HUMANIZING THE DIGITAL EXPERIENCE

TDK Developers Conference 2018

TDK InvenSense EPCOS tronics microsystems Chirp MICRONAS

Chirp Ultrasonic Time-of-Flight Sensors

The world's first ultrasonic sensors based on piezoelectric MEMS ultrasonic transducers

TDK Developers Conference
September 17-18, 2018
Santa Clara Marriott

Overview

- Introduction to ultrasonic time-of-flight (ToF) rangefinding
- Comparison of ultrasonic ToF and optical infrared (IR) ToF sensors
- Chirp MEMS ultrasonic sensors
  - Theory of operation
  - RMS range noise
  - Range accuracy
- Chirp's CH-101 medium range and CH-201 long range ultrasonic sensors
  - Specifications
  - MCU interfacing
  - Range noise and field-of-view (FoV)
- Example applications

Ultrasonic Sensing Today

- Measure range from the time-of-flight of an ultrasonic pulse (aka sonar or echolocation)
- Multiple rangefinders see different zones (left, right, center…)
- Immune to noise, lighting, object color, wind…

1. Automotive

Source: Audi

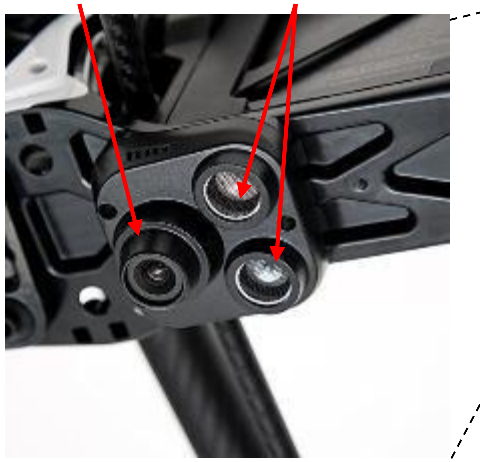
Automotive ultrasonic rangefinder

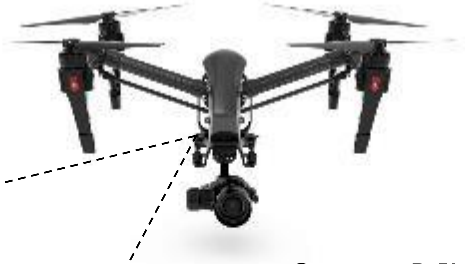
Source: Bosch

2. Drones / Robotics

Camera

Ultrasonic rangefinders

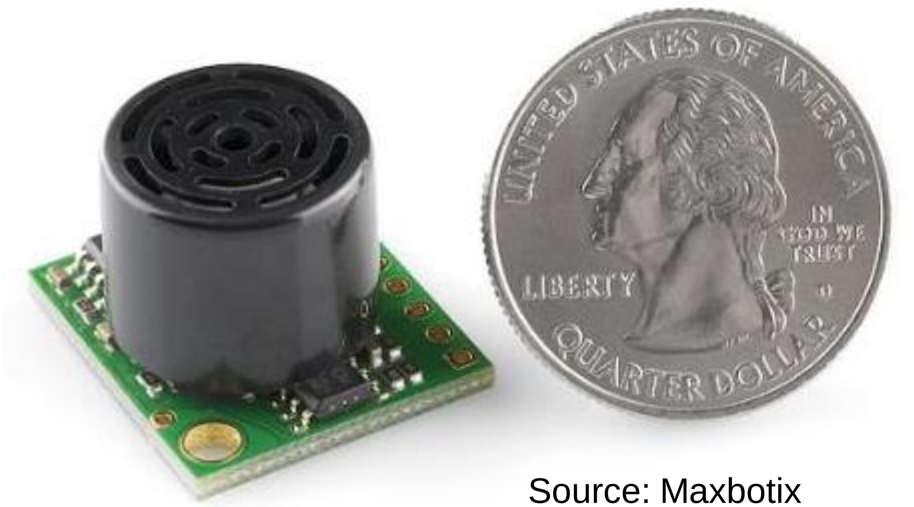




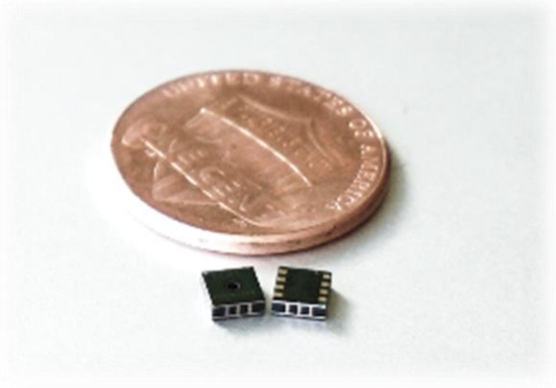
Source: DJI

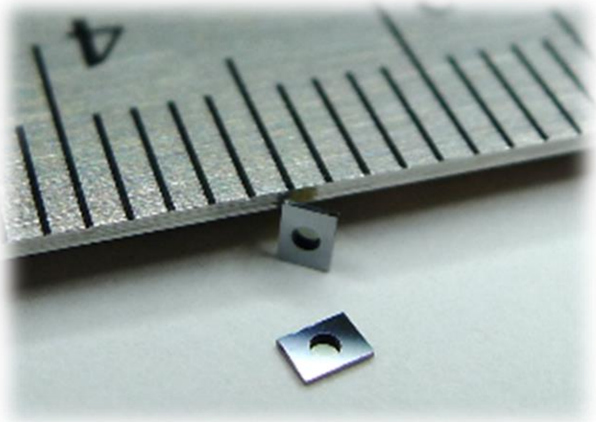
Downward facing ultrasonic rangefinder senses hover height in DJI’s Inspire 1 drone

Chirp: the Future of Ultrasonic Sensing



Source: Maxbotix





Today's Ultrasonic Rangefinders

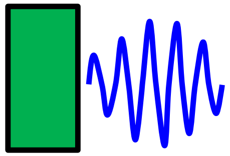
- Conventional manufacturing
- Lots of discrete electronics
- Too big for consumer applications
- Best solution for rangefinding today

Chirp

- Sonar on a chip
- Integrated DSP chip – 100x lower power
- Millimeter-sized sensor – 1000x smaller
- Same great rangefinding performance

Ultrasonic ToF Sensor Basics

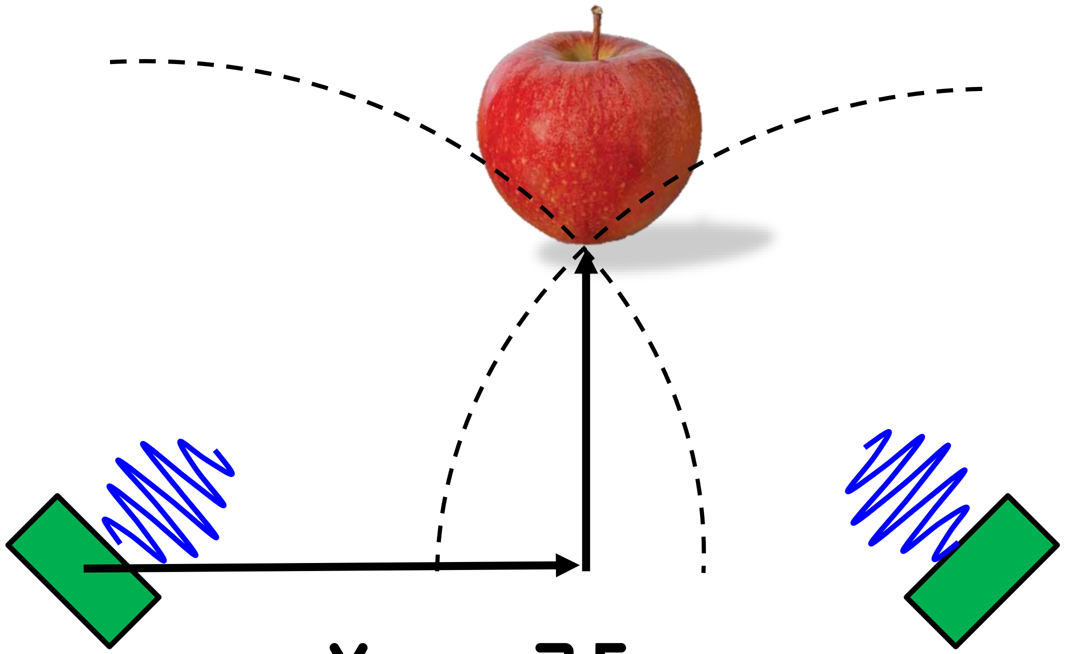
$$R = c\frac{T}{2}$$



Object Range: 523 mm

- Single element for both transmit and receive
- Detects distance to object based on time of flight (ToF)
- Millimeter precision over wide measurement range
- Insensitive to sunlight and works in total darkness
- Range accuracy independent of object color, size, texture

3D Location via Trilateration



X = 25 mm

Z = 278 mm

Comparing Ultrasonic and Infrared (IR) ToF Sensors

- Ultrasonic ToF is much lower power than IR ToF
  - Typical competing IR ToF: 20 mW at 10 samples/sec,
  - Chirp's CH101: 50 µA at 10 samples/sec (~500x lower power)

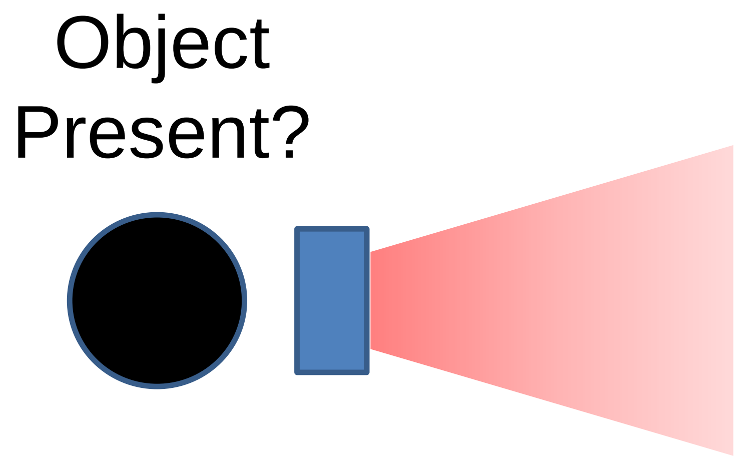
- IR ToF sensors are sensitive to lighting
  - Range and accuracy is greatly reduced by ambient light
  - Does not work at all in sunlight

- Ultrasonic ToF provides much lower-noise range sensing
  - Typical IR ToF spec for a white target indoors is 4.8 cm RMS range noise at 120cm range
  - Chirp's CH101 has 10x lower noise at 120 cm (5 mm RMS)
  - Chirp's CH201 has 100x lower noise at 120 cm (0.5 mm RMS)

- IR ToF sensors have a very narrow field-of-view (FoV)
  - Typical IR ToF: 25 degrees
  - Chirp: ~180 degrees, can be custom tailored to a narrower FoV if desired

