

# Using a fixed threshold in ultrasonic distance-ranging automotive applications

By Arun T. Vemuri

Kilby Labs Systems Engineer

## Introduction

In ultrasonic distance-ranging automotive applications such as ultrasonic park assist (UPA) and blind-spot detection (BSD), ultrasonic waves transmitted by the system are reflected by objects present in the vicinity. The system receives the reflected wave, or echo, and compares the object's echo amplitude against a threshold to detect the object. The echo for objects that are closer to the system is stronger than that for objects that are farther from the system. Hence, it is relatively common for the threshold to be varied with time. This article shows that a variable threshold is not required and that the threshold can remain fixed.

## Ultrasonic distance ranging

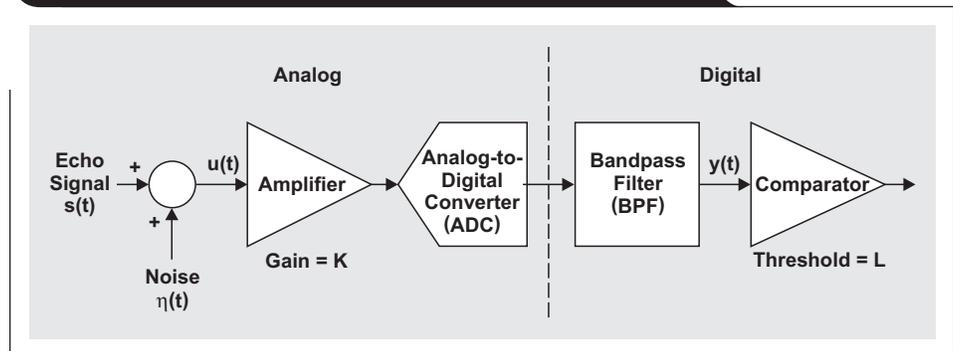
One application for ultrasonic distance ranging is an advanced driver-assistance system (ADAS) in a passenger car. Ultrasonic transducers installed in the front and rear bumpers and wing mirrors of an automobile transmit ultrasonic waves and then receive the ultrasonic waves reflected back by nearby objects. An ultrasonic wave's time of flight (TOF) is used to calculate the distance to the objects to assist the driver in parking the car, identifying parking spots, or detecting objects in the driver's blind spot. Up to four transducers are installed in the front and rear bumpers, and one transducer is installed in each wing mirror.

In an ultrasonic ADAS, piezoelectric transducers typically are used to convert electrical signals into ultrasonic waves, and reflected ultrasonic waves into electrical signals. The low receiver sensitivity of piezoelectric ultrasonic transducers usually results in very small electrical signals when the reflected waves are received.

Figure 1 shows a typical signal chain used to process the echo voltage. The Texas Instruments (TI) PGA450-Q1 is an example of an integrated automotive ultrasonic sensor signal conditioner for applications such as UPA systems.

The echo signal,  $s(t)$ , received by the ultrasonic receiver is corrupted with noise. The input-referred noise,  $\eta(t)$ , in Figure 1 is the sum of noise from the external environment and all signal-chain components as a function of time ( $t$ ). This corrupted signal,  $u(t)$ , is amplified by an amplifier with gain,  $K$ , and is digitized with an analog-to-digital converter (ADC). The digitized AM signal is routed through a bandpass filter (BPF), which is primarily used to improve

Figure 1. ADAS using echo processing to detect objects



the signal's signal-to-noise ratio. The filtered signal,  $y(t)$ , is compared against a threshold,  $L$ , to detect the presence of an object. BPFs typically are followed by an amplitude demodulator that translates the signal to baseband for comparison. However, for the purpose of this article, the demodulator can be ignored. Thus, the key to detecting the object is the choice of threshold ( $L$ ). So how does one go about choosing  $L$ ?

## Echo amplitude

Ultrasonic waves generated by the transmitter are a series of sinusoid pulses at carrier frequency and are characterized by sound pressure level (SPL). The SPL is given by

$$\text{SPL} = 20 \log_{10} \left( \frac{p_{\text{rms}}}{p_{\text{ref}}} \right), \quad (1)$$

where  $p_{\text{rms}}$  is the RMS sound pressure, and  $p_{\text{ref}}$  is the reference sound pressure. The commonly used reference sound pressure is 20  $\mu\text{Pa}$ , or 0.0002  $\mu\text{bar}$ .

