# CH101 and CH201 SmartSonic Evaluation Kit User Guide

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# 1 INTRODUCTION

This document is a general introduction to using the Chirp SmartSonic Evaluation Kit, including the SonicLink demonstration tool. Basic concepts in ultrasonic sensing are explained, and specific usage scenarios for the evaluation kit are explored.

# 2   USING THE CH101 AND CH201 ULTRASONIC SENSORS

## 2.1   MEASURING DISTANCE USING TIME OF FLIGHT

Most of us have had the experience of seeing a lightning bolt and then using the delay between the flash and the arrival of the thunder to estimate how far away the lightning strike was. For many, the initial flash triggers an immediate response of counting the seconds until the thunder is heard. If we happen to know a rough estimate of the speed of sound (e.g. 3 seconds per kilometer, or 5 seconds per mile), we can easily convert the observed time into a useful approximate distance.

The CH101 and CH201 ultrasonic sensors use this same approach, measuring the time it takes for sound to arrive after a known event, to determine distances at much closer ranges and with high accuracy. This elapsed time is known as the "Time of Flight" (ToF). Both the CH101 and CH201 sensors are very similar but have important differences. Throughout this document, "CHx01" is used to refer to either sensor, as they are interchangeable in the current context. When a feature, operating mode, or any other important difference applies to only one sensor, that sensor will be named specifically.

A CHx01 sensor is an ultrasonic transceiver, meaning that it can both transmit and receive ultrasound signals. Unlike various types of passive sensors which simply measure their surrounding conditions, the CHx01 actively injects a signal into its environment. To perform a basic distance measurement, the sensor will emit a very brief pulse of ultrasound. It then immediately enters a "listening" state, in which it samples the received sound, attempting to identify an echo of the pulse that has been reflected off an object in the sensor's vicinity. If an ultrasound pulse is identified, the sensor will analyze the signal to determine the timing and then report the ToF of the received pulse. The actual distance travelled by the ultrasound can then be calculated from the ToF based on the speed of sound.

## 2.2   SENSING CONFIGURATIONS

A CHx01 device may be used alone or in combination with one or more other sensors. A single sensor always operates in "Pulse-Echo" mode, in which it both transmits and receives an ultrasound pulse. Multiple sensors may operate in "Pitch-Catch" mode, in which one sensor transmits the ultrasound pulse, and one or more sensors receive it. This section explains these different configurations.

### Single Sensor Pulse-Echo

The most basic configuration is a single CHx01 device. In this arrangement, the sensor will both transmit and receive ultrasound to perform the measurements. The device will listen for an echo of its own ultrasound signal, calculate the ToF for the received echo, then notify the host system that the measurement has completed. This is often simply called "Pulse-Echo" operation.
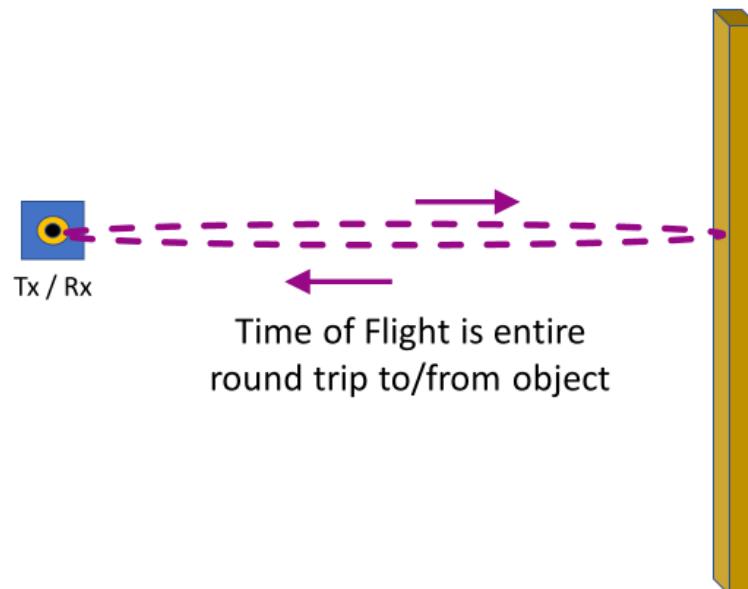


**Figure 1. Single-Sensor Pulse-Echo**

## Multi-Sensor Direct Pitch-Catch

In other applications, multiple CHx01 devices may be used together, in what is often called "Pitch-Catch" operation. One sensor generates an ultrasonic pulse and waits for an echo (Tx/Rx mode), as in the single-device configuration. One or more other sensors are operated in "receive-only" (Rx-only) mode and do not generate ultrasonic pulses. They simply listen for the pulse from the first device. All devices (the transmitting sensor and all receive-only sensors) are synchronized so that the receive-only nodes will start their sampling when the first sensor transmits. All devices then process the received signal, calculate the ToF, and report to the host system.

There are two basic approaches to using a pair of sensors together (one transmitting and another receiving). In some cases, the two sensors are attached to two different objects, and the distance being measured is the direct distance between the two objects. In this situation, the important data values are the range measurements from the receive-only device. The ToF measured in this case is the one-way, direct path between the transmitting and receiving sensors. This mode of operation gives the best performance in terms of measurement accuracy and stability.
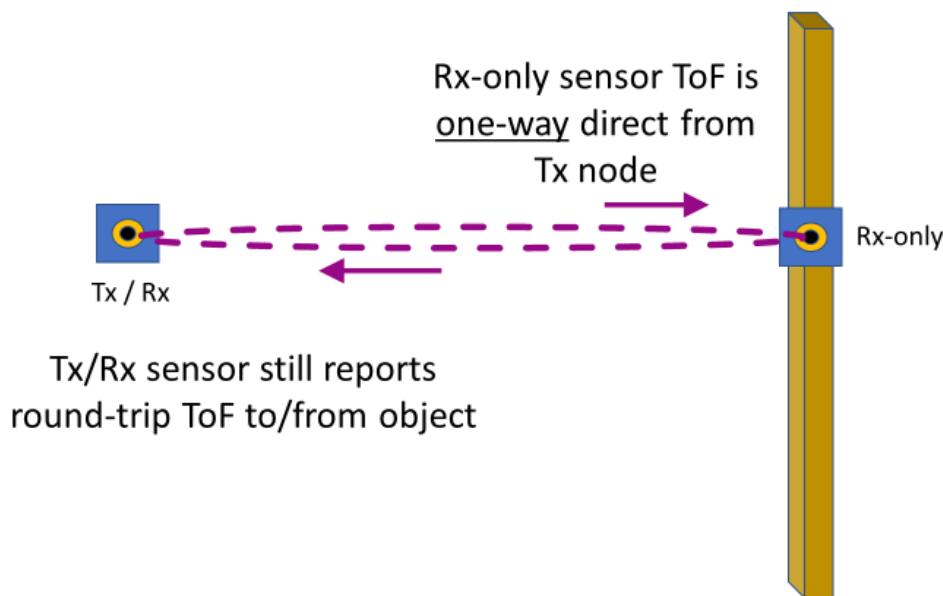


**Figure 2. Direct Pitch-Catch**

## Multi-Sensor Reflected Pitch-Catch

The other way two or more sensors may be used in Pitch-Catch operation is for the devices to be mounted to the same object, with the ultrasonic signal reflected off another object. The receive-only sensor will measure and report the total ToF for the path from the transmitting sensor, bouncing off the target object, and then back to the receiving sensor. Depending on the relative positions of the two sensors and the target object, this distance may differ significantly from a simple single-sensor echo path. Note the use of an acoustic barrier to help prevent the ultrasound pulse from travelling directly between the sensors.
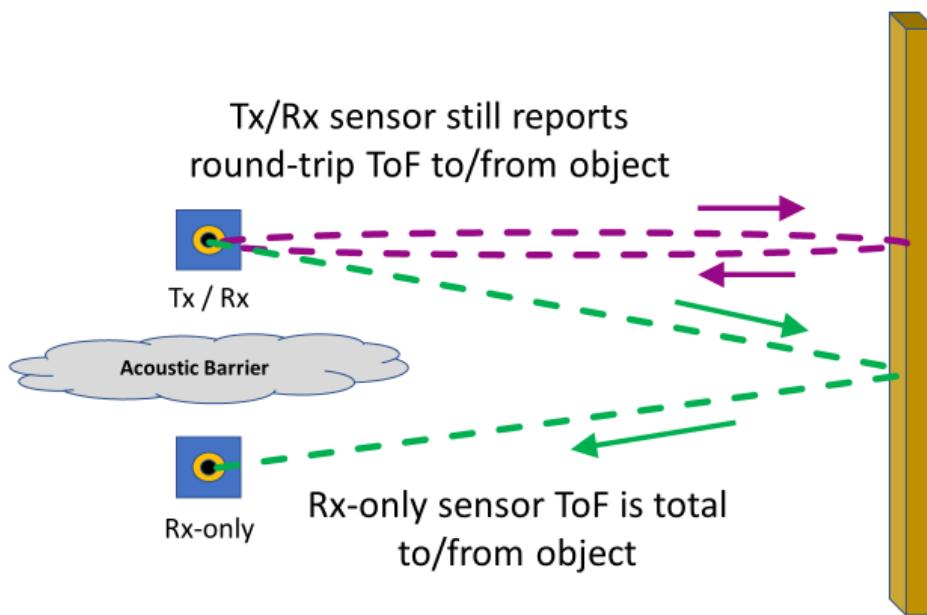
**Figure 3. Reflected Pitch-Catch**

## 2.3 SENSOR SAMPLING AND OPERATING FREQUENCY

When examining the sample timing for a CHx01 device, there are two distinct time bases to consider. The first, slower time-base is the rate at which the sensor begins new measurement cycles (e.g. 10 measurements/sec, 30 measurements/sec, etc.). This is the sample rate that is usually most important to a sensing application, because it determines how often the measurement data will be updated. If the sensor is operating in Free-Running mode, this slow time-base is generated by the sensor's on-chip real-time clock (RTC). In the hardware triggered modes, an external host maintains the slow time-base and triggers the sensor(s) at the appropriate time (See Section 2.5 below).

The second, fast time-base is the internal sample rate used within an individual ultrasonic measurement. The received ultrasound is first demodulated from the ultrasonic transmit frequency to the baseband, and each measurement cycle actually consists of many individual samples of the demodulated baseband signal. The timing of this internal baseband sampling is a function of the sensor's operating frequency. In normal range-finding mode, the baseband sample rate, $f_s$, is equal to the sensor's ultrasonic operating frequency, $f_{op}$, divided by 8,

$$f_s = f_{op} / 8.$$

For CH101 devices, the operating frequency is generally around 175 kHz, while CH201 devices operate around 85 kHz, so the typical baseband sample rate is around 22 kHz for CH101 and around 11 kHz for CH201. CH101 also has a special short-range range-finding mode that uses a higher baseband sample rate, $f_{s,short-range} = f_{op} / 2$, for better performance at short range.

The specific operating frequency used by an individual sensor is set during power-up and initialization, during the device's built-in self-test (BIST). The frequency value may be calculated from device registers read over I²C. In SonicLink, each sensor's frequency is displayed in the console window. Embedded applications may obtain the sensor frequency using the Chirp API and driver.

Because the timing of the individual samples within a measurement is based on the sensor's specific operating frequency, the exact sample timing will vary slightly between devices. This difference becomes significant when the sample offsets (in time) need to be converted to physical distance, because the physical distance represented by a given sample index will vary slightly. Therefore, the device's operating frequency is a component in the calculations when interpreting the reported range value from the sensor, which is expressed in terms of a sample index. (See Converting Between Sample Index and Range, below.)

The internal CHx01 RTC is calibrated against a known time base during device initialization. This is done by applying a pulse of known duration (typically 100 milliseconds) to the sensor's INT line. The device will return a clock count value which corresponds to the calibration pulse length. This count value is later used in the range calculation, along with the duration of the calibration pulse, to establish an accurate conversion between the internal sensor sample offsets and physical distance.