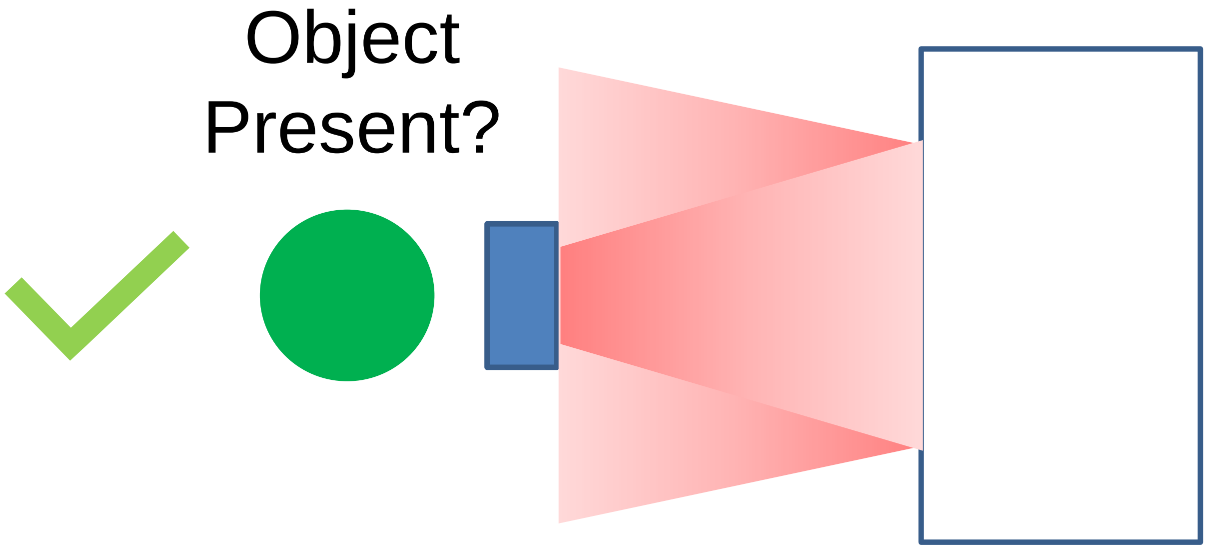
- IR ToF can operate beneath cover glass, but
  - Cover-glass reflects IR light, creating cross-talk
  - With high cross-talk, IR ToF sensor's maximum range is greatly reduced

Existing Optical Proximity Sensors



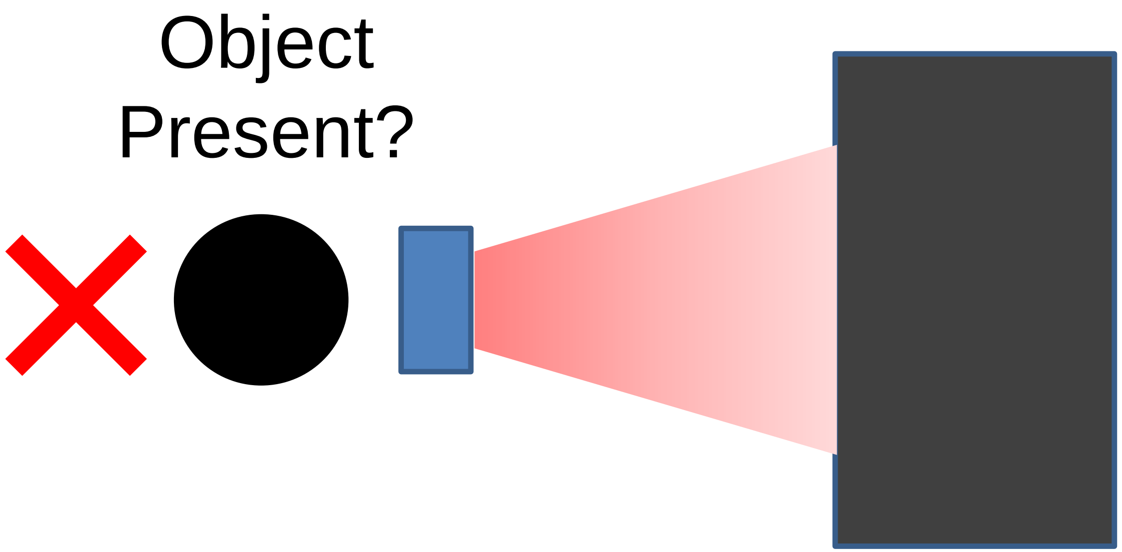
- Optical prox sensor detects reflected light intensity

Existing Optical Proximity Sensors



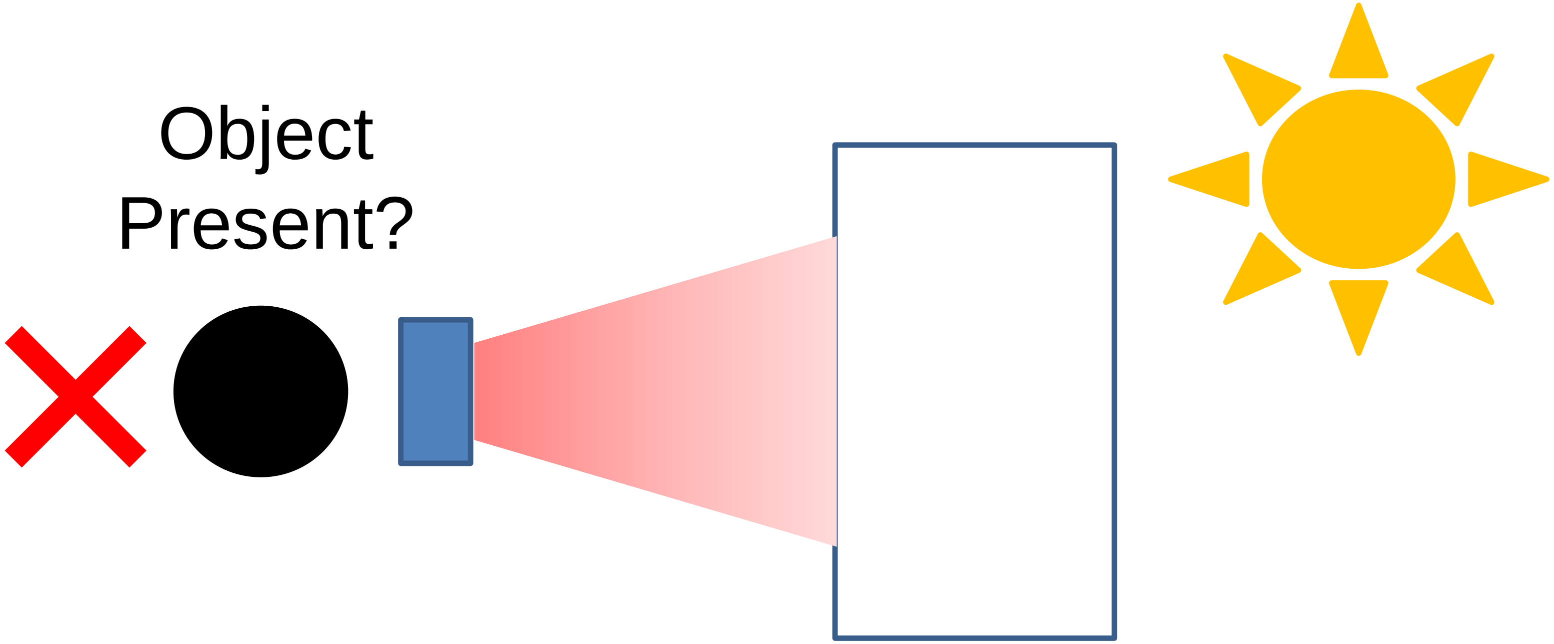
- Reflected intensity gives True/False value
- No real measurement of object range

Object Color is a Problem for Optical Sensors



- Dark and IR transparent objects often not detected

Outdoor Environments are a Challenge for IR Sensors



- The sun is an extremely bright IR source
- Very hard for IR sensors to operate in direct sunlight

Limitations of IR ToF Sensors (1): Sunlight

Example datasheet of 2nd Generation IR ToF Sensor

Table 11. Max ranging capabilities with 33ms timing budget

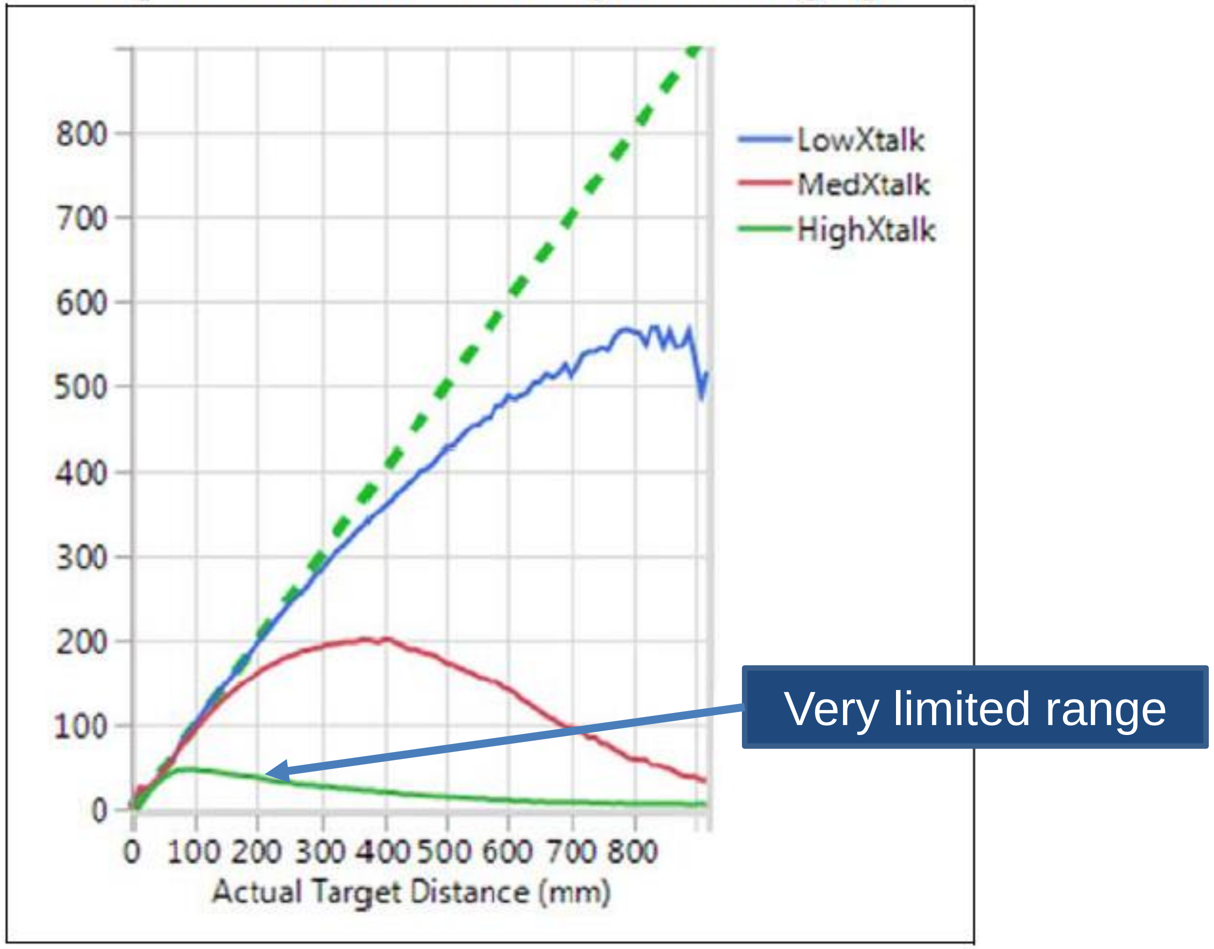
Target reflectance level (Full FOV)	Conditions	Indoor (2)	Outdoor overcast (2)
White Target (88%)	Typical	200cm+ (1)	80cm
	Minimum	120cm	60cm
Grey Target (17%)	Typical	80cm	50cm
	Minimum	70cm	40cm