The SPL of ultrasonic waves created by the transducer at an object depends on the object's distance from the transducer. Specifically, the pressure is inversely proportional to the distance:

$$p \propto \frac{1}{d},$$

where  $p$  is the pressure of the sound waves, and  $d$  is the distance of the object from the transducer. Ultrasonic transducer specifications provide the SPL at 30 cm from the transducer. Given this value, the SPL at arbitrary distance  $x$  from the transducer can be calculated by using the distance law,

$$\frac{p_{30\text{-rms}}}{p_{x\text{-rms}}} = \frac{x}{30}, \quad (2)$$

where  $x$  is the distance between the transducer and the object, and  $x > 30$  cm. Therefore, the SPL at  $x$  is given by

$$SPL_x = SPL_{30} - 20 \log_{10} \left( \frac{x}{30} \right).$$

That is, there is loss of sound pressure as the ultrasonic wave travels from the transducer to the object.

The sound waves reflect from the object and return to the transducer, further losing sound pressure. Additionally, due to absorption in air and by the object, the SPL of the received echo can be approximated by Equation 3, shown at the bottom of this page, where  $\alpha$  is the absorption coefficient of air. Note that the SPL absorbed in air is proportional to the distance traveled by the sound waves in air. In other words, the SPL loss is proportional to  $x$ . A factor of 2 is used because the sound waves travel twice between the transducer and the object—once from the transducer to the object, and once from the object to the transducer.

Based on Equation 1, the sound pressure of the echo pulse received by the transducer can be calculated as

$$P_{\text{echo\_rms}} = P_{\text{ref}} \times 10^{\frac{SPL_{\text{echo}}}{20}}. \quad (4)$$

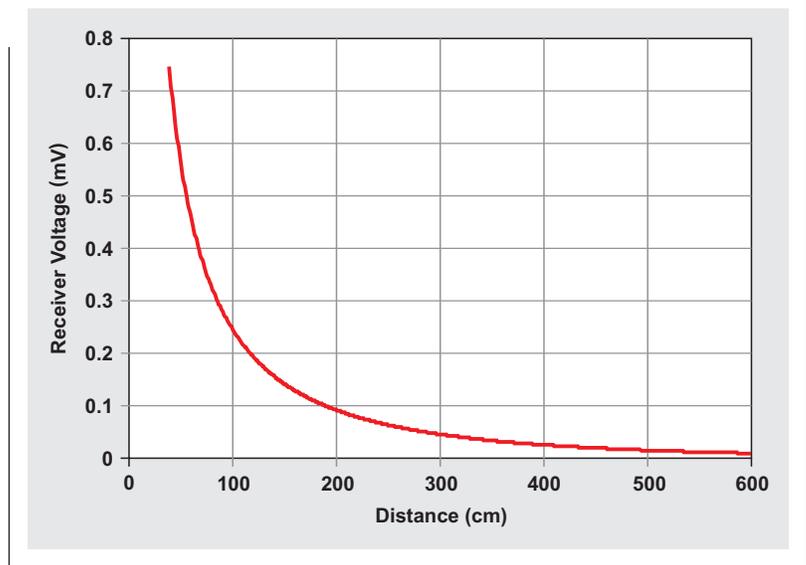
The ultrasonic receiver converts the received waves into electrical signals. The conversion process is characterized by receiver sensitivity, which is specified in dB. A receiver has 0 dB of receiver sensitivity when it produces 10 V for 1  $\mu\text{Pa}$  of sound pressure. Thus, receiver sensitivity specified in dB can be converted to V/ $\mu\text{Pa}$  by using Equations 5 and 6.

$$RxSensitivity_{\text{dB}} = 20 \log_{10} \left( \frac{\gamma \text{ V}/\mu\text{Pa}}{10 \text{ V}/\mu\text{Pa}} \right), \quad (5)$$

where  $\gamma$  is the receiver sensitivity in V/ $\mu\text{Pa}$ . Equation 5 can be rearranged as

$$\gamma \text{ V}/\mu\text{Pa} = 10^{\frac{RxSensitivity_{\text{dB}}}{20} + 1}. \quad (6)$$

**Figure 2. Receiver voltage as a function of the object's distance from the transducer**



Equations 4, 5, and 6 can be combined into Equation 7, shown at the bottom of this page, to find the voltage produced by the ultrasonic receiver. Equation 7 can be simplified as

$$\gamma_{\text{echo\_rms}} = K P_{\text{ref}} \times \frac{30}{2x \times 10^{0.1\alpha x}}, \quad (8)$$

where the gain ( $K$ ) is a constant.