## 2.4 AMPLITUDE SCANS (A-SCANS)

When examining ultrasonic sensor data, a very useful visualization tool is the Amplitude Scan, or A-Scan. An A-Scan is a graph in which the Y-axis represents the amplitude of the received ultrasound, and the X-axis corresponds to the sample index in time. Because the individual samples are evenly spaced in time at the baseband sample rate, the X-axis therefore also represents the distance travelled by the ultrasound pulse.

A-Scans have an important advantage over a simple range value because it is possible to observe the entire trace of sampled data. Multiple different target objects whose reflections show up in the trace can be viewed simultaneously. Often, this is very helpful in understanding the range values that are reported and how multiple objects may affect the ultrasound. SonicLink provides a built-in display of A-Scan data for connected sensors. Figure 4. SonicLink A-Scan display shows an example A-Scan display, captured with a target object at approximately 250 millimeters.
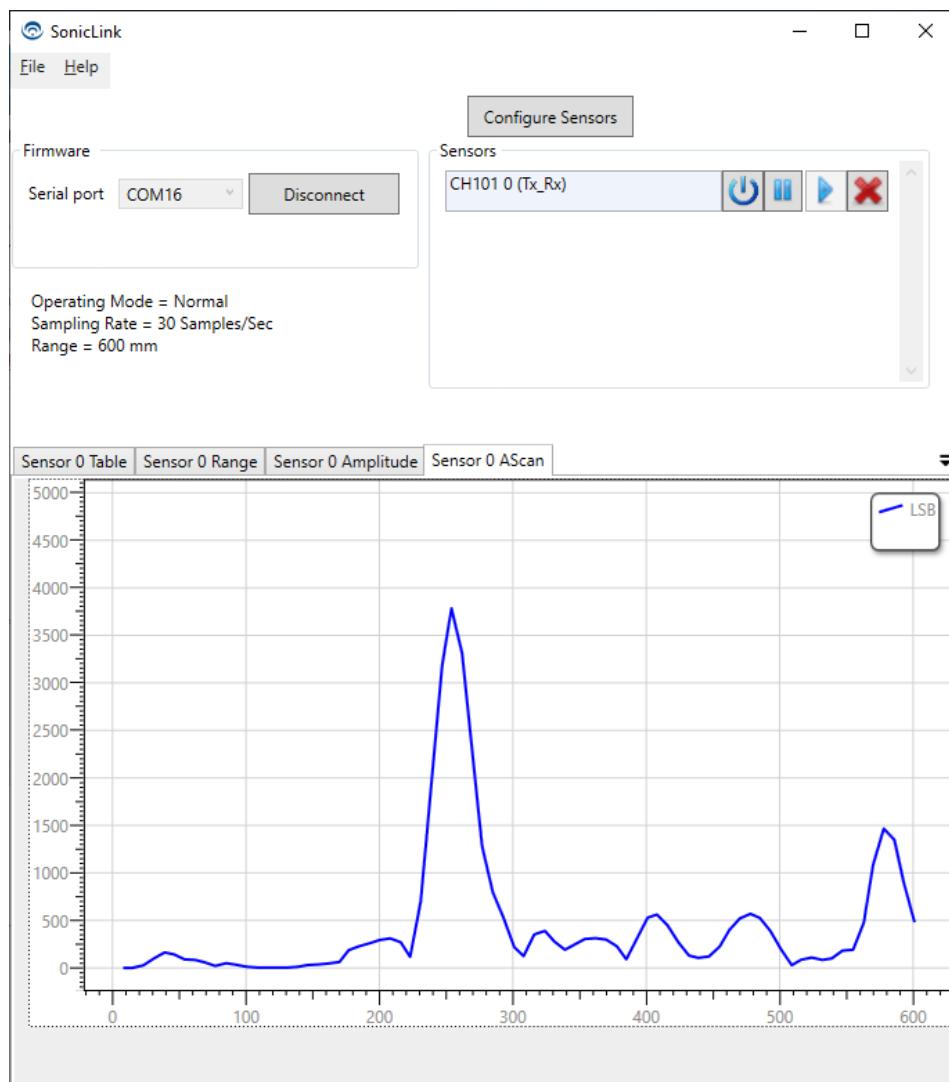


**Figure 4. SonicLink A-Scan display**

## The Signal Path and I/Q Data

It is important to understand how the CHx01 creates A-Scans by processing the sound waves received by the sensor. A CHx01 sensor includes a piezoelectric micromachined ultrasonic transducer (PMUT) and an ASIC microcontroller, both in the same package. The PMUT is used to convert received sound waves into an analog voltage signal, which is then digitized by the ASIC's internal ADC. An example of this signal can be seen in Figure 5, where the direct output of the ADC is shown as $v_{RX}$.
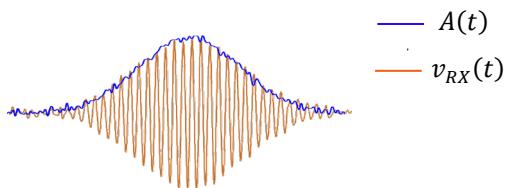


**Figure 5. Raw ADC output $v_{RX}(t)$ and processed A-Scan signal $A(t)$**

Storing and operating upon the raw output of the ADC would be inefficient and time-consuming on the CHx01, so the ADC output is connected directly to a demodulator and a filter. The demodulator splits the output signal into its In-Phase (I) and Quadrature (Q) components, which are then filtered and stored in the CHx01's internal memory as pairs of signed 16-bit integers. This filtered baseband I/Q data still contains the amplitude and phase of the original signal and is significantly more efficient in both memory space and processing time requirements than operating on the original ultrasonic-frequency data. The I/Q data is used internally by the sensor to measure range and can also be read out to a host for additional processing, such as for generating A-Scans.

## Generating A-Scans From I/Q Data

The I/Q data produced by the sensor is the basis of the A-Scan plot. Each pair of I and Q data are the components of a complex number (*I + jQ*) that represents the amplitude and phase of a received ultrasound sample, as shown graphically below:
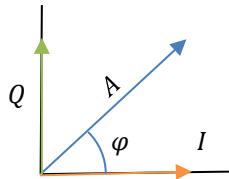


**Figure 6. Relationship between I and Q Values, Amplitude, and Phase**

To convert any given I/Q pair to the amplitude of that sample, square both I and Q, and take the square root of the sum:

$$\text{Amplitude: } A = \sqrt{(I^2 + Q^2)}$$

The units of I, Q and amplitude are LSBs (the least-significant bits of the CHx01's internal analog to digital converter) and are not calibrated to any standard units.

The I/Q data from the sensor may be read by an external host system via the I²C connection. The number of I/Q sample pairs in each measurement is equal to the receive time ($t_{rx}$) multiplied by the baseband sample rate,

$$n = t_{rx} \cdot f_s.$$

In SonicLink, the user specifies a desired full-scale range (FSR) and the receive time is derived from the FSR and the speed of sound at room temperature,

$$t_{rx} = 2 \cdot FSR / (343 \text{ m/s}).$$

The factor of two appears in this equation because the FSR is specified as the one-way range.

When the I/Q data is read from the sensor, the additional time required to transfer the I/Q data over the I²C bus must be taken into account when planning how often the sensor can be read (sample interval). It is important that any data I/O to the sensor, including reading the I/Q data, completes before a new measurement cycle is triggered.

To illustrate the number of I/Q samples and bytes of data to be transferred, consider the following examples.

**Ex. 1:**   CH101 sensor operating at $f_{op}$ = 176 kHz, with 1m full-scale range.

$f_s = f_{op}$ / 8 = 22 kHz          and $t_{rx}$ = 2·$FSR$ / (343 m/s) = 5.8 ms, therefore $n = t_{rx} \cdot f_s$ = 128 I/Q pairs, or 512 bytes per A-scan

**Ex. 2:**   CH201 sensor operating at $f_{op}$ = 80 kHz, with 5m full-scale range.

$f_s = f_{op}$ / 8 = 10 kHz          and $t_{rx}$ = 2·$FSR$ / (343 m/s) = 29.2 ms, therefore $n = t_{rx} \cdot f_s$ = 292 I/Q pairs, or 1168 bytes per A-scan

## 2.5 SENSOR OPERATING MODES

### Free-Running (Self-Timed) Transmit/Receive Mode

When the sensor is in Free-Running mode, it uses a periodic timer based on the sensor's internal real-time clock (RTC) to control the overall pattern of operation. The timer is set to a specific delay corresponding to the sensing interval. When the timer expires, the sensor will wake up and begin an ultrasonic range measurement. When the measurement is complete, the sensor will notify the remote host device by asserting the INT line.

Free-Running mode may only be used by individual sensors operating independently. Multi-sensor configurations must use one of the triggered modes described below.

The internal RTC used in Free-Running mode provides good accuracy, but it is not as stable as a crystal-controlled oscillator typically found on a microcontroller board. Therefore, hardware-triggered mode (see next section) should be used for critical timing applications.

**Note:** Free-Running mode cannot be selected in SonicLink. It is available for embedded applications using the Chirp SonicLib API.

### Hardware-Triggered Transmit/Receive Mode

In many applications, the ultrasonic measurements require more exact timing than the sensor's internal RTC provides in Free-Running mode, or the sensor operation needs to be coordinated with other application activities. In these cases, the sensor's measurement cycle can be initiated by using a hardware trigger, in which the remote host device asserts and then releases the INT line. When the sensor detects that the INT line has been asserted, it will begin a measurement cycle.

The most typical mode for a single sensor is Hardware-Triggered Transmit/Receive (Tx/Rx). In this mode, the sensor will generate an ultrasonic pulse when it is triggered by the INT line from the host. The sensor then listens for a response (echo) for an amount of time based on the maximum range setting of the device. When the measurement cycle is complete, the sensor will notify the host by asserting the INT line. Note that the INT line operates in two directions when used in hardware-triggered mode – first as an input to the sensor (output from host) to initiate the measurement and then as an output from the sensor (input to host) for the measurement-complete notification.

Generally, the host application will repeatedly trigger the sensor based on the host's periodic timer that can maintain an accurate sensing interval. Conversely, the application may wait until specific conditions are met, then initiate an isolated measurement.

### Hardware-Triggered Receive-Only Mode

When more than one ultrasonic sensor is used, they may be configured so that one device operates in hardware-triggered Tx/Rx mode as described above, and one or more other sensors operate in hardware-triggered Receive-Only mode (Rx-only). In this case, all sensors are triggered by the remote host simultaneously via their INT lines. The single Tx/Rx node generates an ultrasonic pulse and listens for an echo as normal. All Rx-only nodes will simultaneously begin their own listening periods, but without sending an ultrasonic pulse. Instead, the Rx-only sensors simply wait to detect the pulse that was sent from the Tx/Rx sensor (either directly, or as an echo off another object).

When each sensor completes its measurement cycle, it will notify the remote host by asserting its INT line.

### Idle Mode

If the sensor will not be used by the application for an extended period, it may be placed into a low-power Idle mode. No sensing will be performed when in Idle mode. To resume sensing operation, the sensor must be placed into one of the regular modes (see above).

**Note:** Idle mode may not be selected in SonicLink. It is available for embedded applications using the Chirp SonicLib API.

## 2.6 SETTING THE MAXIMUM RANGE

The CHx01 sensor has a configurable full-scale range (FSR), meaning that the application may set the maximum distance at which the sensor will detect an object. Any value up to the rated maximum range for the device may be specified.

Range setting values refer to the one-way distance to a detected object.

In practice, the FSR setting controls the amount of time that the sensor spends in the listening (receiving) period during a measurement cycle. Therefore, the FSR setting affects the time required to complete a measurement. Longer full-scale range values will require more time for a measurement to complete.

## 2.7   SETTING THE SAMPLE INTERVAL

Most applications require sensor measurements at regular intervals. The CHx01 sensor provides both internal and external timing options to implement a sample interval.

### Free-Running vs. Hardware-Triggered

In Free-Running (self-timed) mode, the CH101 uses an internal clock (RTC) to autonomously establish the sampling period. The sensor will periodically wake up, perform a measurement, notify the host, and go back to a low-power sleep mode. No interaction with the remote host is required.