Note (1): using long range API profile

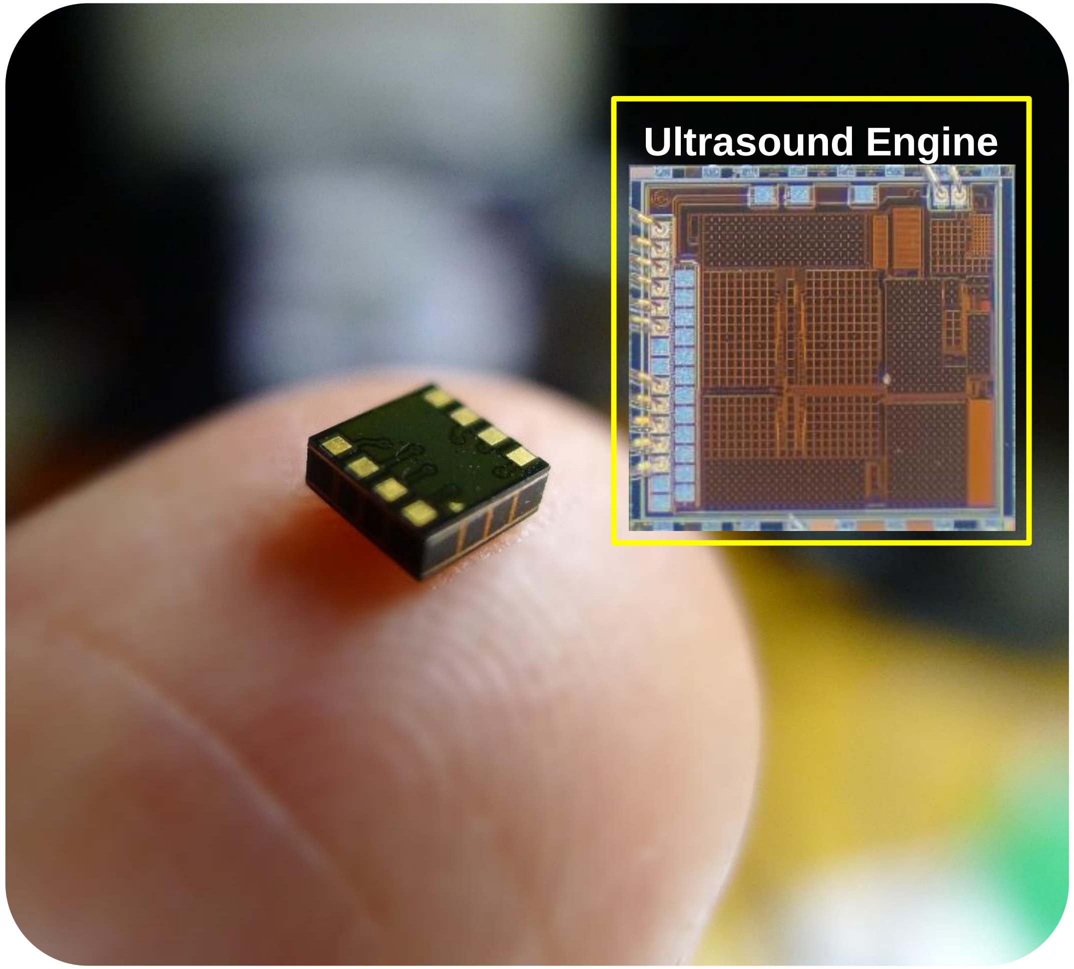
Very limited range

Limitations of IR ToF Sensors (2): Cover Glass

Figure 3. Cover window impact on ranging



Chirp Ultrasonic Time-of-Flight Sensor

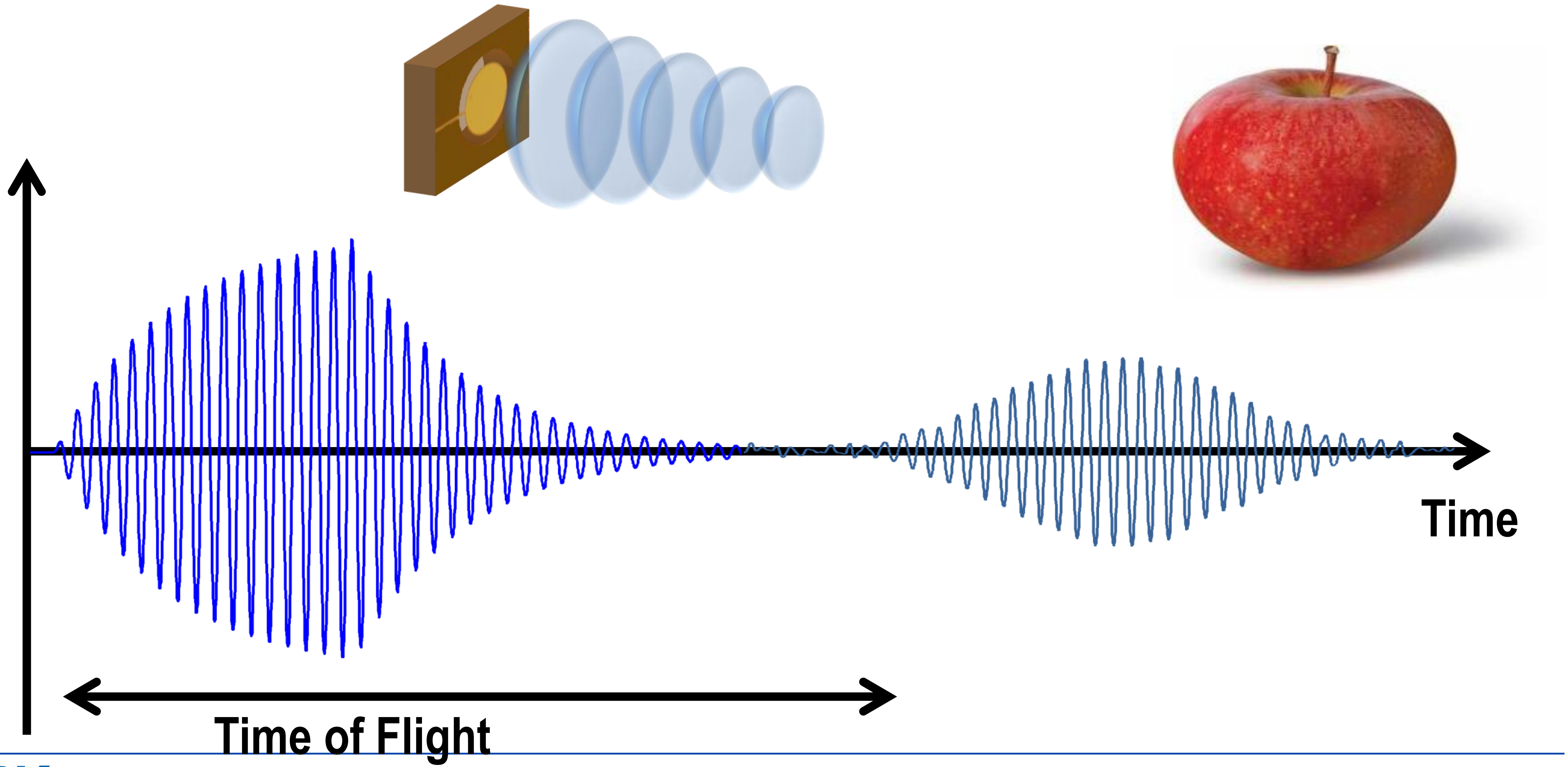


- Ultralow Power (<15 µW)
- Wide 180° Field-of-View
- Small Size
- Highly Accurate Range Measurement

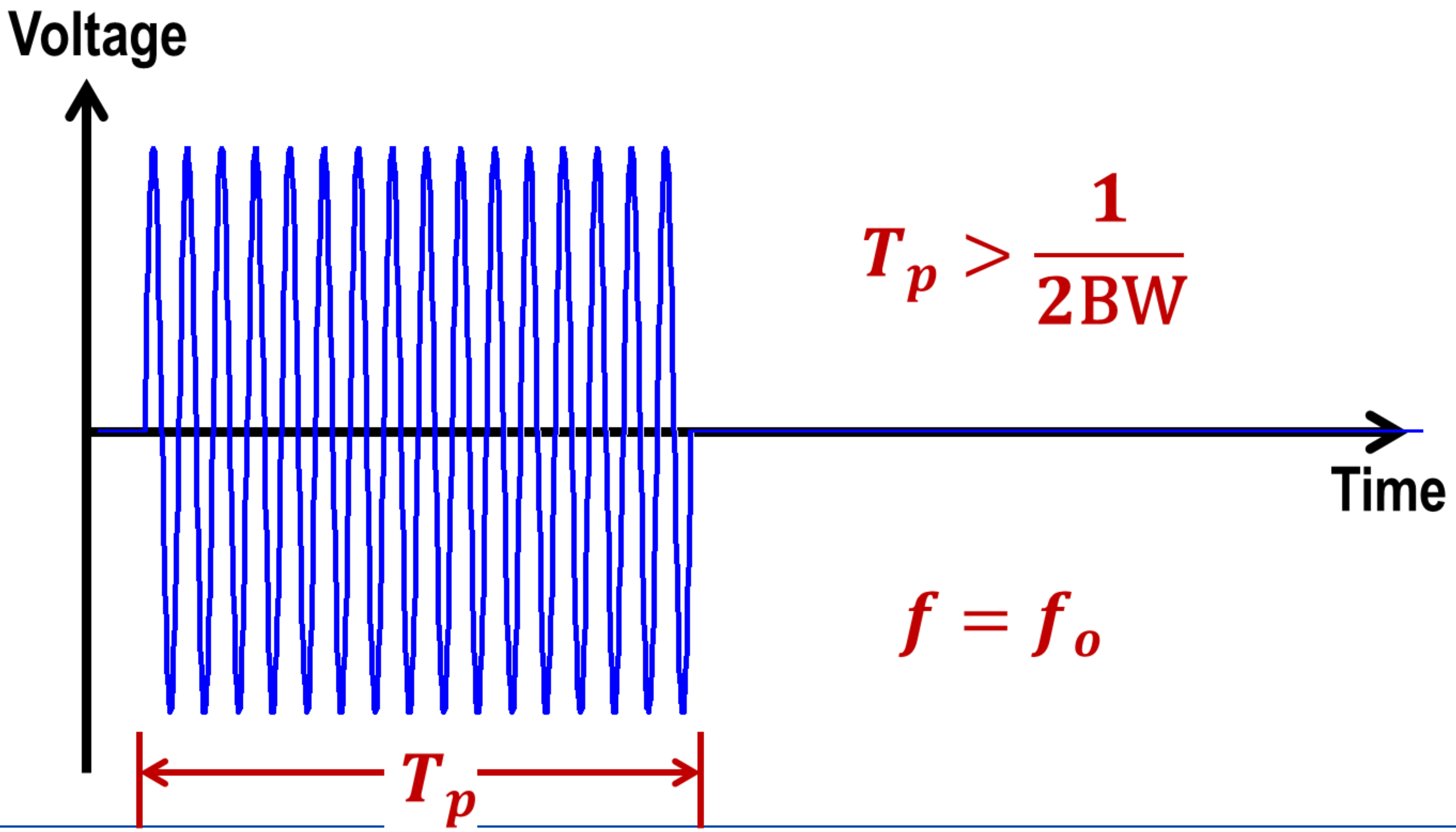
Main features

- Measures range from 1 cm to 5 m
- Accuracy < 1 mm RMS
- On-chip DSP handles all ultrasonic signal processing
- I2C Interface