Equation 8 shows that as the distance  $x$  of the object from the transducer increases, the echo voltage decreases. In other words, if the object is closer, the echo amplitude is large, and if the object is farther away, the echo amplitude is small.

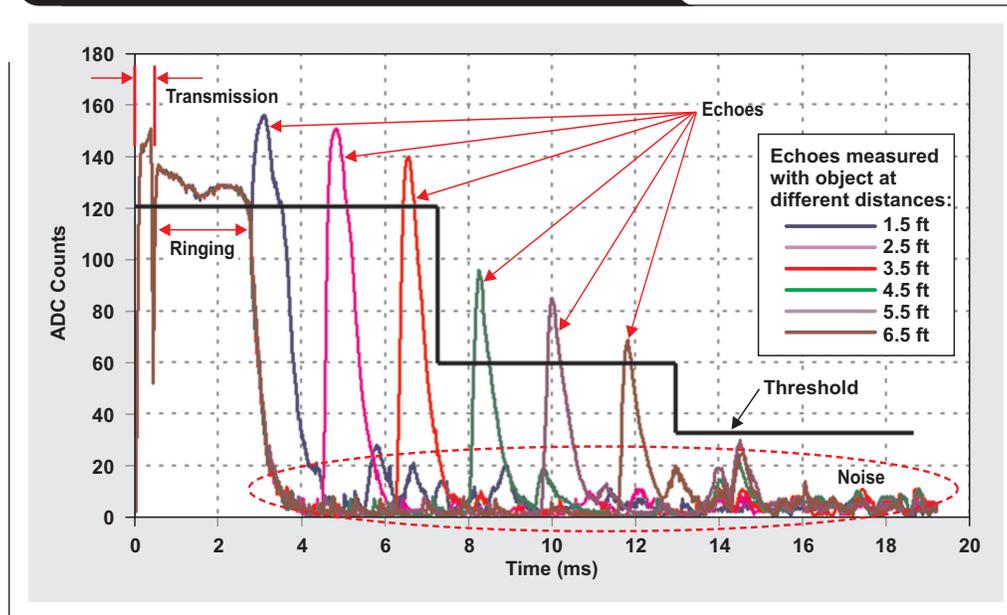
Figure 2 shows the received voltage as a function of the object's distance from the transducer, assuming these parameters:

- Transmitted SPL = 106 dB at 30 cm
- Air absorption = 1.3 dB/m
- Object absorption = 0 dB
- Receiver sensitivity = -85 dB

$$SPL_{\text{echo}} = SPL_{\text{transmitted}} - 20 \log_{10} \left( \frac{2x}{30} \right) - 2\alpha x - SPL_{\text{absorbed by object}}, \quad (3)$$

$$\gamma_{\text{echo\_rms}} = P_{\text{ref}} \times 10^{\frac{SPL_{\text{transmitted}} - 20 \log_{10} \left( \frac{2x}{30} \right) - 2\alpha x - SPL_{\text{absorbed by object}} + RxSensitivity_{\text{dB}}}{20}} + 1 \quad (7)$$

**Figure 3. Demodulated echo-signal waveforms with one possible threshold schedule**



### Variable-threshold scheduling

The previous section showed that the amplitude of the echo received from objects decreases in magnitude as the object's distance from the transducer increases. Further, it is known from Figure 1 that the input signal to the echo-processing path is  $u(t) = s(t) + \eta(t)$ , where  $s(t)$  is the echo signal and  $\eta(t)$  is the input-referred noise. In other words, the echo-processing system has to detect the presence of an object by processing the echo signal that not only decreases in amplitude with distance but also is corrupted by noise. One approach normally taken when choosing threshold values is threshold scheduling. In this method, the threshold value is varied with time. Specifically, the threshold value is set to a high value just after the ultrasonic waves are transmitted and is then decreased as elapsed time increases. The rationale behind this approach is to use the predictable decay in signal amplitude to determine the threshold values: The closer the object, the larger are the echo and the threshold for detecting the object. The farther away the object, the smaller are the echo and the threshold.

The concept of the variable threshold is illustrated in Figure 3. This figure shows several sample demodulated echoes for objects at different distances. A test setup with TI's PGA450-Q1 evaluation module was used to collect the waveform data. This figure shows one possible threshold schedule.

