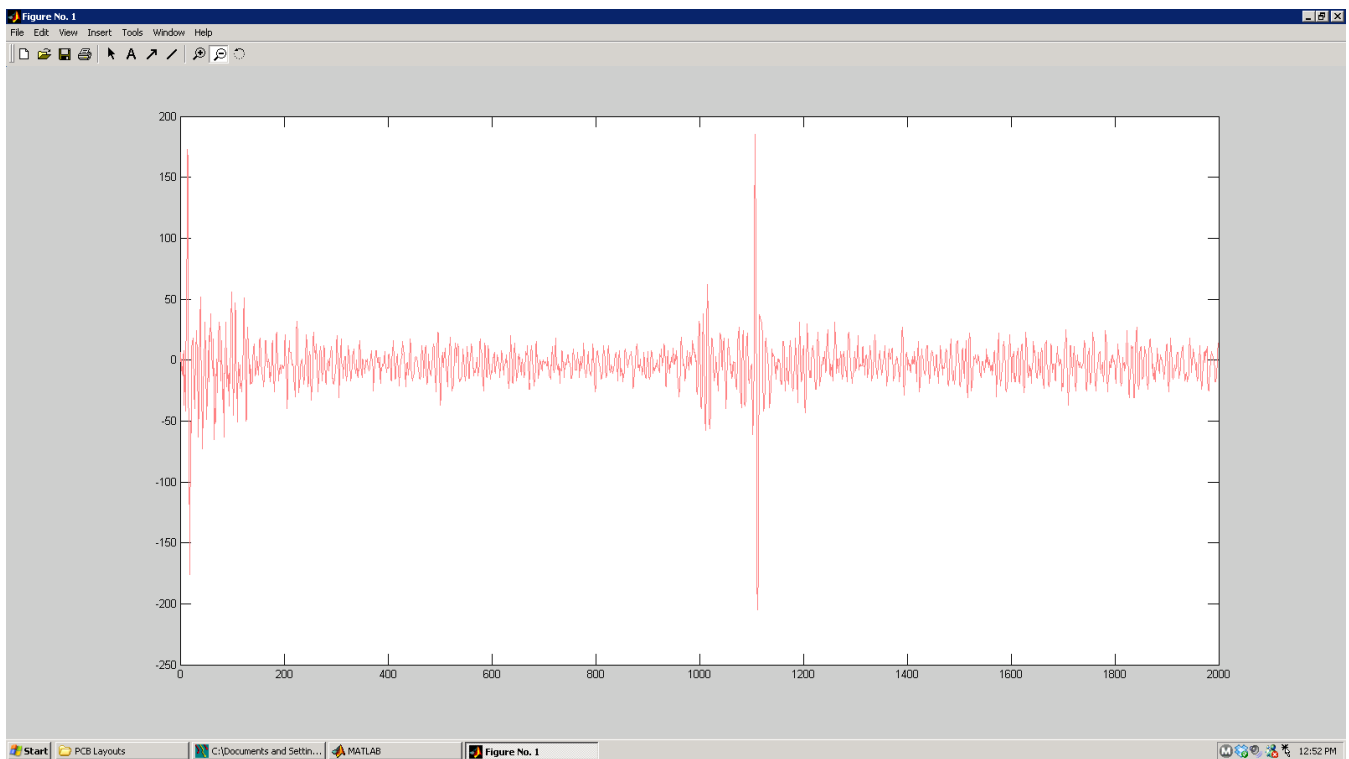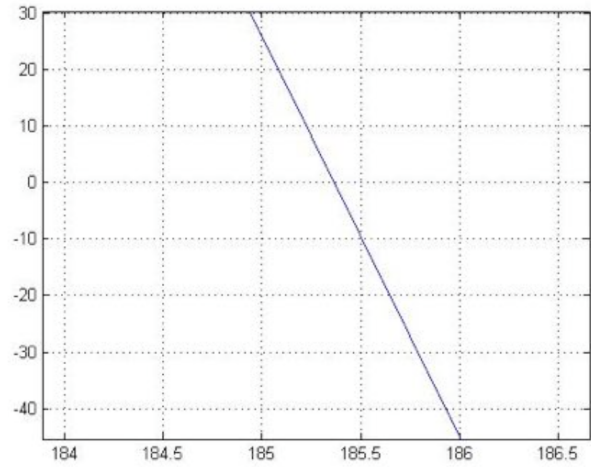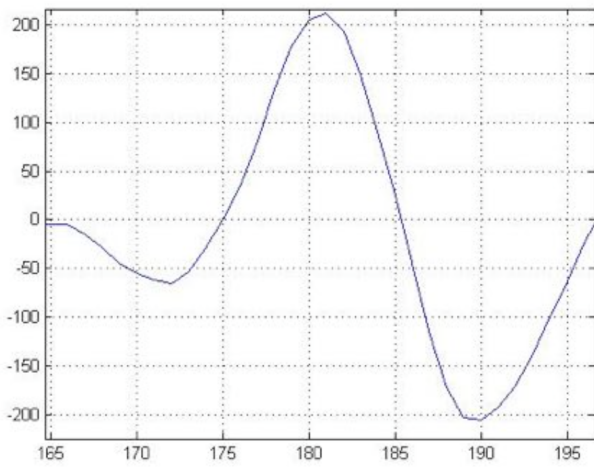