Pulse- Echo ToF Measurement



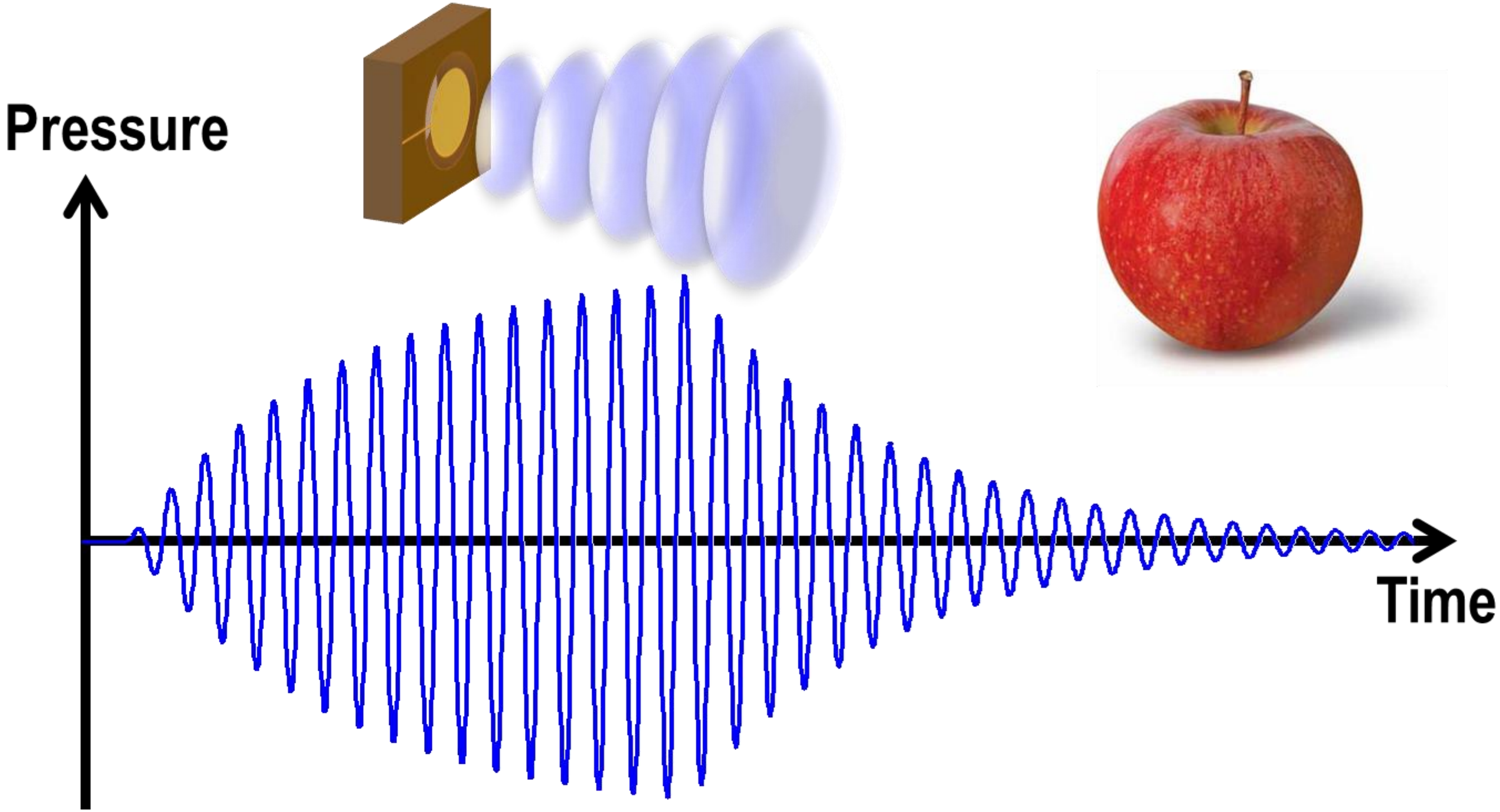
ToF Measurement (1) Transmit Burst



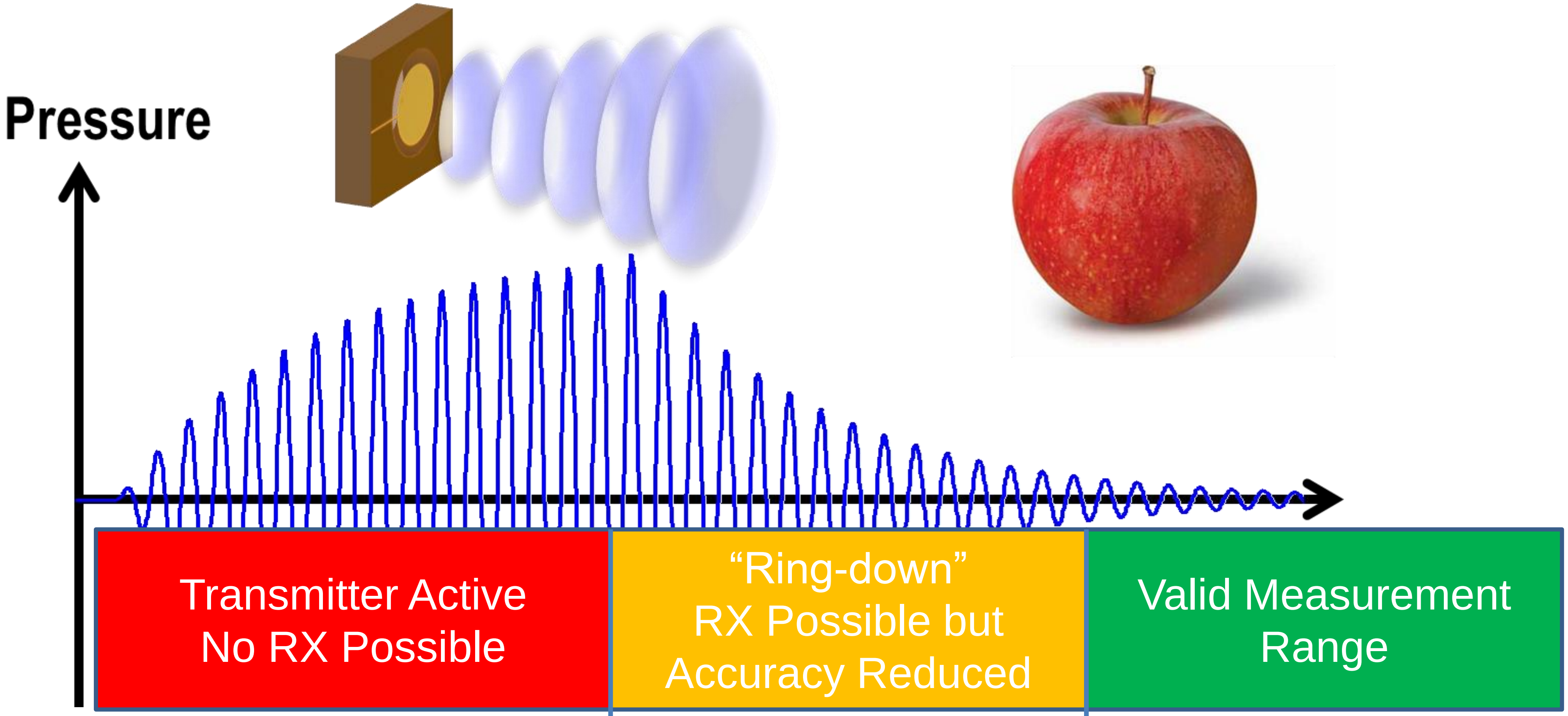
$$T_p > \frac{1}{2BW}$$

$$f = f_o$$

ToF Measurement (2) Sound Pressure Pulse



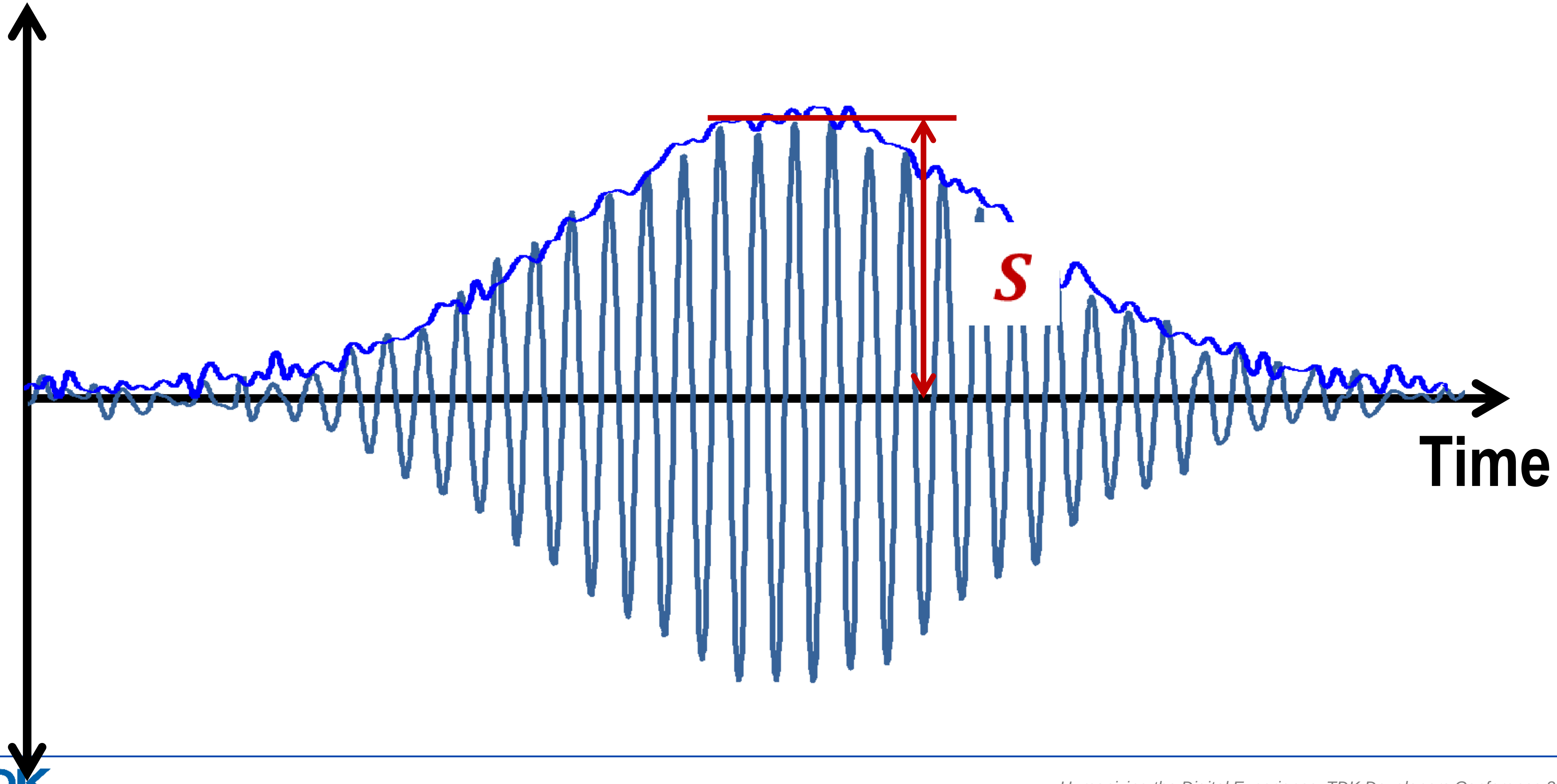
ToF Measurement (2) Sound Pressure Pulse



CH-101 (Normal Mode): 150 us (5 cm) 300 us (10 cm)

CH-101 (Short-Range Mode): 60 us (2 cm) 200 us (7 cm)

ToF Measurement (4) Received Signal



Pulse Amplitude Recovery: IQ Demodulation

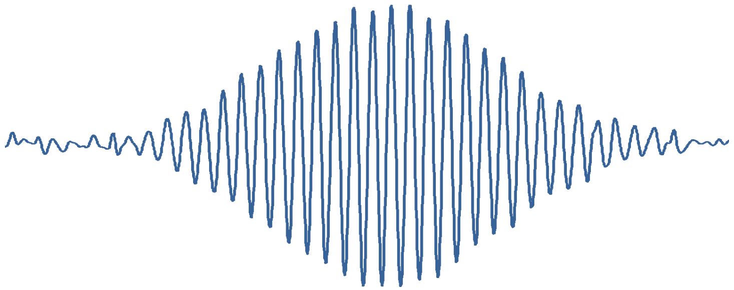
Received Signal
@ ultrasonic TX frequency