In the Hardware-Triggered modes (either Tx/Rx or Rx-only), the sensor is awakened (triggered) by the INT line being asserted by the remote host system, performs its measurement, notifies the host system, and then goes back to low-power sleep. The remote host system is responsible for setting up a periodic timer to initiate the sensor measurements on the desired schedule.

### Processing Time Requirements

When deciding on a sample interval, it is important to allow enough time for a full measurement cycle, including all data output from the sensor, to complete before the next cycle is initiated. If a new measurement cycle is begun while the sensor is still outputting data, the current measurement may be corrupted. Typical measurement times for CH101 and CH201 are shown in Table 1 below.

The largest variable in the sensor processing timing is the maximum range setting. The maximum range setting determines how much time the sensor will spend listening for a detected ultrasonic pulse, once the cycle has been initiated. Each meter of range represents two meters of sound travel (both to and from the target object), so requires about 6 milliseconds of listening time.

When the listening period completes, the sensor processes the received signal. Typical processing time is approximately 5 milliseconds for CH101 at 100 cm FSR and 6 ms for CH201 at 500 cm FSR.

The Static Target Rejection (STR) feature, if used, requires additional processing time. STR filters out static objects from the reported data over a specified portion of the overall range. The processing time requirements will vary based on how many samples are included in the STR processing. For long STR range values (i.e. the full 150 possible samples in the CH101), the additional processing time may be up to 3 milliseconds, as shown in Table 1 below. Note that CH201 uses a special sensor firmware version for STR, with a maximum of 290 samples per measurement, so full 5 meter range may not be possible.

*Note: When STR is enabled in SonicLink, the STR range is always set to match the selected full-scale range for the sensor.*

The maximum range setting and STR will both affect how long the sensor takes to notify the host system that a measurement is complete.

If the I/Q data is read from the sensor after each measurement, the transfer time over the I²C bus is also very important. At 400 kbps, the time required to transfer 150 I/Q pairs or 600 bytes is 12 ms. For example, the time for a CH101 sensor to complete a rangefinding measurement at 100 cm full-scale range is 10.4 ms without I/Q data transfer. Transferring 150 I/Q pairs required 12 ms additional time, so the total time to complete the measurement and transfer the data is 22.4 ms in this example.

**(a)  CH101**

| FSR (CM) | MEASUREMENT TIME (MS) | | TYPICAL A-SCAN I²C TRANSFER TIME (MS) |
| --- | --- | --- | --- |
| | STR OFF | STR ON | |
| 30 | 3.8 | 4.7 | 6 |
| 60 | 6.6 | 8.6 | 12 |
| 100 | 10.4 | 13.6 | 12 |

**(b)  CH201**

| FSR (CM) | MEASUREMENT TIME (MS) | | TYPICAL A-SCAN I²C TRANSFER TIME (MS) |
| --- | --- | --- | --- |
| | STR OFF | STR ON | |
| 100 | 8 | 10 | 8 |
| 300 | 22 | 25 | 23 |
| 500 | 35 | n/a | 38 |

**Table 1. Typical measurement time and A-scan I²C transfer time for CH101 and CH201. When A-Scan data is read from the sensor, the transfer time should be added to the Measurement Time to estimate the total time required to complete the measurement and get the A-Scan data.**

## 2.8 MEASURING RANGE (DISTANCE)

### How the Sensor Reports Range

After the CHx01 sensor completes its listening period, it analyzes the captured I/Q data to identify signals that represent objects in its field of view. Those objects may be located in different directions from the sensor, but they are combined into a single record with one amplitude value for each sample.

The sensor determines the presence of an object by comparing the amplitude of each sample within the captured I/Q data against a threshold value. The threshold value that is used may vary across the range of the device to compensate for the weaker signals from far-away objects. When the amplitude of the signal exceeds the corresponding threshold value, an object has been detected and will be reported. The resulting ToF range (mm) and amplitude (LSB) are 16-bit values provided by the sensor.

Because the ultrasonic pulse emitted by the CHx01 is very brief, it creates a sharply defined signal in the received amplitude values, as can be seen in the A-Scan examples in this document. The CHx01 signal processing is designed to report a range value corresponding to the "leading edge" of the pulse, i.e. a point mid-way during its rise before reaching a peak (specifically, the reported value is the halfway point between the range at which the rising signal exceeds the detection threshold value and the pulse peak). Because this midpoint will typically fall between discrete samples, the CHx01 interpolates between sample values when calculating the range. As a result, the CHx01 range output has finer resolution than the spacing between I/Q samples. The CHx01 will report the maximum amplitude of the pulse at its peak.

Figure 5 shows an A-Scan plot with a single target object. The red line indicates the reported range (in mm) and the green lines indicate the reported amplitude value. Below the A-Scan plot, the sensor data table shows the measured range and amplitude values returned by the sensor.
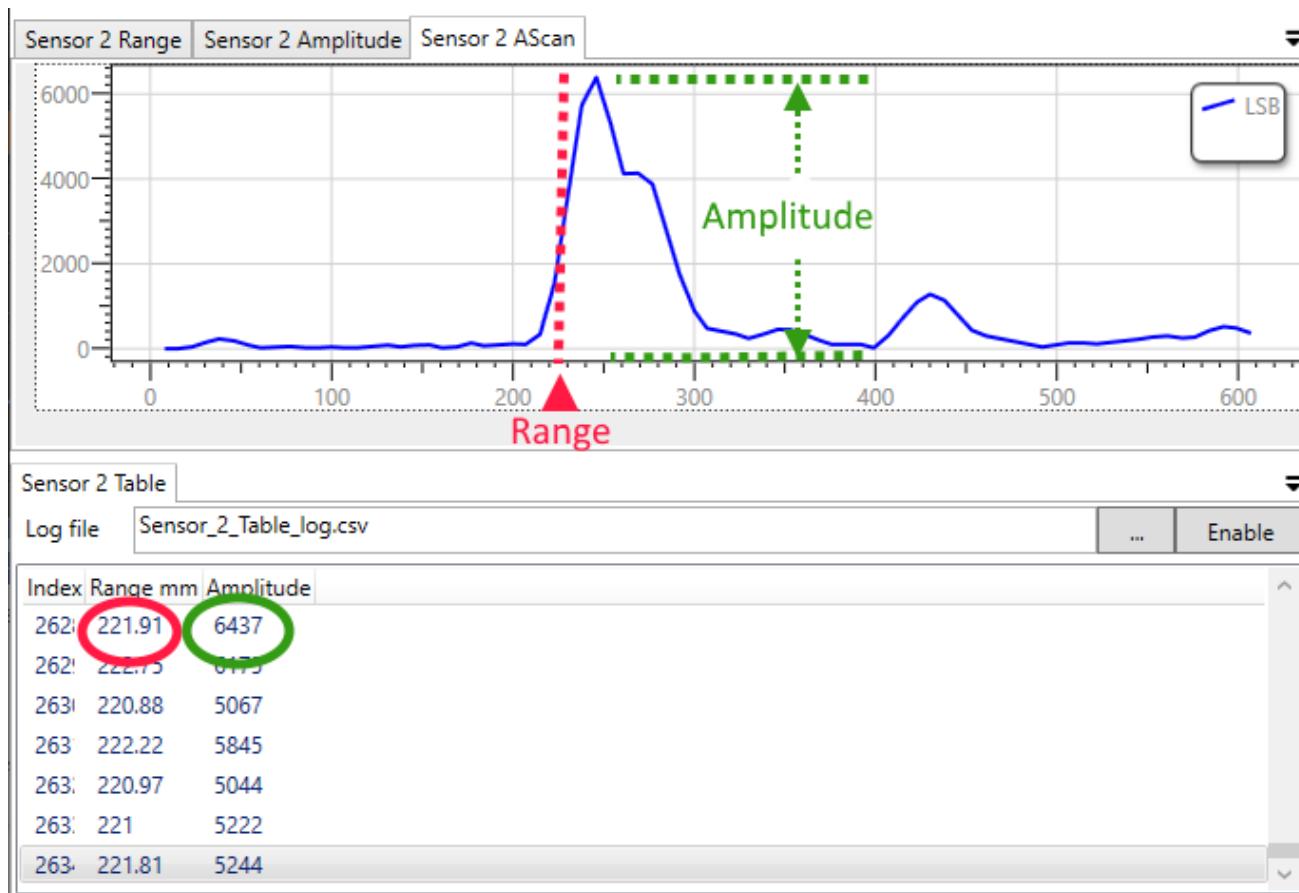


**Figure 7. Single-Target A-Scan**

**Note:** The amplitude displayed in the sensor table is the amplitude computed by the CHx01's on-chip algorithm, which is a factor of 0.82 lower than the value displayed in the A-Scan plot (5244 LSB in the table versus 6400 LSB in the plot). The factor of 0.82 difference is due to the fact that, for faster computation speed, the CHx01 does not use a square-root function to calculate the amplitude.

When multiple objects are in the field of view of the sensor, there may be multiple received signal pulses which exceed the corresponding threshold values. In this case, the CHx01 always reports the closest object that exceeded its threshold. Even if there is a farther, larger amplitude object signal, only the closest object will be reported. To help manage a sensor's behavior in such a situation, see Section 2.10 or Section 4.1 (CH201 only), below.

## Converting Between Sample Index and Range

The sensor operates internally on samples driven by its own internal clock, whose frequency will vary somewhat from one device to another. As a result, the time between samples (and therefore the physical distance each sample index represents) will be different. So, the acoustic operating frequency of the device must be included in any conversions between internal sample index-based values and real-world physical distance.

To convert a sample index to a range value, you must also know the device's acoustic operating frequency, $f_{op}$. The sensor obtains a sample every 8 clock cycles, so the internal sample rate ($f_s$) equals $f_{op}$ / 8, and the time interval between samples ($t_s$) equals 8 / $f_{op}$.

**Note:** When using the CH101 short-range firmware, the internal sample rate is $f_{op}$ / 2, which is 4 times faster than the sample rate in the Normal mode. The following formulae should be adjusted accordingly. See Section 3.1 below.

The formula to convert a sample number into the corresponding time of flight ($t_{ToF}$) is:

$$t_{ToF} = nt_s$$

$$t_{ToF} = n\frac{8}{f_{op}}$$

where the time of flight ($t_{ToF}$) and the sampling interval ($t_s$) are in seconds, the acoustic operating frequency ($f_{op}$) is in Hertz, and the sample index ($n$) is unitless.

Note that this calculation returns the total ToF. So, if the range that is being reported is based on the echo off an object, it represents the total distance both to and from the object (round-trip). To obtain a one-way distance from an echo's round-trip ToF, the range value must be divided by two.

To convert the sample number into the corresponding one-way physical distance ($d$), multiply by the speed of sound in air and divide by two, like so:

$$d = \frac{1}{2} \cdot c \cdot t_{ToF}$$

$$d = \frac{1}{2} \cdot c \cdot \frac{8}{f_{op}} \cdot n$$

where the distance ($d$) is in meters and $c$ is the speed of sound (343 meters per second in air at standard temperature and pressure).

For ease of use, SonicLink allows users to input distances in millimeters and automatically converts these to samples. Additionally, the Chirp SonicLib API provides helper functions that will convert distances in millimeters to samples and vice versa, as some API functions expect arguments in samples (such as STR functions). Because of this, understanding the relationship between samples and distance gives users a powerful debugging and performance-tuning tool. We have included some worked examples below for illustrative purposes.