While the method of variable-threshold scheduling works in principle, it suffers from two weaknesses:

1. Variable-threshold scheduling requires memory inside the device to store the time-versus-threshold values in the schedule table. If the threshold has 3 possible values

as shown in Figure 3, the table will have 6 possible entries. Moreover, for an advanced driver-assistance system (ADAS) in an automobile, customers can store entries for multiple potential installation locations because the transducer can be fitted anywhere on the bumpers or wing mirrors. For example, if the transducer has 10 possible installation locations, up to 60 entries have to be stored in the device. This adds to the device's cost because additional memory is required.

2. System manufacturers "calibrate" the schedule table after installing the transducers in the bumpers and wing mirrors. Calibration is the process of determining the threshold values and times at which the threshold should be switched. The calibration process usually is time-consuming (and hence expensive), especially if multiple entries in the table are needed.

In summary, the main weakness of variable-threshold scheduling is that it increases the overall cost of the ultrasonic ranging system.

### Fixed threshold

In contrast to the variable-threshold approach, which uses time-based threshold values, the fixed-threshold approach uses signal noise as the baseline. The noise in the system is used to determine the threshold so that the absence of objects does not result in detection of objects.

Again, from Figure 1 it is known that the input signal to the echo-processing path is  $u(t) = s(t) + \eta(t)$ . The echo signal is a series of sinusoid pulses at a carrier frequency,  $f_c(t)$ , and is given by

$$s(t) = S \times \sin(2\pi f_c t), \quad (9)$$

where  $S$  is the amplitude of the echo signal. Therefore,

Equation 10 gives the RMS value of the amplified signal:

$$s_{\text{rms}} = \frac{KS}{\sqrt{2}} \quad (10)$$

Note that this series of pulses occurs for only a short duration, making the signal's amplitude appear to be modulated over a long duration of time.

The  $y(t)$  output of the bandpass filter (BPF) can be expressed as

$$y(t) = f(\text{BPF}) \rightarrow \{f(\text{ADC}) \rightarrow K[s(t) + \eta(t)]\}, \quad (11)$$

where  $f(\text{BPF})$  is the digital-filter function of the BPF and  $f(\text{ADC})$  is the quantization function of the ADC. Assuming that the reference time for the echo signal is  $t_0 = 0$  (which usually is the time at which ultrasonic waves are transmitted by the transmitter), an object is declared to be present at time  $t_{\text{object}}$  under the conditions  $y(t) < L$ ,  $t_{\text{end}} < t < t_{\text{object}}$ , and  $y(t_{\text{object}}) \geq L$ , where  $t_{\text{end}}$  is greater than zero and is the end of the initial burst of transmitted pulses.

The question is, "Can one choose a fixed threshold instead of using variable-threshold scheduling?" To answer this question, the noise components can be considered by using Equation 12 and assuming that  $t$  is an instantaneous value:

$$\eta(t) = \eta_{\text{ext}}(t) + \eta_{\text{amp}}(t) + \frac{1}{K} \eta_{\text{ADC}}(t) + \frac{1}{K} q(t) + \frac{1}{K} \eta_{\text{BPF}}(t) \quad (12)$$

The variables are defined as follows:

$K$  = amplifier gain

$\eta_{\text{ext}}(t)$  = external noise

$\eta_{\text{amp}}(t)$  = amplifier noise

$\eta_{\text{ADC}}(t)$  = ADC circuit noise

$q(t)$  = ADC quantization

$\eta_{\text{BPF}}(t)$  = mathematical errors in BPF calculations

The individual noise components are independent of each other. Further, it is assumed that each noise component is Gaussian with zero mean and non-zero variance.

When Equations 9 and 12 are substituted into Equation 11, the BPF output becomes

$$\begin{aligned} y(t) &= f(\text{BPF}) \rightarrow \{f(\text{ADC}) \rightarrow K[S \times \sin(2\pi f_c t) + \eta(t)]\} \\ &= KS \times \sin(2\pi f_c t) + f(\text{BPF}) \rightarrow [K\eta_{\text{ext}}(t) + K\eta_{\text{amp}}(t) + \eta_{\text{ADC}}(t) + q(t) + \eta_{\text{BPF}}(t)]. \end{aligned} \quad (13)$$

Based on Equation 9, the RMS of the BPF noise is

$$\eta_{\text{rms}} = \sqrt{\frac{1}{Q} \times \frac{f_c}{f_s} \times \left[ (K\eta_{\text{ext}})^2 + (K\eta_{\text{amp}})^2 + \eta_{\text{ADC}}^2 + q^2 + \eta_{\text{BPF}}^2 \right]}, \quad (14)$$

where  $Q$  is the quality factor of the BPF,  $f_s$  is the ADC sampling frequency, and all noise terms are RMS values.