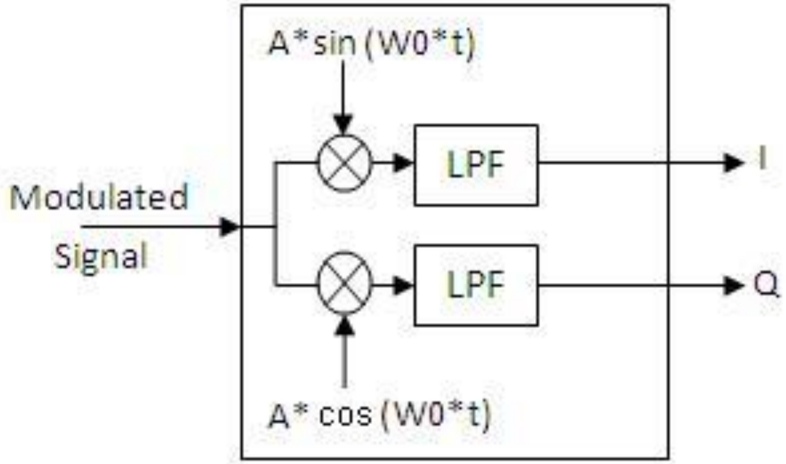
IQ Demod

Baseband Amplitude

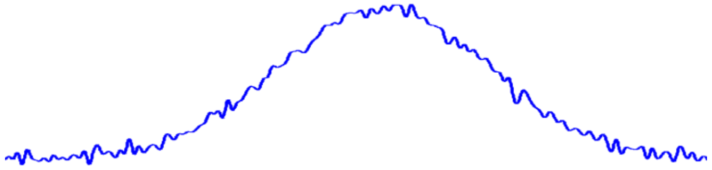
TX clock

$$A(t) = \sqrt{I^2(t) + Q^2(t)}$$



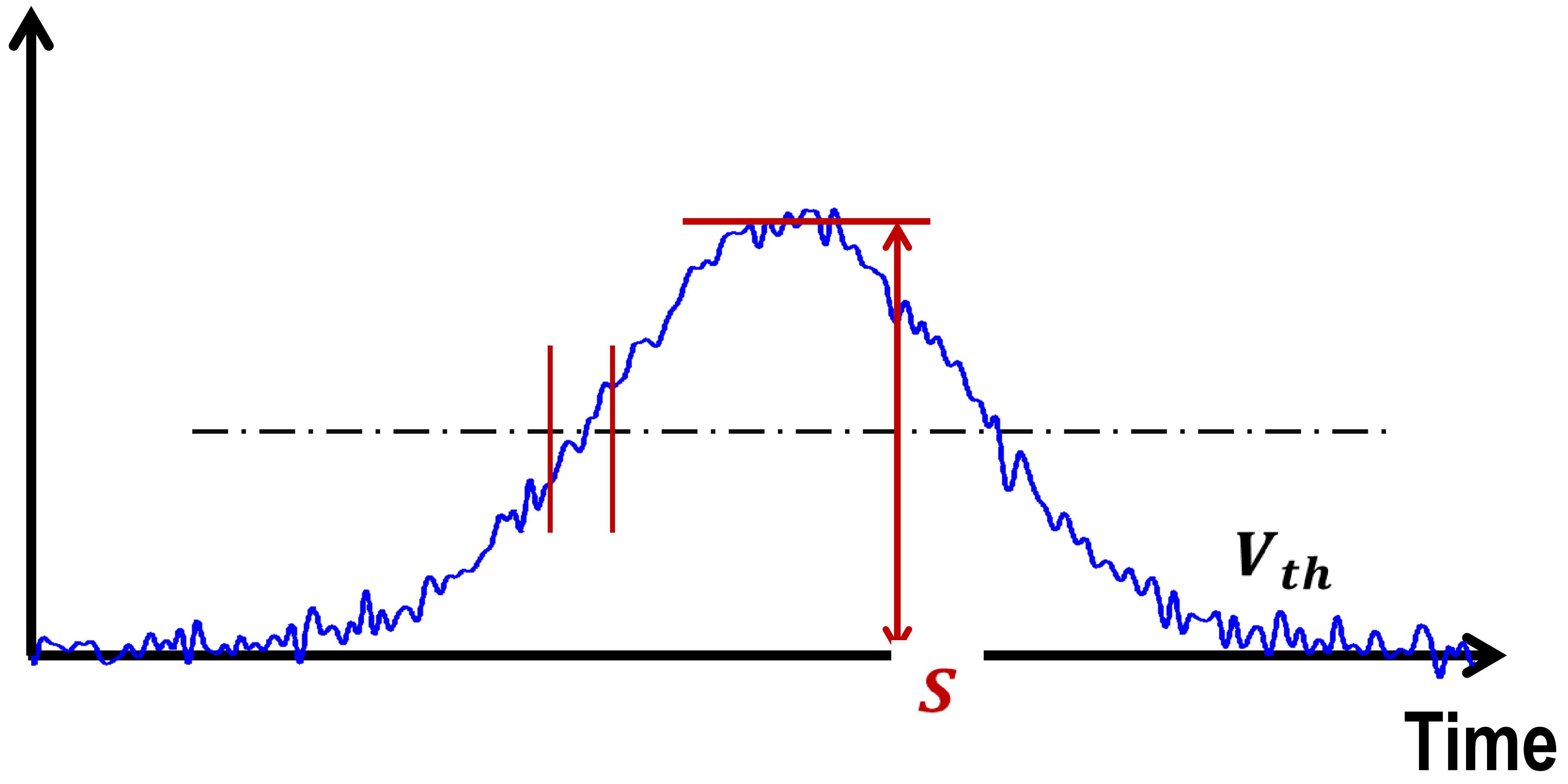


TX clock



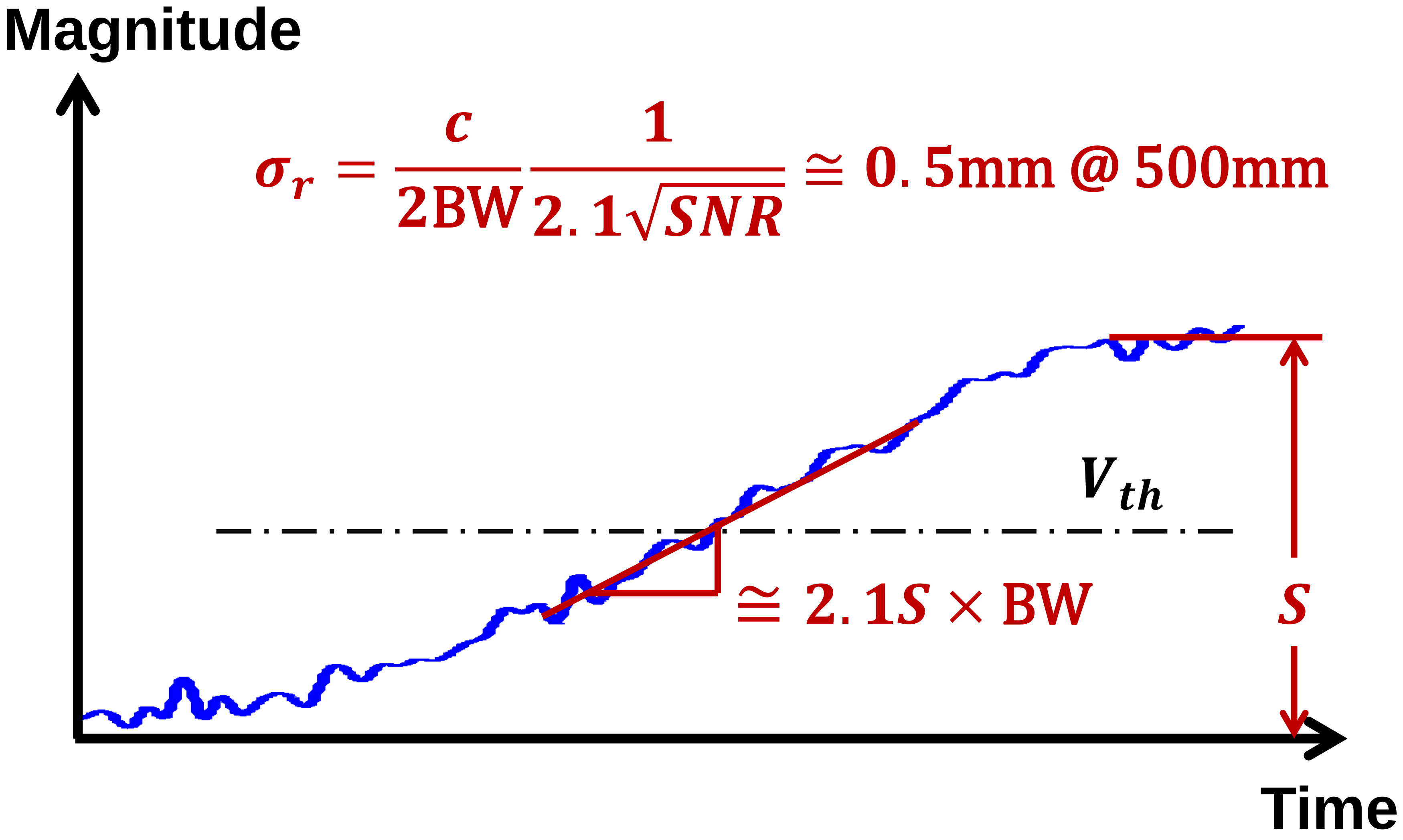
Phase can also be extracted:
- Doppler - target velocity
- Phase encoding of data

ToF Measurement: Threshold Crossing

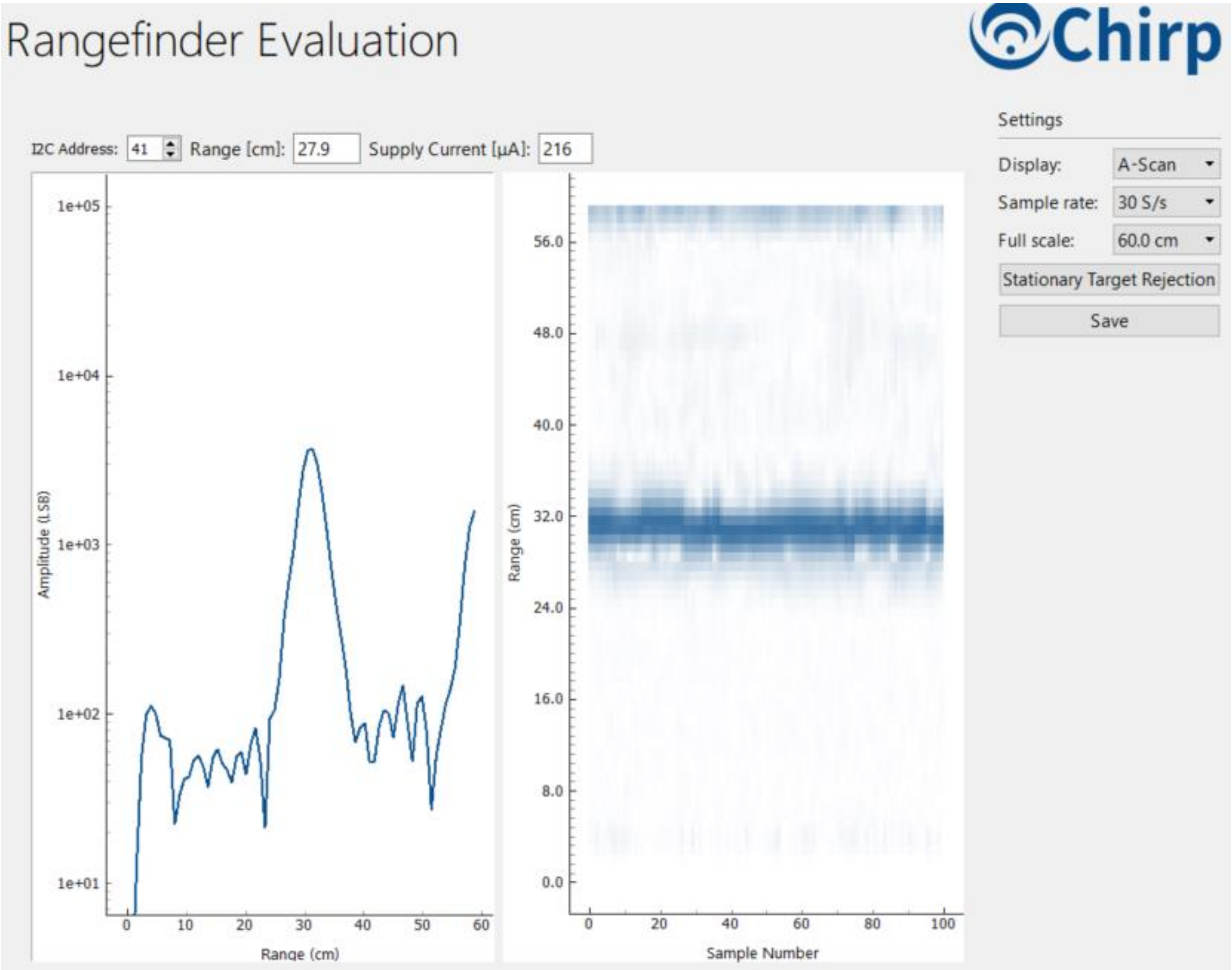


BW & SNR determine accuracy

$$\sigma_r = \frac{c}{2\mathrm{BW}} \frac{1}{2.1\sqrt{SNR}} \cong 0.5\mathrm{mm} \;@\; 500\mathrm{mm}$$