**Example 1:** A user debugging their application notices an unexpected peak in the A-Scan trace. The user's CH201 is detecting a target before this peak, so the CH201 will not automatically convert the range for them. To find out what is causing this behavior, the user will need to convert the distance to this peak (in samples) manually to the one-way distance to this unexpected reflection. Given that the CH201 has an acoustic operating frequency ($f_{op}$) of 88 kHz and the unexpected peak starts at sample $n$ = 50, what is the one-way distance from the sensor to this reflection?

$$d = \frac{1}{2} \cdot 343 \cdot \frac{8}{f_{op}} \cdot n$$

$$d = \frac{1}{2} \cdot 343 \cdot \frac{8}{88} \cdot 50$$

$$d = 780 \; mm$$

*The user should look 779.6 mm away from the sensor to discover the source of this reflection.*

**Example 2:** A user notices that a second peak that consistently appears beyond the desired target at a fixed offset (i.e. distance). The user suspects that they may be able to use this information to improve the functionality of their application. To investigate this opportunity, the user needs to know how far away this second peak is, and notes that the second peak is always 15 samples away from the target. Given that the user is using a CH101 with short-range firmware, with an acoustic operating frequency of 175 kHz, how far away is this second peak?

$$d = \frac{1}{2} \cdot 343 \cdot \frac{2}{f_{op}} \cdot n$$

$$d = \frac{1}{2} \cdot 343 \cdot \frac{2}{175} \cdot 15$$

$$d = 29 \; mm$$

*The user should look 29 mm away from the target to find the source of this second peak.*

## 2.9   UNDERSTANDING A-SCAN DATA

A-Scan data is very useful when trying to interpret readings from the CHx01 sensor, especially in cluttered environments. This example shows a simple case with two similar target objects at different distances from the sensor, and what the A-Scan display will indicate.

In this example, a CH101 sensor is connected to a SmartSonic board by a flat flex cable and attached to a mounting plate facing horizontally. Two cups are placed on a table within the sensor's field of view at slightly different distances, as shown in the following photo:
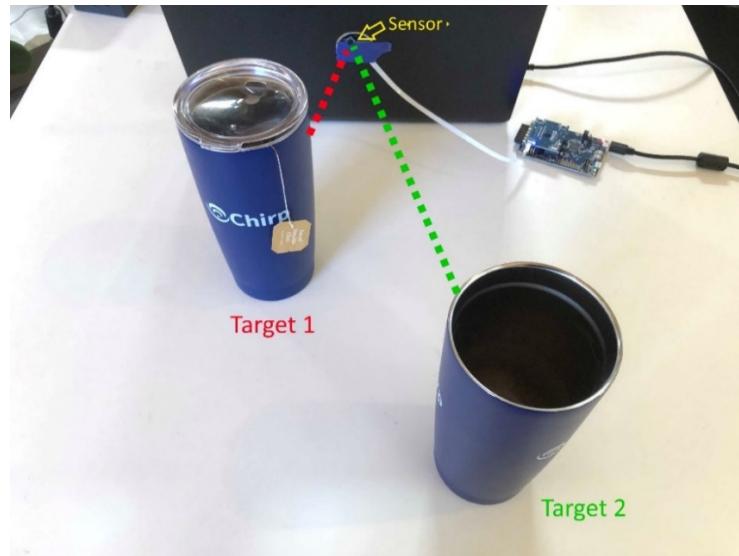


**Figure 8. Two-Target setup**

The A-Scan captured from this set-up looks like this:
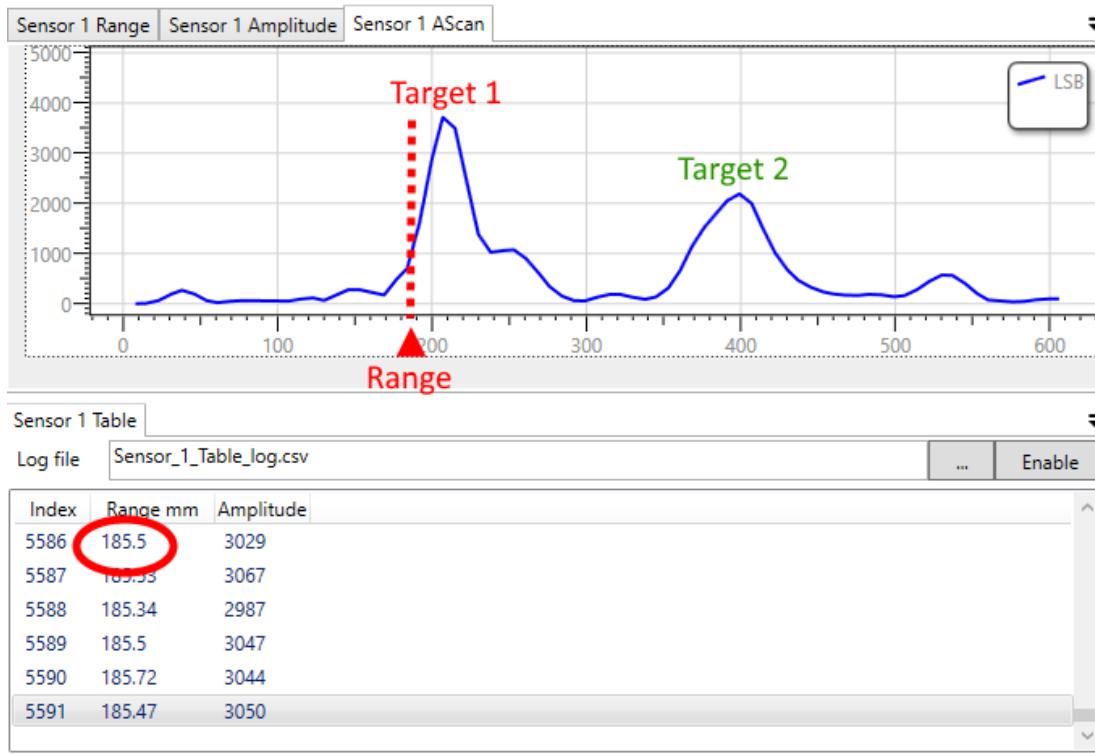


**Figure 9. Two-Target A-Scan**

The A-Scan shows that the reported range value is the distance to Target 1 because it is the first (closest) object that was detected. Although the amplitude of the Target 1 signal is stronger than Target 2, that is <u>not</u> the basis for the decision which target to report. Even if the Target 2 signal were stronger, the reported range would still refer to Target 1.

Note that because the amplitude of the echo signal decreases with the square of the distance, it would be unusual for the further of two identical targets to return a higher amplitude signal. However, this may be a consideration when observing smaller targets with a larger object (e.g. a wall) in the background.

For applications where the sensor is used to find the range to the closest target, Chirp recommends using the range output and not the I/Q data output, as this enables operation at high sample rates and with low power consumption. Transferring the I/Q data over I²C is time-consuming (at 400 kbps, the time required to transfer 150 I/Q pairs or 600 bytes is 12 ms) and also increases power consumption. For such applications, the A-Scan display of the I/Q data is intended to be used as a debugging and development tool only.

However, some customers may want to develop more complicated algorithms that required the use of a complete I/Q trace to improve single target identification or enable multi-target tracking. For such algorithms, the host application may read the full I/Q (A-Scan) data, or a subset, and analyze it as necessary.

## 2.10  STATIC TARGET REJECTION (STR)

Static Target Rejection (STR) is a runtime option available on the standard GPR firmware for the CH101 and is also available in special STR firmware for the CH201. STR enables the on-chip range-finding algorithm to ignore static objects when determining the range to the nearest moving target. Users often find that the CH101's wide FoV allows it to detect unexpected or undesirable objects as targets, such as on a cluttered desktop containing coffee cups, computer monitors, and other large, flat surfaces. Although the CH201 typically uses a narrower FoV, the same issues may occur.

Static Target Rejection works by applying a moving-average high-pass filter over the Full-Scale Range. In typical operating conditions with a stationary CHx01 and a static target, the steady amplitude from the target's echo will be filtered and ignored. Moving targets will vary in distance and amplitude, and even movements of millimeters can create a detectable signal. Note that, under some conditions, such as high airflow around the sensor, the echo amplitude of a static target can vary enough to register as a target.

Enabling Static Target Rejection requires additional processing by the CH101, resulting in an increase in latency, up to 3 ms for 1m FSR. Because of this additional time requirement, users should not enable both STR and A-Scan output at the maximum FSR (1m) and maximum A-Scan sample rate (10 samples/sec) in SonicLink. The required processing for the STR algorithm and I/Q data transfer time would be too long to complete during the 100 ms measurement period.

## How to use Static Target Rejection

In the following example, a user is trying to detect a moving hand. However, an unexpected nearby target (the coffee cup) prevents them from seeing the expected target (their hand).
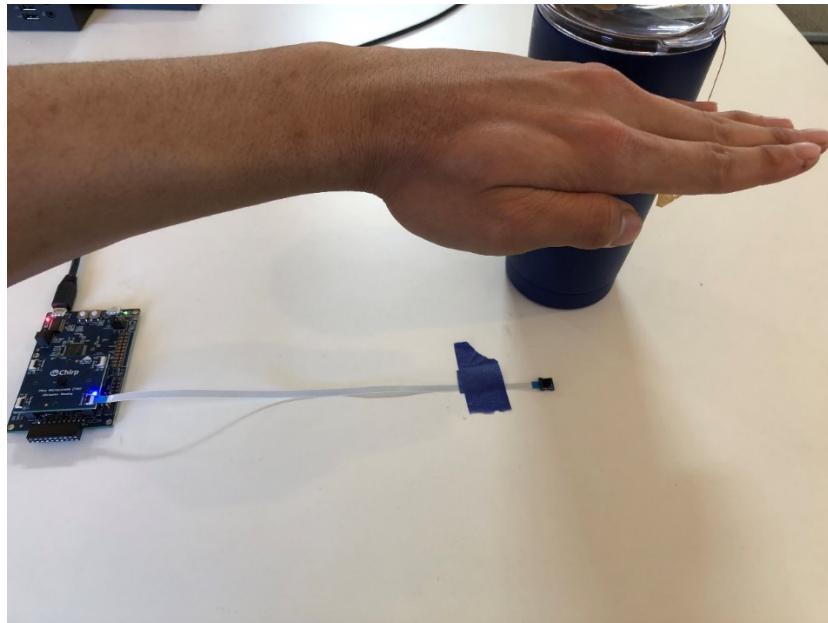


**Figure 10. STR Setup**

Looking at the A-Scan view, the user can clearly see what's happening; the coffee cup (at ~170 mm range) is closer than the user's hand (at ~280 mm range), so the CH101 dutifully reports the nearest target.
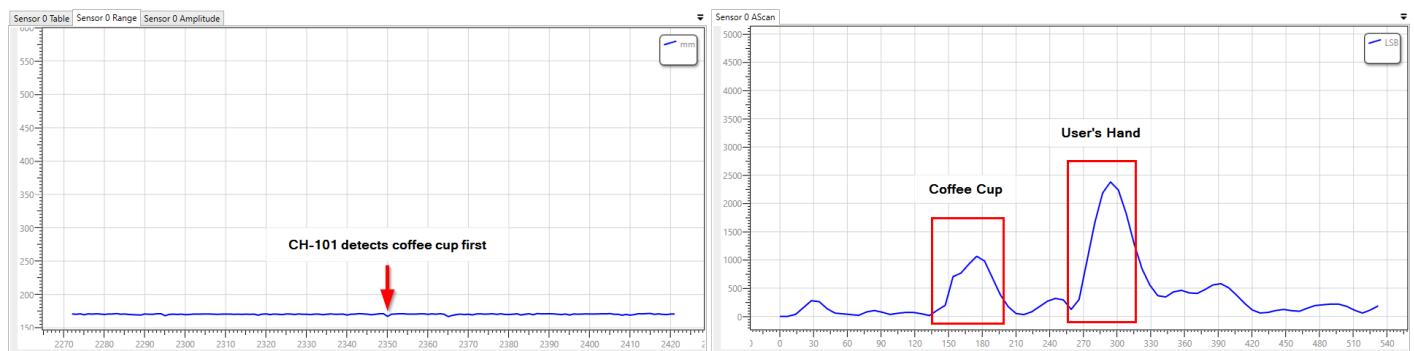