The correlation waveform is shown in more detail below. To distinguish the correlation pulse from the background noise, a specialized processing filter follows the envelope of the noise without being significantly affected by signal correlations present in the record. This noise reference is scaled by 1.25 to provide a detection threshold for the correlation.
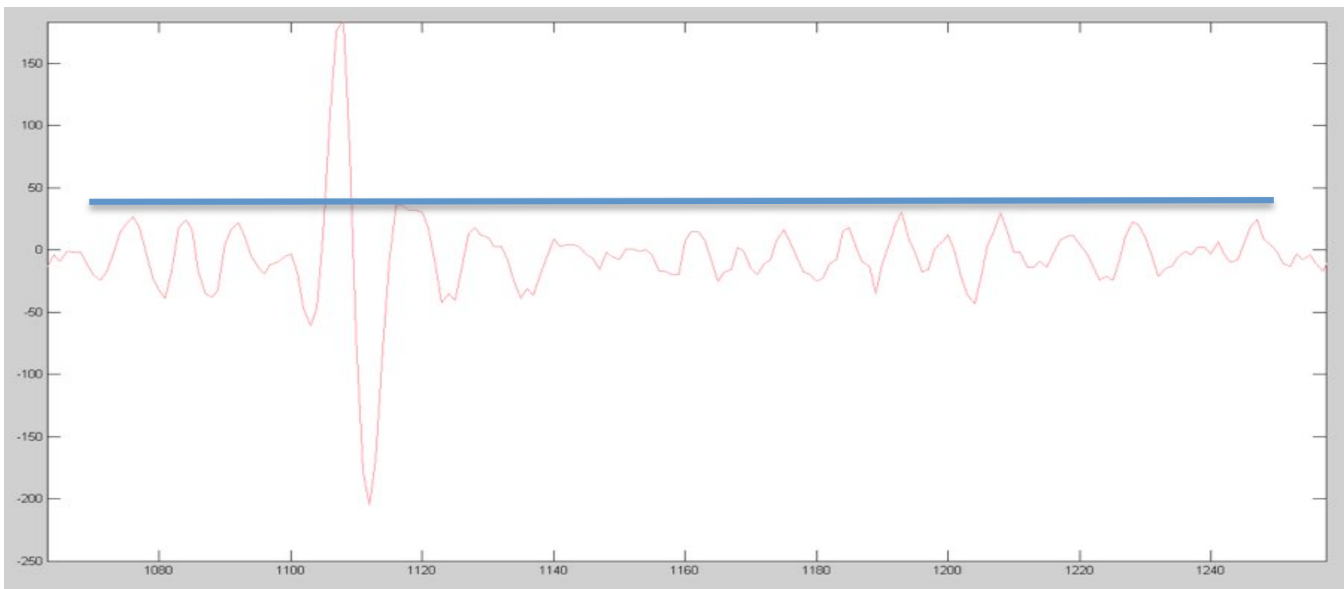
If more than one signal is detected within the correlation record, the return with the next highest signal strength is stored and is available for additional processing. A flag within the status register indicates the presence of a valid second reflection such as from a window or from a shorter-range object illuminated by the beam. The on-board processing of secondary returns is limited to weaker target reflections in the foreground. The correlation record can be downloaded by the user to examine target details in post processing.