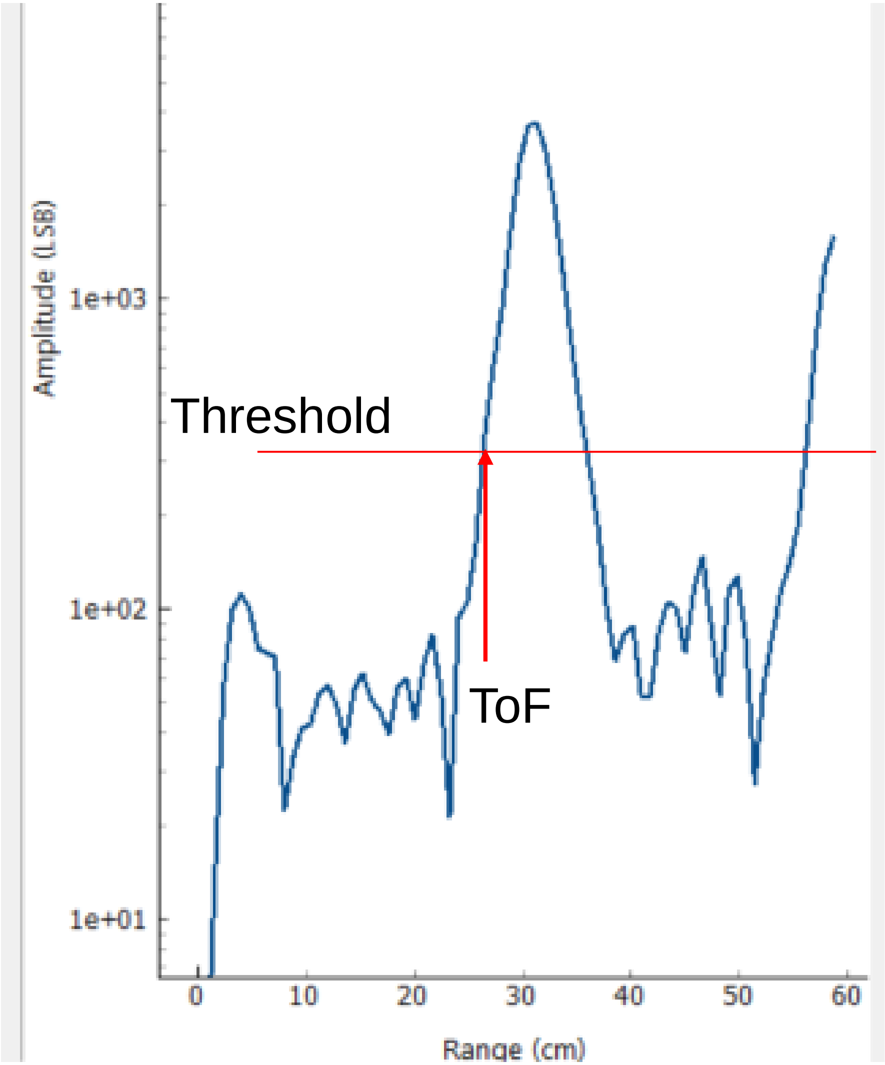


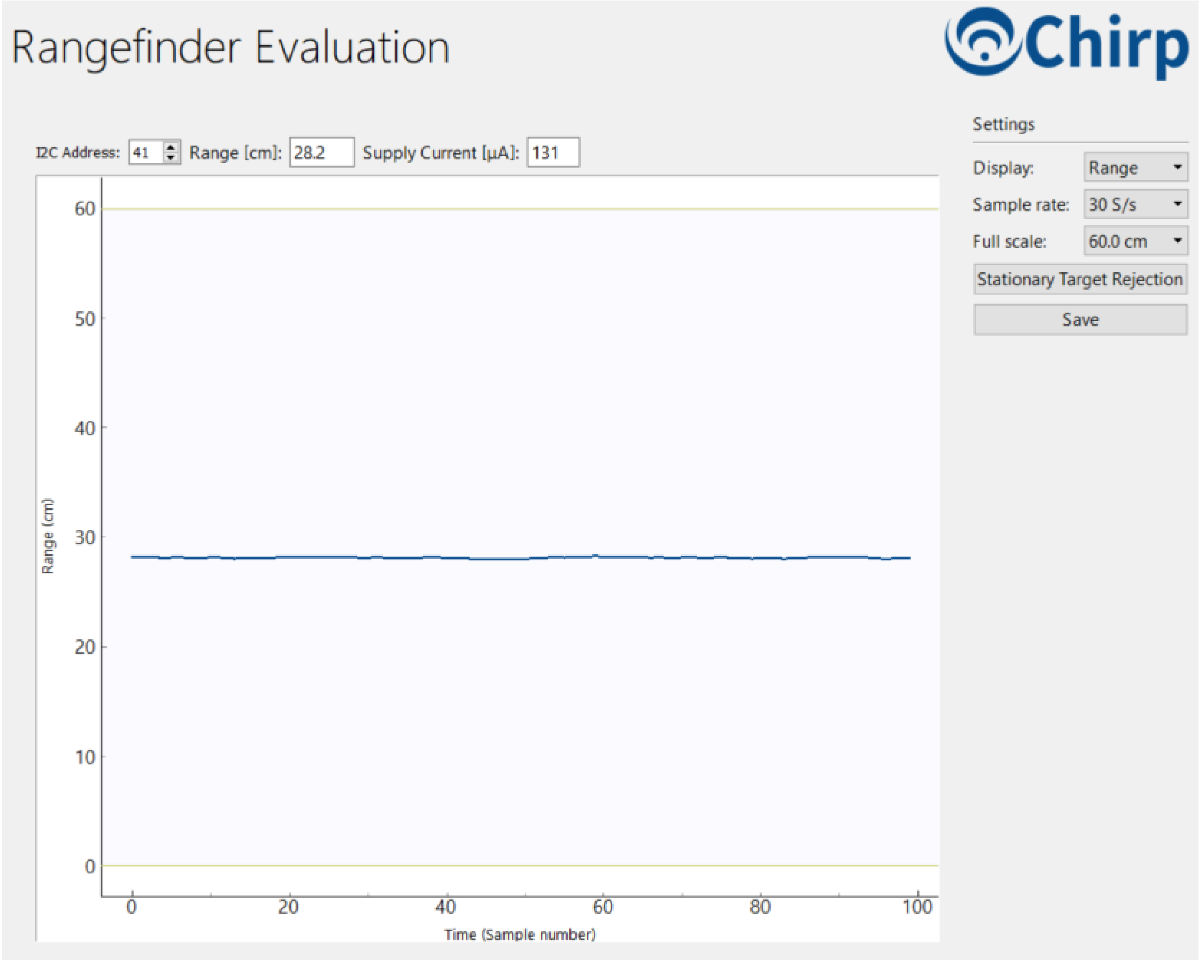
Rangefinding Example: Amplitude-Scan (A-Scan)



- Normal Mode min range 10 cm
- Targets closer than 10cm will appear to be at 10 cm

CH-101 Rangefinding Example: Range Output





Range Display Option

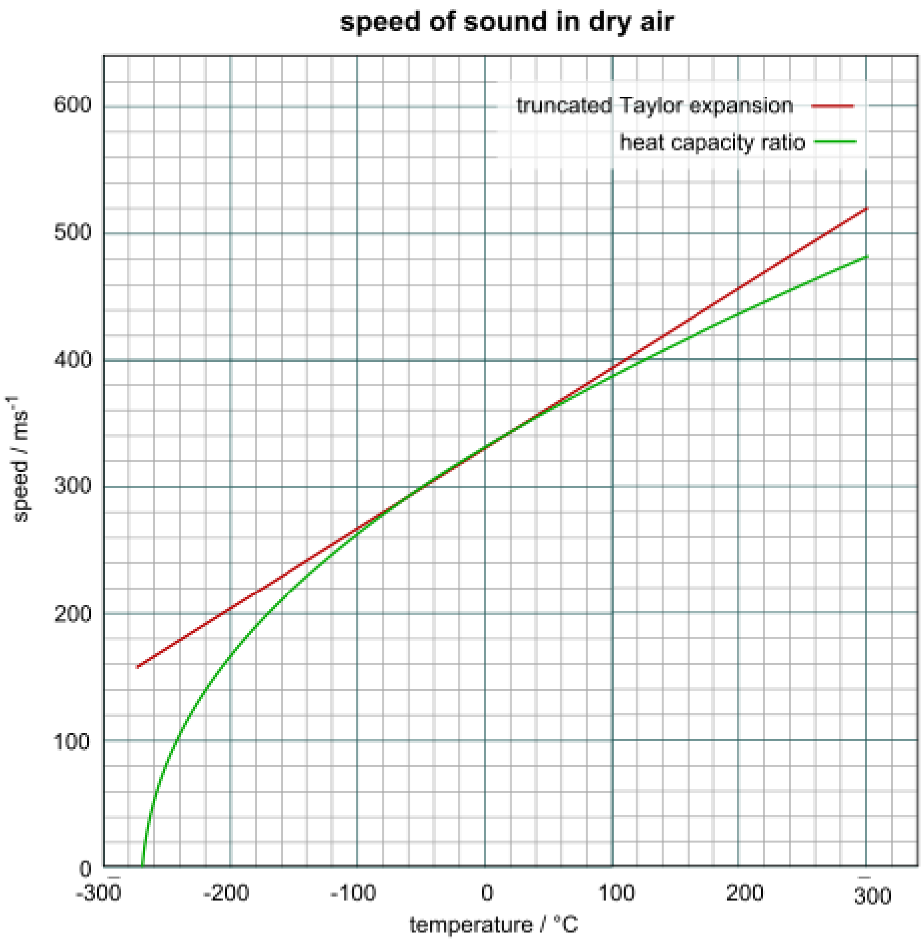
Accuracy

Time-of-Flight measurement accuracy depends on:

1. Knowing the **speed of sound** accurately
   - Depends on temperature (next slide)
   - Practically independent of humidity, pressure, etc

2. Having an accurate **time-base**
   - On-chip real-time clock (RTC) uncalibrated accuracy ~15%
   - Simple to calibrate RTC by asserting a pin for 100 ms to measure RTC
   - For absolute accuracy, should also correct for RTC tempco (~200 ppm/C)

Speed of Sound in Dry Air



- c [m/s] = 331.3 + 0.606*T
- where T = temperature in °C
- **c = 343 m/s @ 20°C (68°F)**