**Figure 11. Two-Target Detection without STR**

By opening the "Config Sensors" menu in SonicLink, the user can enable Static Target Rejection:
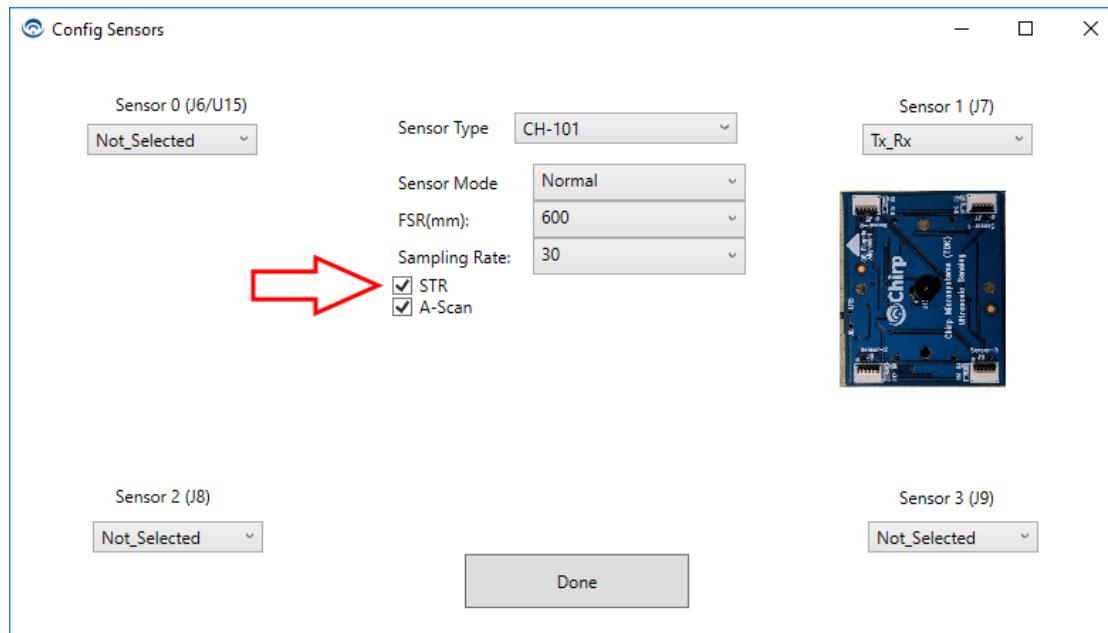


**Figure 12. Enabling STR in SonicLink**

With Static Target Rejection set, the user restarts data collection. The user waves their hand over the sensor to confirm that Static Target Rejection is working as expected, and the range output now tracks the moving hand's motion.
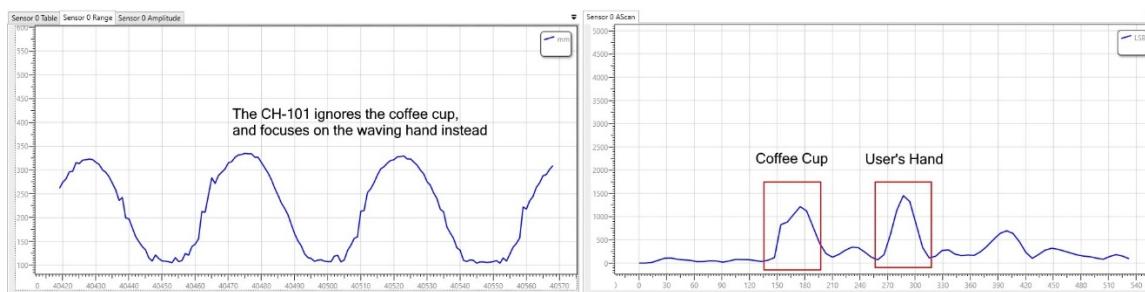


**Figure 13. Two-Target Detection Using STR**

# 3   CH101-SPECIFIC FEATURES

## 3.1   SHORT RANGE MODE

When a target is too close to the sensor, the target will be detected but the range output may not be accurate. The minimum distance for accurate range output is different for static (non-moving) targets and moving targets; moving targets can be detected at closer range because they are easier to detect than static targets. When programmed with the General Purpose Rangefinder (GPR) firmware, the range output is accurate for a static target at a minimum distance of 100 mm. When an object is closer than 100 mm from the sensor, the range output will indicate approximately 100 mm range.

The CH101 sensor may also be programmed with Short Range firmware to operate in a special short-range mode to optimize the range measurement accuracy for objects at close range. This is not a runtime-selectable option and must be enabled by initializing the CH101 device with an alternate short-range firmware image during system startup. SonicLink allows selection of Short-Range or Normal (GPR) mode during sensor configuration.

When in short-range mode, the CH101 samples at four times the normal rate, to obtain more data during the shorter ToF. As a result, the maximum possible FSR of the sensor is also reduced by a factor of four, to 250 mm.

In short range mode, the CH101 range output is accurate for moving objects at a minimum range of approximately 40 mm. When an object is closer than 40 mm, the range output will fluctuate between several short-range values. Due to internal filtering in the CH101 sensor, non-moving objects closer than 90 mm may not be detected until either the sensor or object is moved slightly.

The following photo shows an example setup with a CH101 sensor aimed at a drinking cup target. The distance between the sensor and the cup is approximately 38 mm.



**Figure 14. Short Range Setup**

At this close range, a CH101 device using standard GPR (not short range) firmware will detect that an object is present, but it will be unable to report an accurate range measurement. Typically, a relatively constant range value, corresponding to the low-end of the device's reporting range (approximately 100 mm), will be returned. The A-Scan output from a sensor using standard GPR firmware is shown in Figure 15, along with the (inaccurate) range measurement values.
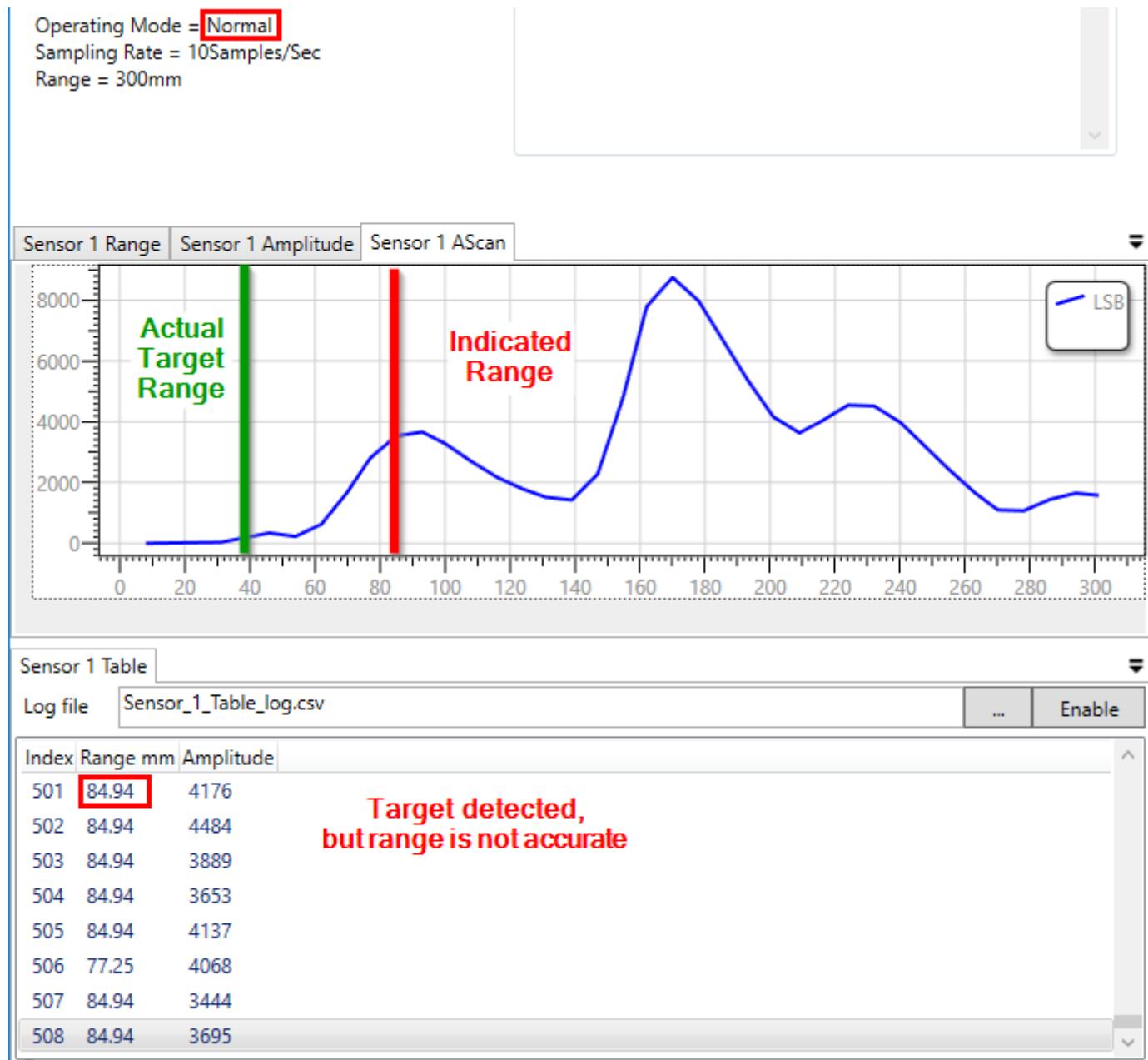
**Figure 15. Short Range Errors When Using Standard GPR Firmware**

If short-range operation is enabled (by changing the device configuration in SonicLink), the CH101 is now able to accurately measure the distance to objects at closer range. Figure 16 shows the A-Scan for a device in short-range mode, with the same setup as above.

Operating Mode = ShortRange
Sampling Rate = 10Samples/Sec
Range = 150mm
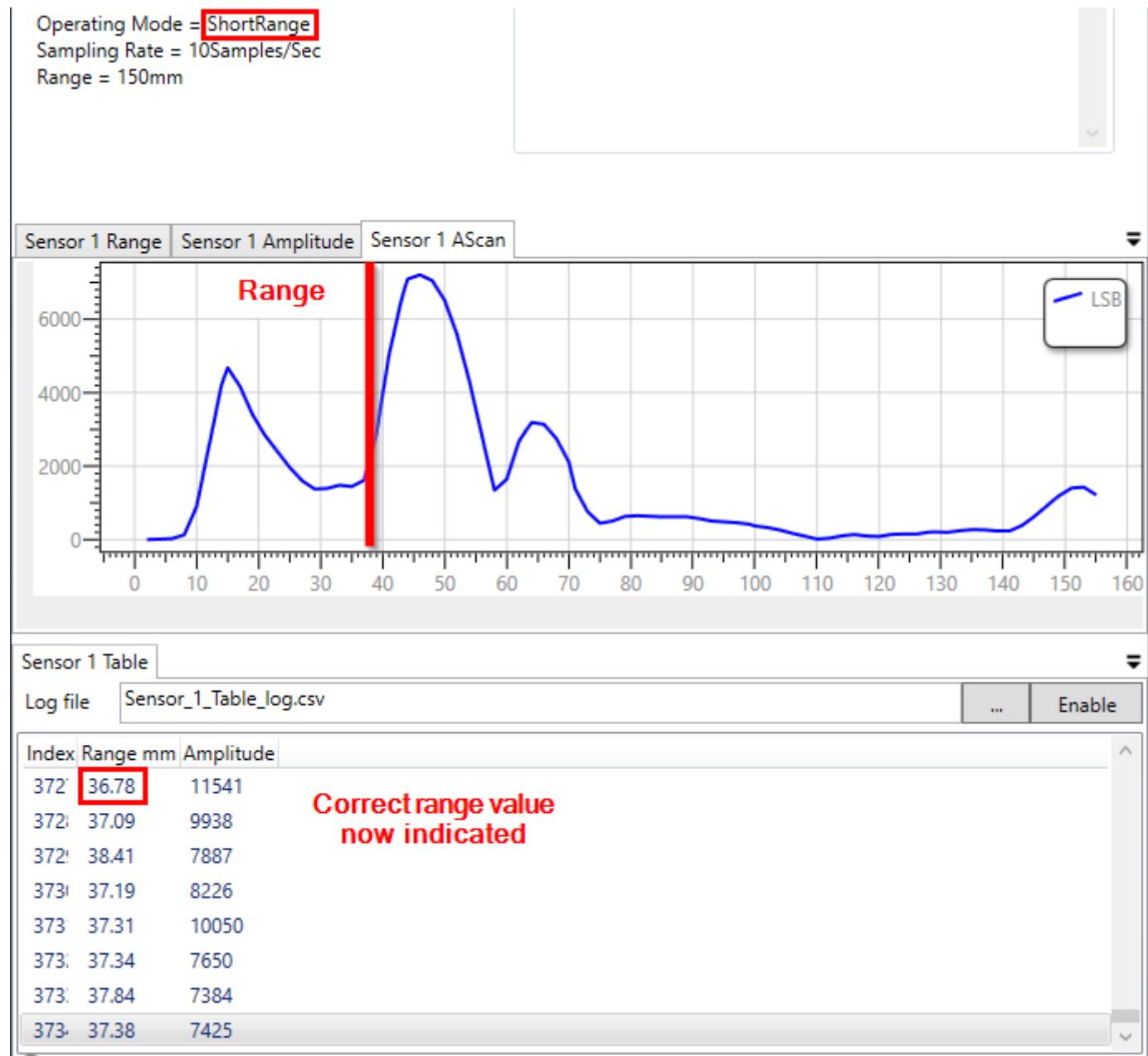