Given the RMS of noise described by Equation 14, and assuming a 6.6 crest factor, the chosen threshold is

$$L = 6.6 \sqrt{\frac{1}{Q} \times \frac{f_c}{f_s} \times \left[ (K\eta_{\text{ext}})^2 + (K\eta_{\text{amp}})^2 + \eta_{\text{ADC}}^2 + q^2 + \eta_{\text{BPF}}^2 \right]}.$$

The preceding equation can be expressed as

$$L = 6.6K \sqrt{\frac{1}{Q} \times \frac{f_c}{f_s} \times \left[ \eta_{\text{ext}}^2 + \eta_{\text{amp}}^2 + \frac{\eta_{\text{ADC}}^2 + q^2 + \eta_{\text{BPF}}^2}{K^2} \right]}. \quad (15)$$

In other words, a fixed threshold can be chosen by using Equation 15. Figure 4 shows an example echo response with a fixed threshold.

The obvious advantage of using this method is that it requires only one entry to be stored in memory. If the transducer has the potential to be installed in 10 locations, a total of 10 entries must be stored. This is a sixfold decrease in memory requirements from the variable-threshold method described earlier. Note that Equation 15 also provides a mechanism to scale the threshold, if the amplifier gain (K) is changed.

Equation 15 provides an analytical method to determine the threshold value. Usually, determining the threshold by using noise analysis could be involved. An alternative to performing noise analysis is to calibrate the transducer on

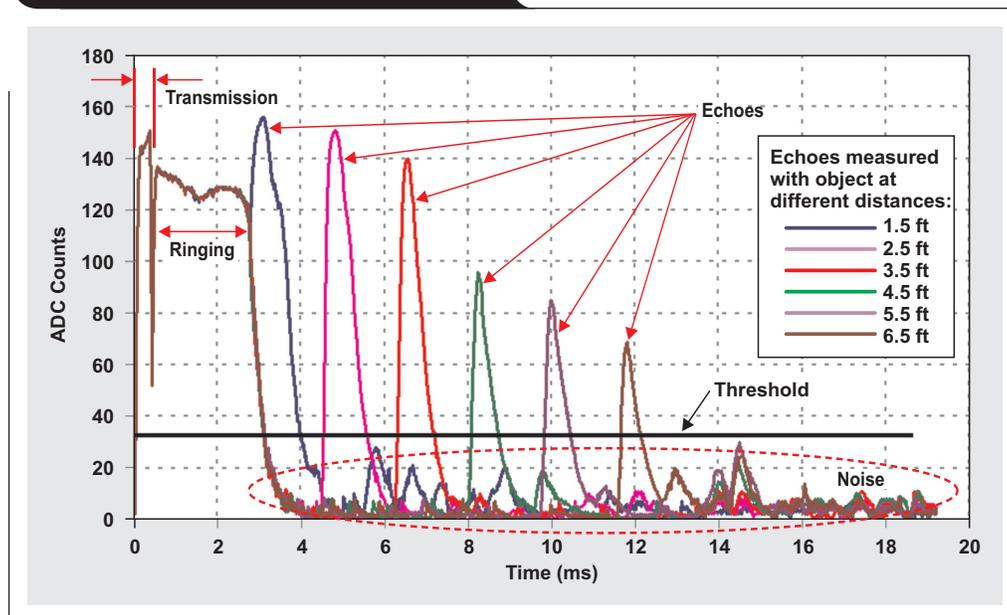
the automobile for one threshold. This calibration can be performed by placing the object at the maximum required ranging distance from the transducer. A threshold value can be chosen that is high enough to exceed the noise value of the processed signal when no object is present and that ensures that the signal crosses the threshold only in the presence of an object. Note that when this method is used to choose the threshold, the BPF decay should also be considered. Finally, to increase robustness of object detection, the signal's amplitude must be greater than the fixed threshold for a certain duration.

### Related Web sites

[amplifier.ti.com](http://amplifier.ti.com)

[www.ti.com/product/PGA450-Q1](http://www.ti.com/product/PGA450-Q1)

**Figure 4. Fixed threshold for echo data**



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