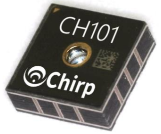
- Range error w/o temp cal: 0.17%/°C

Temp	Speed of Sound	Range error @ 1 m using 343 m/s
10°C (50°F)	337 m/s	+1.8 cm
20°C (68°F)	343 m/s	0 cm
30°C (86°F)	350 m/s	-1.8 cm

Chirp ToF Sensor Specifications

Features & Benefits:

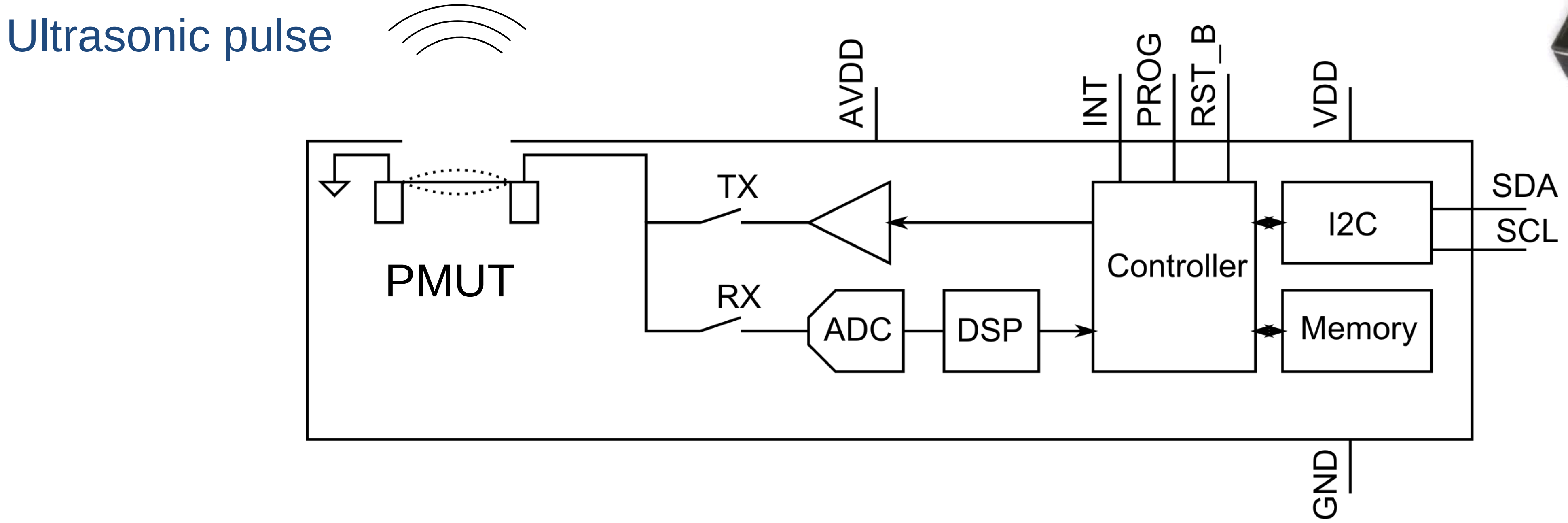
- Range + Proximity + Gesture sensor in one
- Low always-on power
- High accuracy
- Programmable operating range
- Fast response time
- Wide and customizable FOV per customer requirements
- Insensitive to ambient light or color of objects

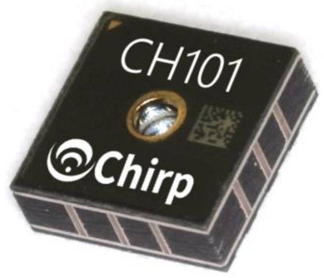


Specification	CH-101	CH-201
Dimensions	3.5 x 3.5 x 1.25 mm	3.5 x 3.5 x 1.25 mm
Operating Range	Up to 1.2 m	Up to 5 m
Voltage	1.8V	1.8V
Interface	I2C	I2C
Supply Current @1 sample/sec @max range	12 µA	20 µA
Supply Current @30 samples/sec @ max range	110 µA	330 µA
Sample Rate	Up to 100 samples/sec @ 1m	Up to 30 samples/sec @ 5m
FOV	Up to 180 degree	Up to 180 degrees
Range Noise	1 mm rms (@30cm)	0.2 mm rms (@1 m)

Chirp CH-x01 Block Diagram

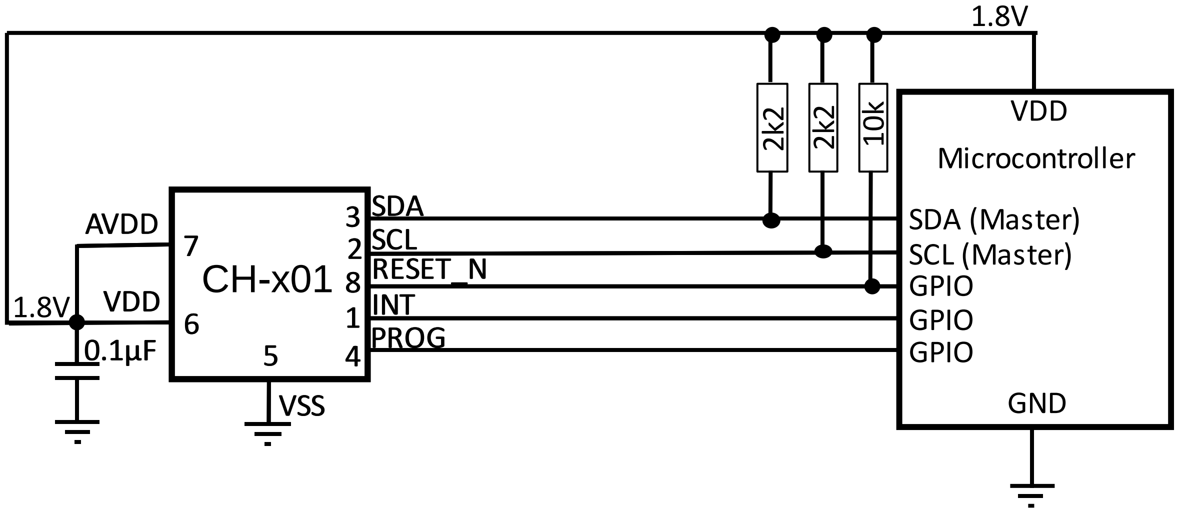
- The CH-101 and CH-201 are systems in package (SiP), containing a piezoelectric micromachined ultrasonic transducer (PMUT) and a programmable system-on-chip (SoC) that handles all the ultrasonic signal processing
- Chirp can factory-program CH-x01 to enable different functionality, such as time-of-flight range-finding, proximity sensing, human presence

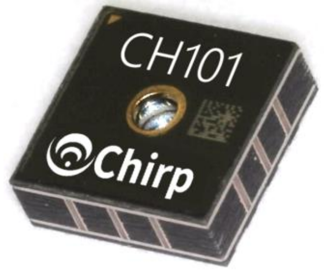




CH-x01 MCU Interface Schematic

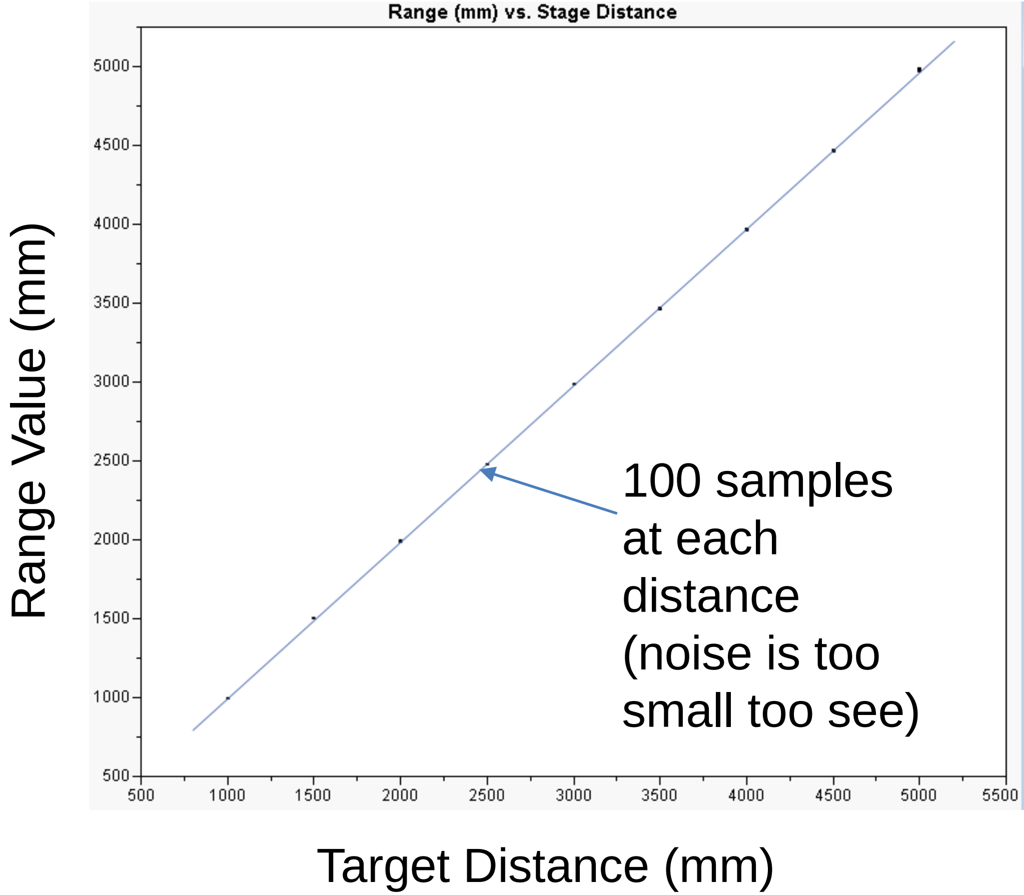
- Both sensors share a common I2C interface and operate from a single 1.8V supply
- Multiple sensors can share the same I2C bus
- Chirp's platform-independent C driver software helps customers with embedded software development