**Figure 16. Correct Short Range Detection When Using Short Range Firmware**

## 3.2 CH101 MULTI-SENSOR PITCH-CATCH OPERATION

The CH101 normally operates in Pulse-Echo (PE) mode, where a single sensor emits ultrasound (transmits), and then listens for echoes (receives). This is the simplest operating mode, as it requires only one sensor. However, there are cases where Pulse-Echo operation is not ideal; the CH101 cannot transmit and receive simultaneously, so targets very close to the sensor will not be detectable (the CH101 will still be emitting ultrasound when nearer echoes return). Additionally, the 2D/3D position of targets cannot be determined when using a single sensor.

When multiple CH101 sensors are present, they can also operate in Pitch-Catch mode, where one sensor acts as a transmitter, and all other sensors act as receivers. There are two types of Pitch-Catch operation: Direct transmission Pitch-Catch (DPC) and Reflected transmission Pitch-Catch (RPC). Both types of operation are configured the same way and generally enable a smaller minimum detection distance but differ in their physical implementation and interpretation of results. SonicLink enables both types of operation by setting one CH101 to transmit/receive (Tx/Rx) mode, and all other sensors to receive only (Rx-only).

In Direct Pitch-Catch mode, two (or more) CH101 sensors are oriented towards each other, and the direct path between sensors is recorded as the range. Fundamentally, Chirp's SonicTrack™ and SonicSync™ solutions use CH101 sensors operating in this mode. This mode has increased maximum range, as one meter of Pulse-Echo distance is two meters of round-trip distance. This mode also benefits from near immunity to multipath interference; the shortest path between two points will always be a straight line between those points. Any multipath interference will necessarily be a longer distance and lower amplitude than the true signal. In this mode, the range reading from the Tx/Rx sensor can generally be ignored.

In Reflected Pitch-Catch mode, two (or more) CH101 sensors are oriented such that the transmission from one sensor will reflect off a target and be received by a different sensor. This mode enables detection targets that may otherwise be undetectable (due to location within the FoV, reflectivity, or other factors). Unlike Direct Pitch-Catch, Reflected Pitch-Catch does not benefit from increased maximum range or multipath interference immunity. Care must be taken during system integration and implementation of RPC-based systems to minimize direct path transmission between the sensors. The direct-path physical distance (between the sensors) should be also different than the distance to likely targets, to avoid confusing the direct path readings and actual target measurements.

## How to set up a Direct transmission Pitch-Catch system

The following example demonstrates how to set up and evaluate a Direct Pitch-Catch system based on the SmartSonic Evaluation Kit. Using two MOD_CH101 modules and flat flex cables (FFCs), connect the modules to the FFCs, and then secure the modules to the test system. In Figure 17 below, the sensors are attached to right-angle brackets to allow the sensors to stand freely. Initially, the sensors are placed 30 cm apart, using a ruler added to the setup.
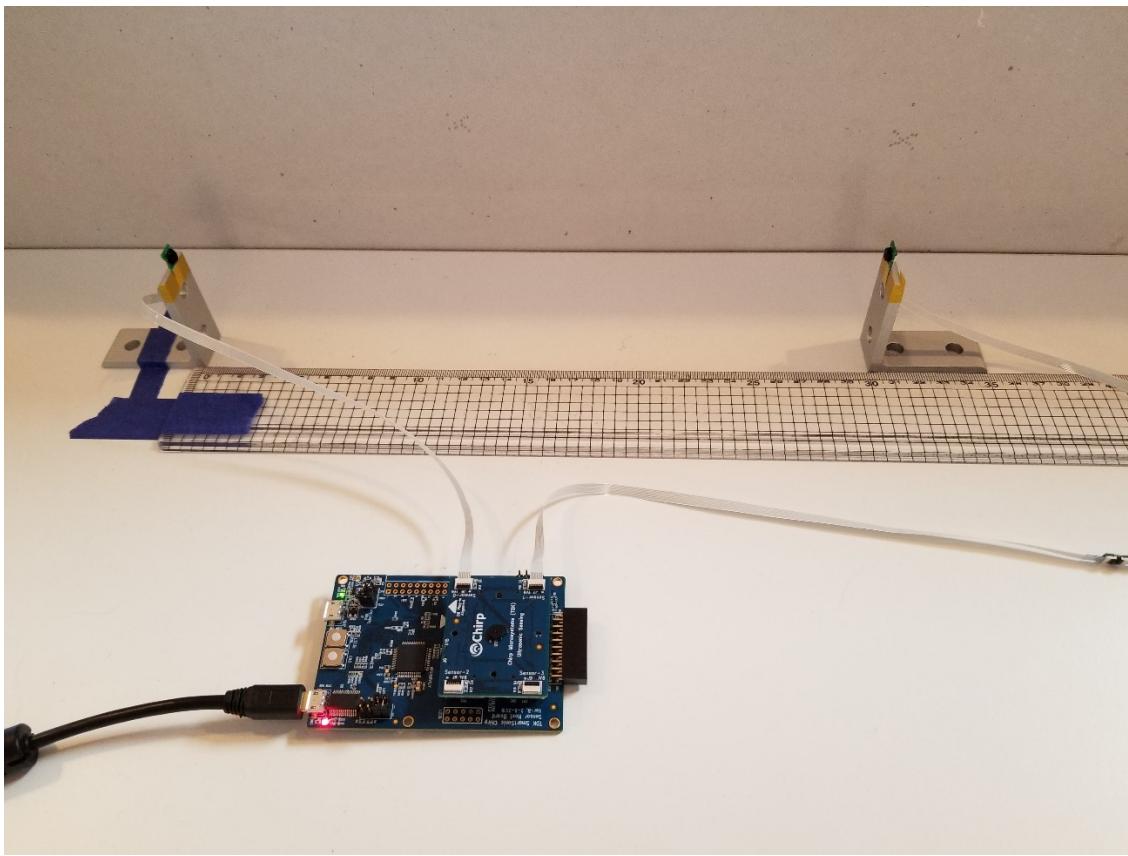


**Figure 17. Direct Pitch-Catch Setup**

From SonicLink, configure Sensor 0 to be the Tx/Rx sensor, and Sensor 1 to be Rx Only, as shown in Figure 18.

**Note**: the current minimum range for Direct Pitch-Catch configurations using the standard CH101 GPR firmware is approximately 20 cm. Using CH101 GPR Short-range firmware, the minimum is approximately 4 cm.
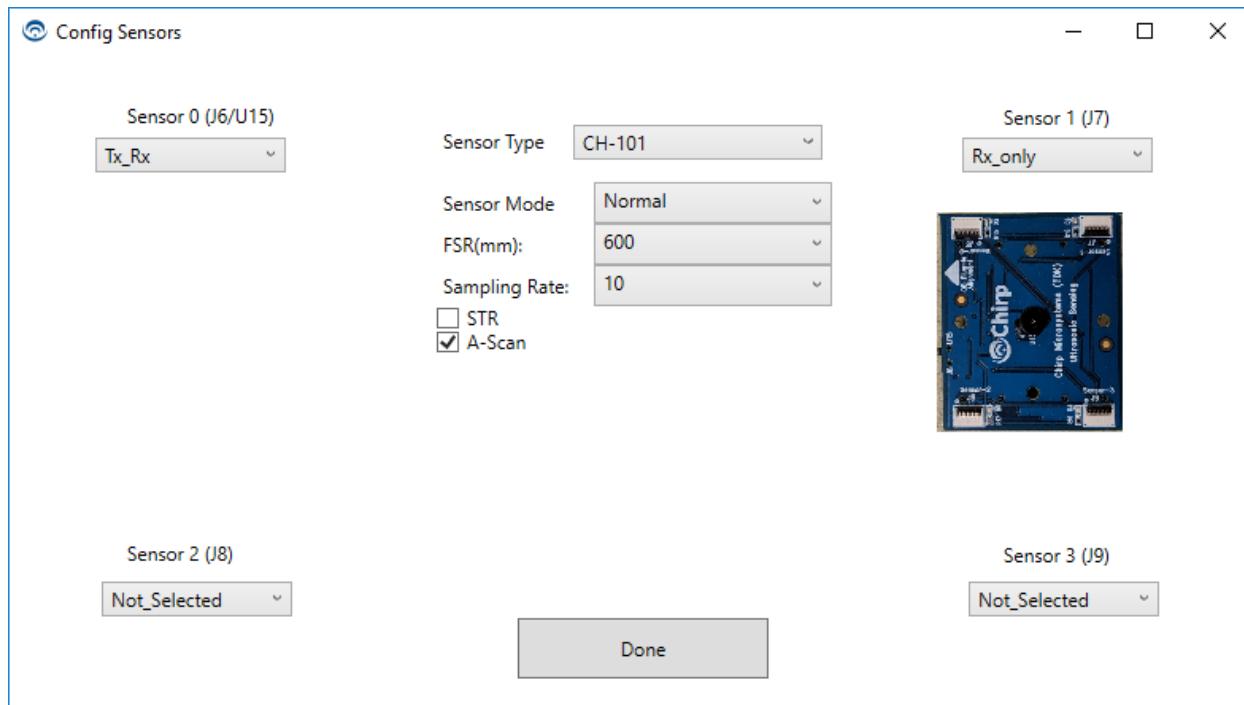
**Figure 18. Two-Sensor Pitch-Catch Configuration in SonicLink**