# Processing the Correlative Pulse

The calculation of the effective delay is based on the coarse location within the correlation record and the interpolated crossing between sample points. For the full resolution correlation record used in the LIDAR-Lite processor, each sample represents 2nsec in time or roughly one foot or .3 meters. To obtain a result in cm requires 30 resolution points obtained by interpolating between data points. The figure below illustrates a single correlation pulse obtained by processing either the reference or signal.
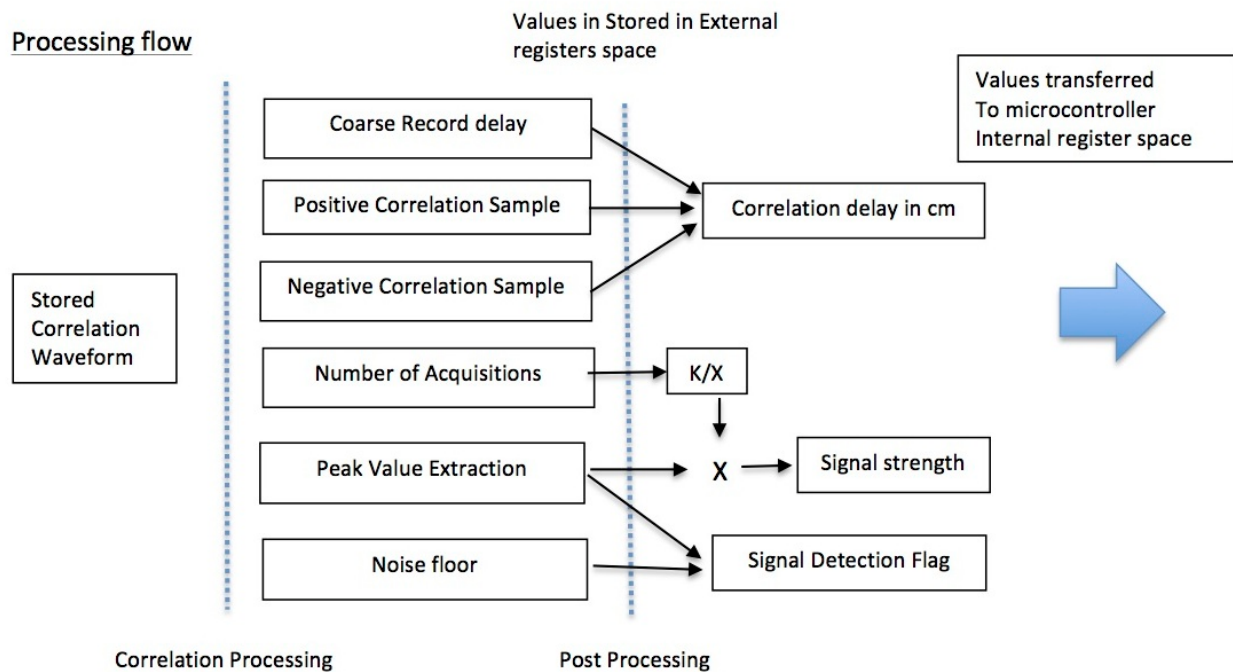
The correlation waveform on the left shows a zero crossing on the falling edge around the location 185. The detail of the crossing on the right shows a linear fit from the upper crossing point at 185 with a value of 26 and a value at 186 of -44. The calculation of the crossing is equal to (26/ (26- -44))*30 or 11.14cm.

To get the total delay we multiply the index of the upper point 185 and multiply by 30 to get the coarse delay in cm. The total delay is then 30 _ 185 + 10 = 5560. If we have a delay for the reference waveform, with a crossing at 30_30 +15 or 915cm we get a measured delay of 5560-915 = 46.45 meters.

# Processing

A module within the processor analyzes the correlation record looking for the largest peak waveform within the record. As it moves through the record, the crossing characteristics of each new larger peak is sampled. At each peak, the coarse delay to the positive sample prior to the zero crossing along with correlation values above and below the crossing and the peak value are stored. With each new peak sample, the previous peak and the crossing data (now the next largest peak sample) is stored to allow post processing of the data to extract the distance and peak value. The secondary peak in some cases may be the small reflection of the beam passing through a window or possibly the reflection off objects in the foreground.

The figure below details the processing flow within the correlation processor after a final correlation waveform is complete.

Processing flow

Values in Stored in External registers space

Values transferred To microcontroller Internal register space

Stored Correlation Waveform

Coarse Record delay

Positive Correlation Sample

Negative Correlation Sample

Correlation delay in cm

Number of Acquisitions → K/X

Peak Value Extraction → X → Signal strength

Noise floor → Signal Detection Flag

Correlation Processing

Post Processing

The processed correlation waveform is processed and the various extracted parameters are stored in the external register space. For both the reference and signal records, the coarse record delay and the positive and negative correlation samples are processed to determine the delay in the record to the correlative peak. The difference between the delay measured for the signal and reference determine the effective round trip delay to the target. The delay is scaled to produce a result in centimeters. Signal strength is determined by multiplying the peak value of the correlation by the scaled inverse of the number of acquisitions. It is an inverse relationship because more samples are required to increase the strength of a small signal than a larger one. A valid signal is determined by comparing the signal peak value with the value of the noise floor observed in the range record.