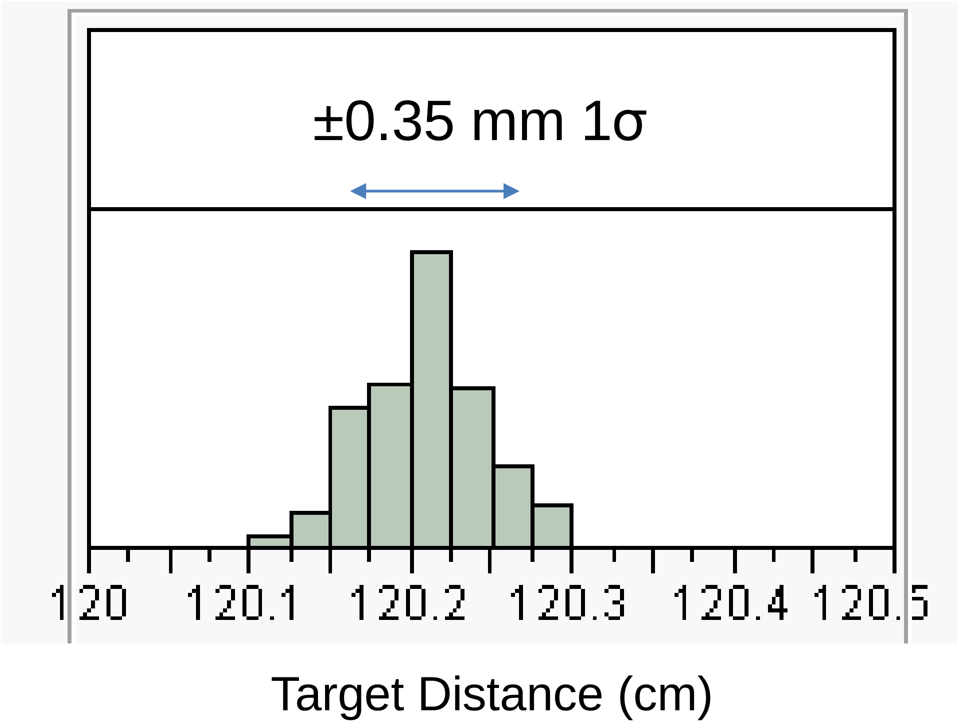


CH-201 Ultrasonic ToF Sensor Performance

Range Measurement up to 5 m



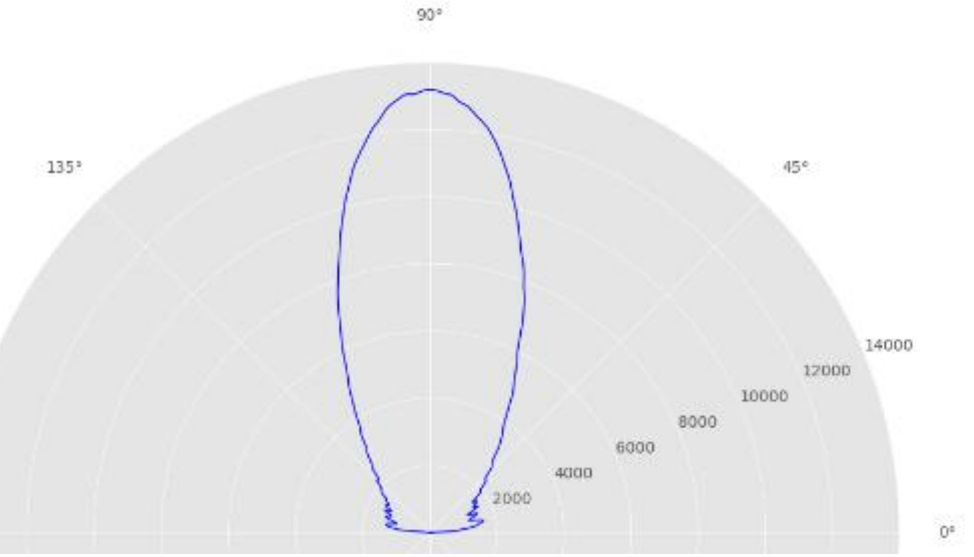
Range Noise @120 cm



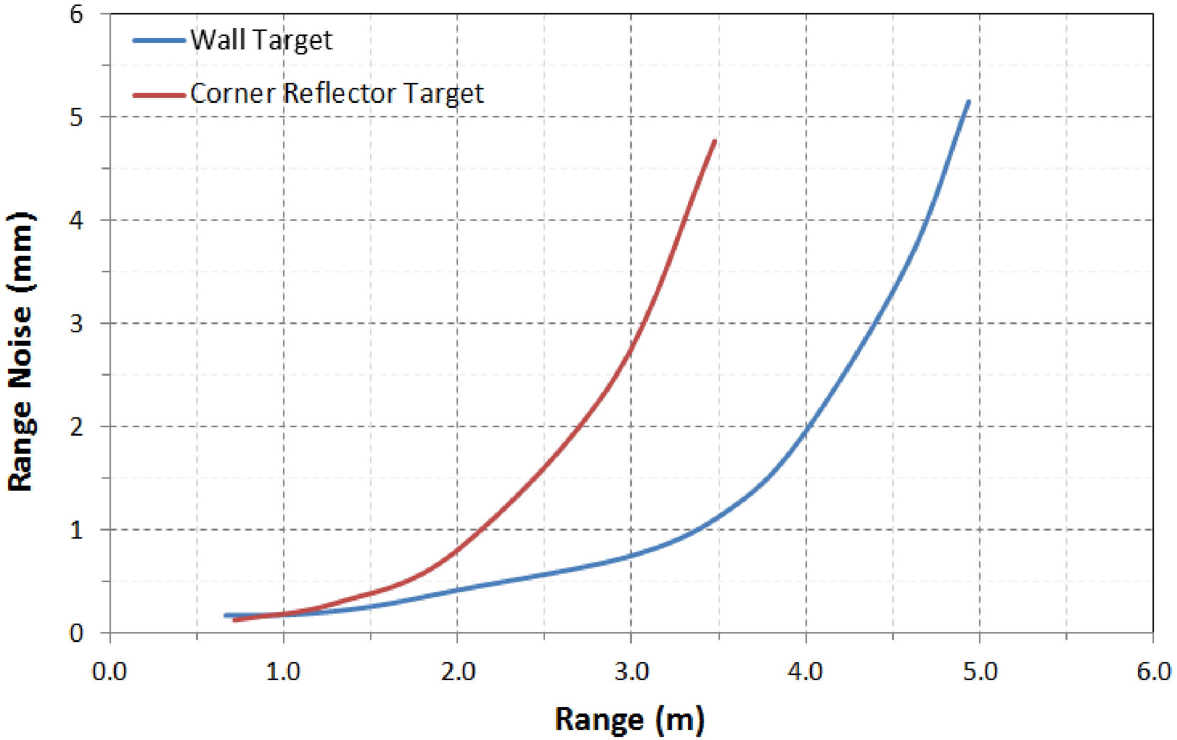
CH-201 is 100x lower noise than competing IR ToF Sensors at 120 cm range

CH-201 Field-of-View and Range Noise

FoV with Narrow FoV Housing



RMS Range Noise vs. Target Range



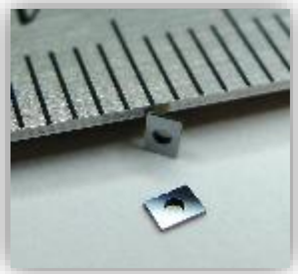
- Customizable FoV through design of product enclosure
- Narrower FoV increases max range

Chirp Provides Solutions

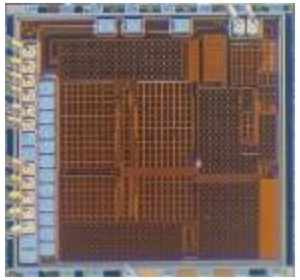
From the Component Level to the System Level

1. Unique Sensor Components → **2. On-Chip Sensing Algorithms** → **3. Complete System Solutions**

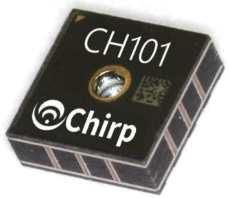
Piezoelectric Micromachined Ultrasonic Transducer (PMUT) Chip

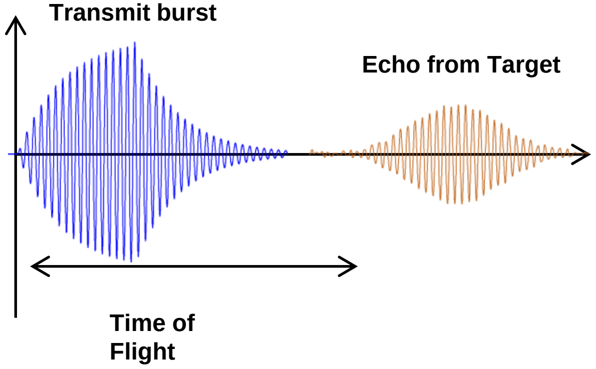


Ultrasound SoC

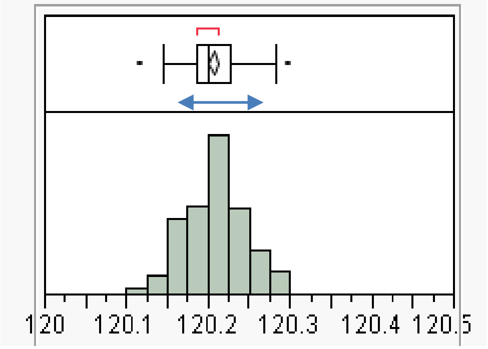


Custom Package



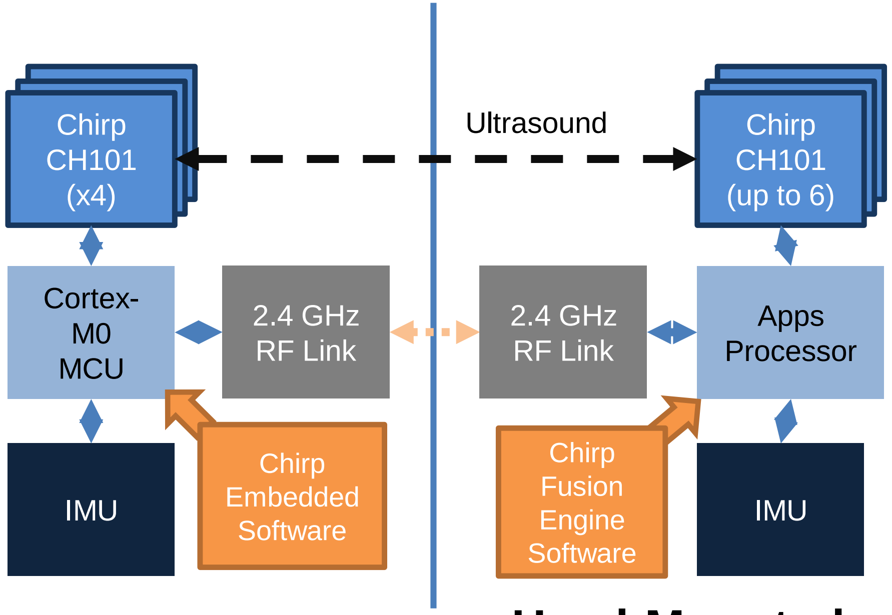


Range accuracy
0.35 mm_{RMS} @ 120 cm



Target Distance (cm)

6-DOF Controller Reference Design



Hand-held Controller | **Head-Mounted Display**

Chirp Ultrasonic ToF Sensors

Enable a Broad Range of Sensing Applications

PC & IoT:
Range & presence detection

Touchless gesture UI

VR/AR 6DoF controller tracking

Fast autofocus & room mapping

Home security:
Door/window sensing

CH-101 Enables Inside-Out Tracking for VR

uBeacon 6DoF Controller Tracking Solution

- Mobile-ready (no base-station)
- Ultrasound – IMU sensor fusion
- Works under any lighting condition
- Near zero computation load
- Ready for mass production

uBeacon 6DOF Controller Tracking System Specs

Parameter	Specification	Notes
Update Rate	60 fps (Ultrasound) & IMU @210Hz	Independent of number of controllers
Latency	< 8 ms	Worst case controller to Android latency
Range	1.2 m (HMD to controllers)	
Accuracy	< 1 mm RMS	Typical baseline size of an HMD
Field-of-View	180° (in both axes) w/ 3 sensors	Expandable to 250° w/ more sensors
Connectivity	Wireless 2.4 GHz	
Software Compatibility	Android / Windows / Linux	

Ultrasonic ToF Range-Finding Solution: Crash Avoidance and Object Tracking

- Wide field of view
- Robust performance under sunlight / street noises
- No privacy concerns
- Fast response with minimal computation
- Developer kit available today

Ultrasonic ToF Range-Finding Solution: Object Presence Detection

- Wide field of view
- Robust performance under bright lights
- Ultralow power for always-on operation
- Detects any color and fabric
- Fast response with minimal computation

Ultrasonic Gesture Interface

Provides a Highly Differentiated User Experience

Natural, intuitive gesture interface

Expands interaction space beyond the device surface

Low power for always-on interaction

Works under sunlight and with gloves

Evaluation kit available today

Summary

- Chirp's ultrasonic ToF sensors have many unique features:
  - Ultralow power consumption, as low as 15 μW
  - Wide field-of-view up to 180 degrees
  - Able to work in any lighting condition, including direct sunlight
  - Insensitive to object color, detects optically transparent surfaces like glass windows & doors
  - Small size allows flexible product design and clean appearance
  - Digital I2C interface and sensor driver for easy MCU integration

Thank You!