This application focuses on the range reported by Sensor 1, the Rx-only sensor. After initializing the sensors and adjusting the display to show the table and A-Scan plot, Sensor 1 reports the following:
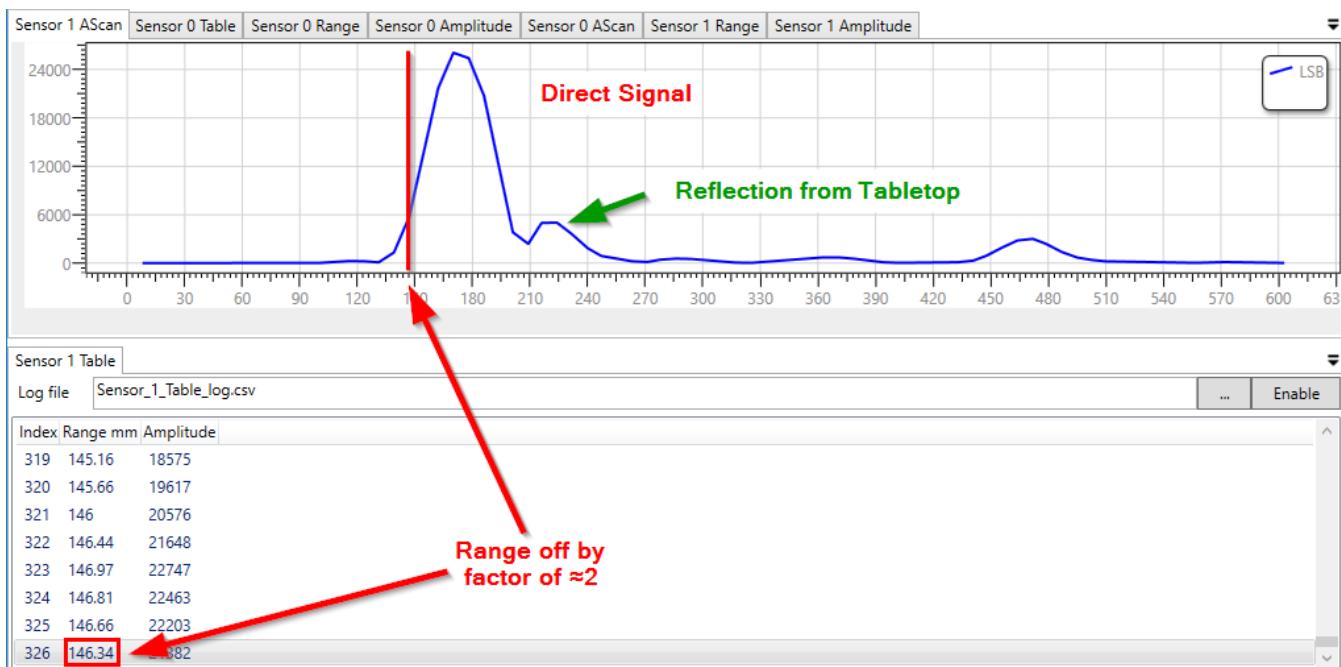


**Figure 19. Receive-only Sensor Pitch-Catch Output**

In the A-Scan, the first pulse corresponds to the direct-path transmission signal, while a smaller, secondary echo corresponds to the reflection from the tabletop. Notice that the reported range is a little less than half of the expected value. When calculating range, the CH101 measures the round-trip distance and divides that by two to get the true distance. In a DPC configuration, the trip is only one direction, so the division by two creates this range error. Additionally, in a DPC configuration, a static range offset of approximately 10 mm needs to be added to the scaled range, using the following equation:

True Range = 2 * Reported Range + 10 mm

Example:

A CH101 device in Rx Only mode reports a range of 145 mm.

True Distance = 2 * (145.0) + 10.0

= 300.0 mm

An embedded application can use functions provided in the Chirp SonicLib API to return either the one-way or round-trip range, but this feature is not currently supported by SonicLink.

# 4  CH201-SPECIFIC FEATURES

## 4.1  RANGE-DEPENDENT DETECTION THRESHOLDS (STANDARD CH201 GPRMT FIRMWARE)

As described above in How the Sensor Reports Range both the CH101 and CH201 sensors will report the range to the closest target detected, even if a larger target is present at a longer range. Generally, this is the desired behavior, as the most interesting targets are usually the closest. However, as seen in Section 2.8 there are cases where the first signal to cross the threshold is not the desired target and leads to potentially confusing results. For CH101, enabling STR can solve some of these problems. STR is not available in the standard CH201 GPRMT (multi-threshold) firmware, which instead allows users to set up to six different range-dependent threshold values over the Full-Scale Range. (STR is available for CH201 in a separate STR-specific firmware version, see Section 4.2)

**Note**: For more information on samples and how they relate to physical range, see Section 2.8. SonicLink uses and saves thresholds in millimeters, and automatically converts them to samples at runtime.

The user-defined thresholds are displayed in the CH201's A-Scan plot, as shown in Figure 20. The thresholds and their corresponding entries in the ThresholdSetting window have been color-coded for illustration purposes.
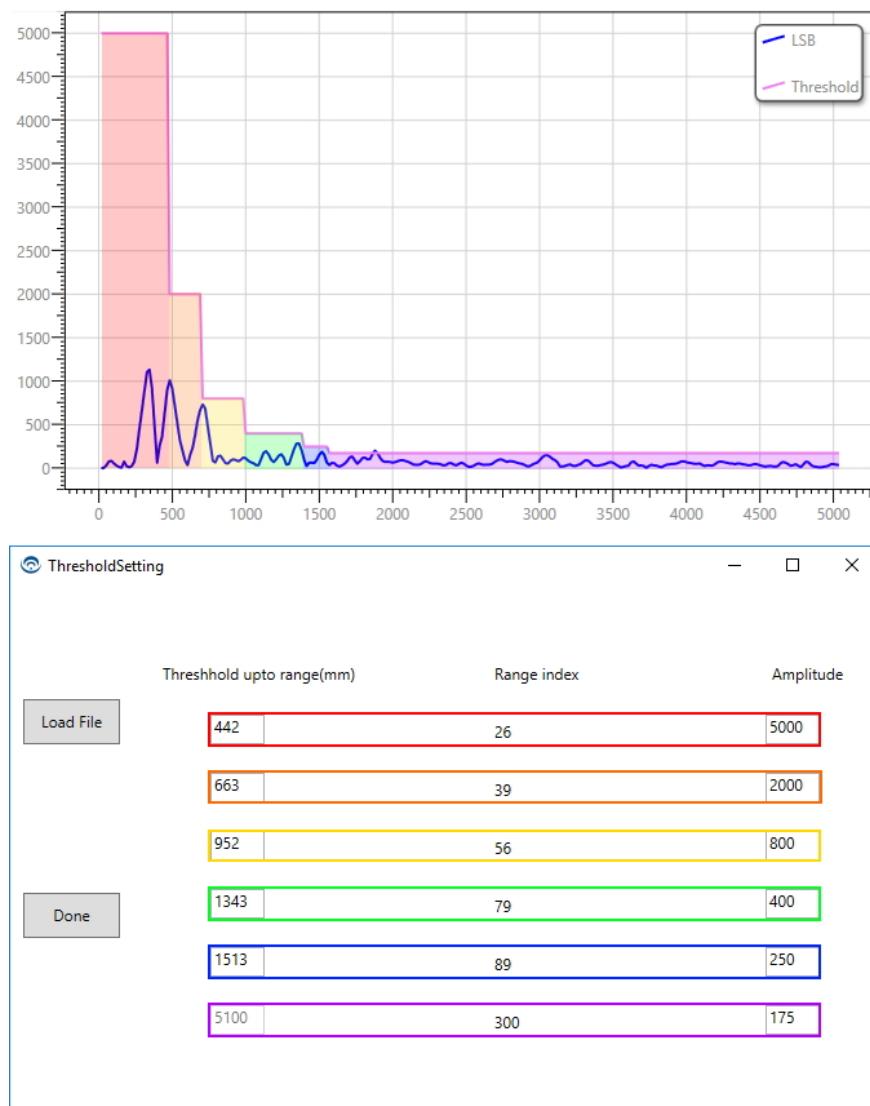


**Figure 20. Standard CH201 A-Scan and Thresholds**

Range-dependent thresholds for the CH201 are defined by two values: the threshold level and the starting sample number. The threshold level is simply the amplitude (in LSBs) that a target must exceed in order to be detected as a target. The starting sample number is the first sample number where the threshold will start. A threshold ends either when the next threshold starts, or at the end of the I/Q trace, whichever comes first. Users may set up to six individual thresholds, or as few as zero (which uses the default threshold values). A single threshold cannot exceed 255 samples in length, but two consecutive thresholds may have the same level. When the user has entered the desired thresholds into the ThresholdSetting window, clicking the "Done" button causes the thresholds to be written to the CH201 sensor.

## Guidelines for selecting range-dependent thresholds

To set effective, reliable thresholds, it is important to know how the amplitude of a target's reflected signal will scale with its distance from the CH201. For large, flat surfaces, (e.g. walls, the ground, etc.), the amplitude scales as $1/R$, where R is the distance between the CH201 and the target. For most other targets, the amplitude scales as $1/R^2$. Additionally, there are three more general recommendations to follow for determining values for thresholds:

1. A good rule of thumb is that the threshold value should be roughly equal to $1/4^{th}$ to $1/8^{th}$ of the desired target's amplitude at a given distance. For example, if the CH201 reports an amplitude of 8000 LSB for a target two meters away, the threshold around two meters should be approximately 1000–2000 LSB. This ratio ensures that the target will be detectable with a high SNR, while allowing for variations in echo amplitude resulting from different operating conditions. A target with amplitude close to the threshold level can still be detected but may produce a noisier range output.
2. The minimum recommended threshold in any operating conditions is 200 LSB.
3. The absolute maximum threshold that can be set is 65535 LSB, the maximum for an unsigned 16-bit integer. In practice, setting any threshold above 40000 LSB will cause the CH201 to ignore all targets in that range. For applications where a user is only interested in targets at a specific range of distances (such as 100–250 cm), very large thresholds can be set at ranges outside the region of interest (e.g. from 0–100 cm and above 250 cm) so that only targets in the region of interest will be detected.

## How to choose appropriate threshold settings

In the following example, a user is trying to choose threshold settings to see a 50 mm diameter pole target as far away as possible. To start, the user mounts their SmartSonic board as desired, and places the 50 mm pole one meter away.



**Figure 21.  Setup for 50mm Pole Detection**

To ensure that the reported target is the pole, the user sets very large thresholds for distances closer than 50 cm, as shown in Figure 22.
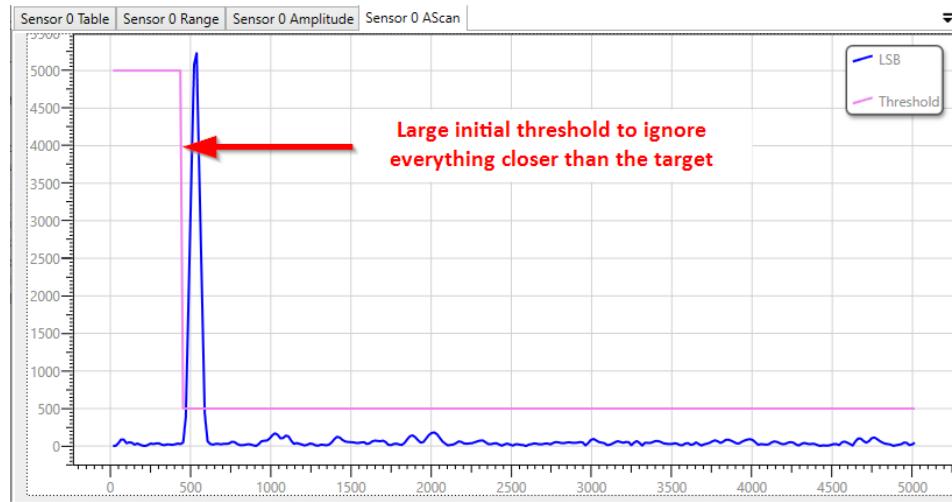


**Figure 22. A-Scan with Large Initial Detection Threshold**

The user observes that the target's echo amplitude is 5200 LSB at 50 cm range and 1750 LSB at 100 cm range, showing that the signal amplitude decays by approximately 4x when the range is doubled. Following the guidelines, the user sets the threshold at 50 cm to 1300 LSB and uses $1/R^2$ scaling to compute the remaining thresholds. At 25 cm (half the distance), the user increases the threshold 4x to 5200, while at one meter (double the distance), the user decreases the threshold 4x to 325. At two meters, the user notices the threshold value should be 81 LSB but follows the guidelines and ensures no threshold is below 200 LSB. The selected thresholds are shown in the A-Scan plot in Figure 23 below.
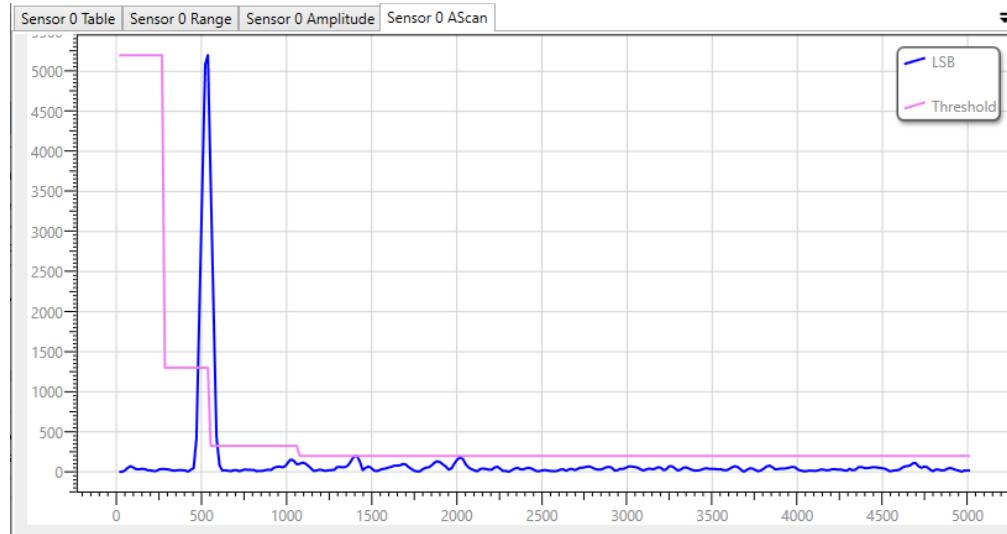


**Figure 23. A-Scan with Multiple Detection Thresholds**

## 4.2 SINGLE DETECTION THRESHOLD (CH201 STR FIRMWARE)

When using the CH201 STR firmware, a single user-configurable detection threshold is available. Setting this value will determine the detection sensitivity for the entire measurement sample set (except for very early samples in each measurement, which use a fixed value).

In SonicLink, enabling STR will automatically select the special CH201 STR and download it to the sensor. (See Section 2.10 for information on enabling STR and how to use it.)

To set the detection threshold value, configure one or more CH201 devices with STR enabled. Return to the main screen and start measurements. Open the ThresholdSetting window by clicking on the "Thresholds" button on the main SonicLink screen.

The ThresholdSetting window for CH201 STR is similar to the one displayed when using multiple range-dependent thresholds (see Section 4.1, above). However, because only a single threshold may be set, and the threshold always applies to all samples in the measurement, most selections are greyed-out.

Figure 24. CH201 STR Single Threshold shows where the single threshold value should be entered on the ThresholdSetting screen. The default value of 200 is shown. Note that measurements made using the CH201 STR firmware only contain a maximum of 290 samples.
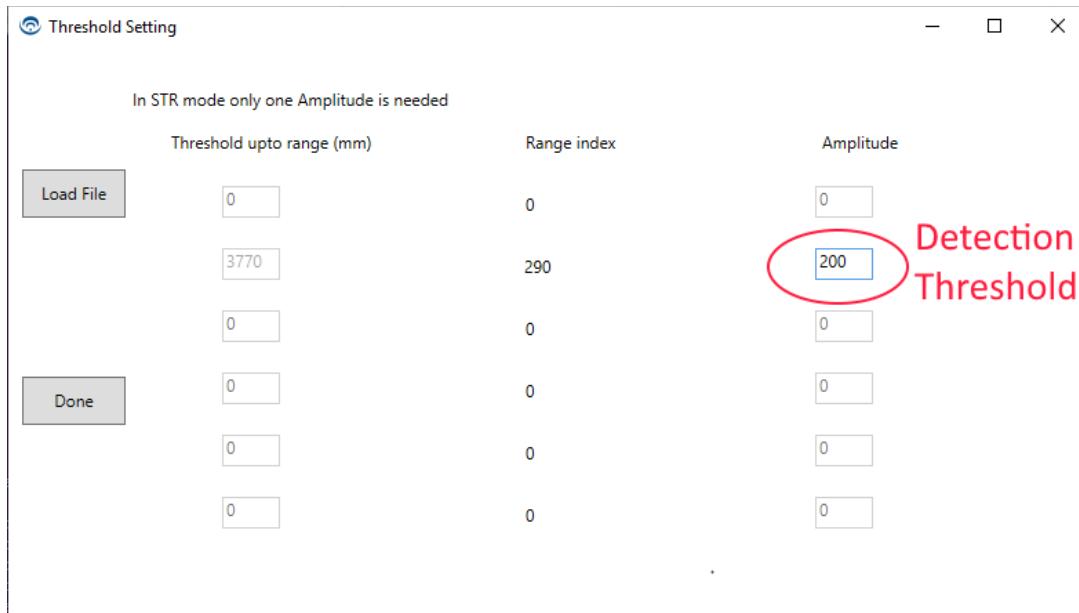


**Figure 24. CH201 STR Single Threshold**

# 5 USING EXTERNAL SENSOR MODULES AND SENSOR BEAM PATTERNS

## Using external sensor modules

The SmartSonic evaluation board can support up to four CHx01 sensors at once. When the CHx01 sensor (U15) on the SmartSonic daughterboard is enabled, users can connect up to three additional CHx01 sensor modules to the Sensor 1, 2, and 3 ports (J7, J8, and J9, respectively). By disabling the onboard CHx01 sensor (using the switch along the top of the daughterboard), users can connect up to four external CHx01 modules, via the Sensor 0, 1, 2, and 3 ports (J6, J7, J8, and J9, respectively). It is important to note that the onboard CHx01 sensor (U15) and a sensor connected to the Sensor 0 port (J6) cannot be used simultaneously.

The CH101 MOD_CH101-03-01 sensor module has an acoustic housing that provides an omnidirectional FoV, so users should take care to keep the area near the sensor clear of other objects which could create reflections in the outgoing and incoming sound waves. For the best acoustic performance, the module should be flush mounted into the center of a flat surface measuring at least 100 mm in diameter. Consult the MOD_CH101 module datasheet (DS-000333) and the Chirp Mechanical Integration Guide (AN-000158) for more information.

The CH201 MOD_CH201-00-01 sensor module has an acoustic housing that provides a narrow FoV (a 45° Full-Width Half-Max (FWHM) beam width). The narrower FoV on the CH201 module focuses the pressure output from the sensor, which enables detection of smaller targets at longer ranges. While mounting the module into a flat surface is still recommended, the module is less sensitive to objects and edges around its periphery than the omnidirectional CH101 module, due to the CH201 module's narrower FoV. Also, despite the module having a narrower FoV, it is important to remember that objects outside of the FoV can still register as targets if they are large or close enough to the sensor.

## CH101 beam patterns

The CH101 sensor on the SmartSonic daughterboard is covered by the same omnidirectional acoustic housing used in the MOD_CH101. Because the surface of the evaluation kit has many edges and protrusions, the beam pattern of the daughterboard's CH101 sensor is not truly omnidirectional. To achieve omnidirectional response, Chirp recommends that customers use external MOD_CH101-03-01 omnidirectional sensor modules mounted into an appropriate enclosure. Alternatively, customers may insert the onboard CH101 sensor into a mounting plate (see the MOD_CH101 datasheet for further information).

A Pulse-Echo beam pattern plot of the CH101 sensor mounted on the SmartSonic daughterboard is shown in Figure 25. Beam Pattern of SmartSonic CH101 Daughterboard (normalized dB). This beam pattern was measured by placing a 1 square meter flat target at a 30 cm distance from the SmartSonic daughterboard and recording the CH101 ToF amplitude as the sensor is rotated 180°. Note that the beam pattern consists of a central main-lobe and four side-lobes at ±35° and ±60°. The multi-lobed beam pattern means that the onboard sensor will give good performance for detecting on-axis targets but may result in poor detection of targets located at angles where the beam pattern shows small amplitude (e.g. ±20° and ±50°). For comparison, the CH101 beam pattern when mounted in the recommended 100 mm diameter mounting plate is shown below. When mounted in the recommended plate, the beam pattern shows a relatively constant amplitude from +80° to -80°, where the Pulse-Echo amplitude is reduced to half of the maximum amplitude observed on-axis.
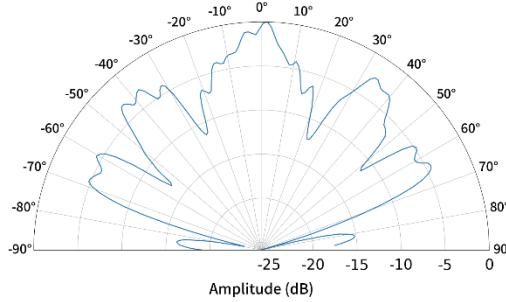


**Figure 25. Beam Pattern of SmartSonic CH101 Daughterboard (normalized dB)**
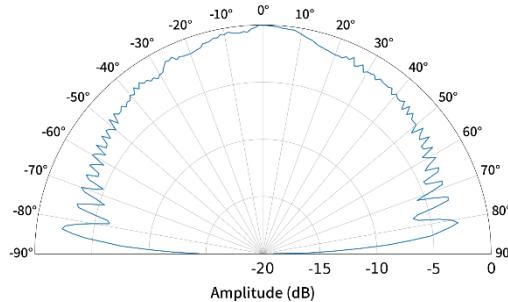
**Figure 26. Beam Pattern of CH101 Module in 100 mm Diameter Plate (normalized dB)**

## CH201 beam patterns

The CH201 sensor on the SmartSonic daughterboard is covered by the same narrow FoV acoustic housing used in the MOD_CH201-00-01 module. Because the surface of the evaluation kit has many edges and protrusions, the beam pattern of the daughterboard's CH201 sensor has some small lobes. To reduce the size of these lobes, Chirp recommends that customers use external MOD_CH201-00-01 narrow FoV sensor modules mounted into an appropriate enclosure. Alternatively, customers may insert the onboard CH201 sensor into a mounting plate (see the MOD_CH201 datasheet for further information).

A Pulse-Echo beam pattern plot of the CH201 sensor mounted on the SmartSonic daughterboard is shown below in Figure 27. This beam pattern was measured by placing a 1 square meter flat target at a 100 cm distance from the SmartSonic daughterboard and recording the CH201 ToF amplitude as the sensor is rotated 180°. Note that the beam pattern consists of a central main-lobe and four side-lobes at ±35° and ±60°. This multi-lobed beam pattern indicates that the onboard sensor will give good performance for detecting on-axis targets but may result in poor detection of targets located at angles where the beam pattern shows small amplitude (e.g. ±30° and ±55°). For comparison, the CH201 beam pattern when mounted in the recommended 100 mm diameter mounting plate is shown in Figure 28. When mounted in the recommended plate, the beam pattern shows a more uniform 45° FWHM main beam observed on-axis.
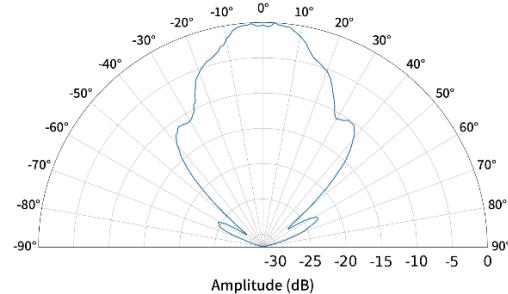


**Figure 27. Beam Pattern of SmartSonic CH201 Daughterboard (normalized dB)**
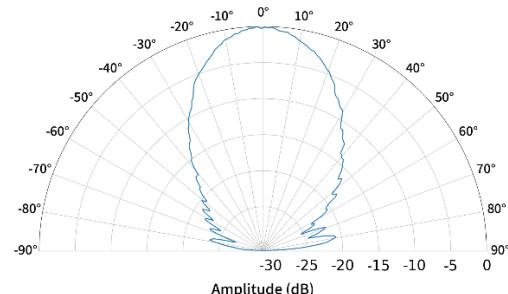


**Figure 28. Beam Pattern of CH201 module in 100 mm Diameter Plate (normalized dB)**

# 6 REVISION HISTORY

| REVISION DATE | REVISION | DESCRIPTION |
|---|---|---|
| 06/10/2020 | 1.0 | Initial Release |

**TDK** Chirp Microsystems