Logarithmic Amplifier for Ultrasonic Sensor Signal Conditioning

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ABSTRACT

This document explains the basic operation of a logarithmic amplifier, how a logarithmic amplifier works in an ultrasonic front end, the advantages and disadvantages of using a logarithmic amplifier versus a linear time-varying gain amplifier, and compares the performance of a logarithmic amplifier versus a linear amplifier. These topics apply to the TUSS44x0 device family (TUSS4440 and TUSS4470), which includes Texas Instrument's latest ultrasonic driver and logarithmic amplifier-based receiver front end integrated circuits. The receive signal path of the TUSS44x0 devices includes a low-noise linear amplifier, a band pass filter, followed by a logarithmic amplifier for input-level dependent amplification. The logarithmic amplifier allows for high sensitivity for weak echo signals and offers a wide input dynamic range over full range of reflected echoes.

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Trademarks

1   Introduction to Logarithmic Amplifier (Log Amp)

1.1   *Principle Operation of the Log Amp*

The logarithmic amplifier calculates the log function of the envelope of an input signal. As the amplitude of the envelope increases linearly, the output of the log amplifier yields the log function of the input. The logarithmic scale is used to quantify relative changes to the input, rather than the absolute difference because the logarithmic function of X does not yield significant change as the value of X approaches larger amplitude values. Figure 1 shows the relationship of input to output for the log function.
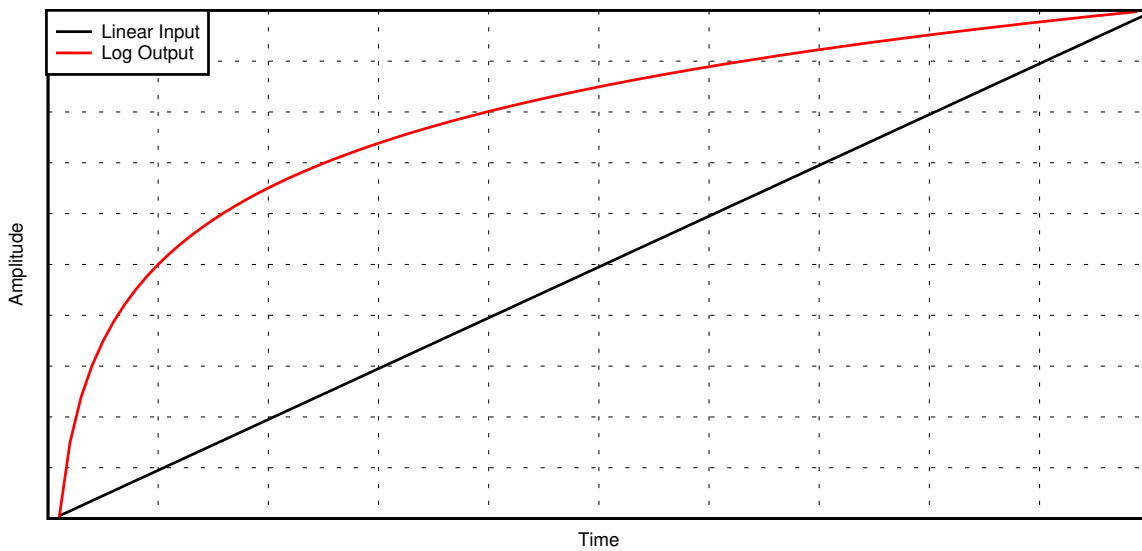
Figure 1. Linear Input and Logarithmic Output

In an electronic signal chain and in the case of a demodulating log amp, the implementation of a log function can be viewed as a form of data compression because the log amp demodulates and the input envelope log is recovered. A log amp is able to support a wide dynamic range of AC input signal amplitudes to regulate gain at a particular frequency when paired with a band-pass filter. The log amp is implemented as form of an automatic gain control to normalize the gain as a function of input amplitude, just as a variable-gain amplifier would, but without the requirement of manually entered user input. As a result, for example, a large dynamic range of the low microvolts to high millivolts is scaled and compressed to a usable range of high millivolts to low volts for more efficient comparator, or ADC capture, or both. Figure 2 shows the relationship between the log amp input to the demodulated and compressed output.

Figure 2. Log Amp Data Compression and Scaling
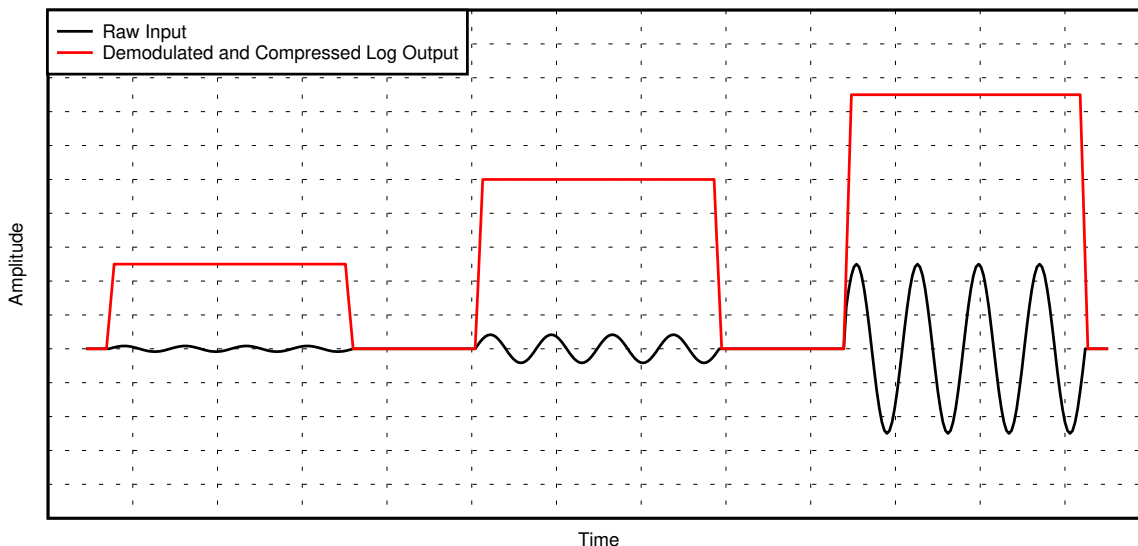
1.2   How the Log Amp Works

A demodulating or piecewise linear approximation log amp consists of a series of cascaded linear amplifiers. For the purpose of this discussion, the example log amp will include seven cascaded linear amplifiers, each capable of a 20-dB (10 V/V) gain. To demonstrate the activity of each linear amplifier stage, consider the following input example. Figure 3 shows the block diagram of a demodulating type log amp.

1.2.1   Sine Wave Input

When a sine wave with a steady peak amplitude is applied at the input of the first linear amplifier stage, the linear amplifier will always scale the input by a factor of 20 dB at the output. For example, if the peak amplitude from the input is 100 μV, then the output will result in a sine wave with a 1-mV peak amplitude. The second linear gain stage, will apply the same gain factor of 20 dB to the 1-mV peak amplitude input signal, yielding a 10-mV peak amplitude at its output.
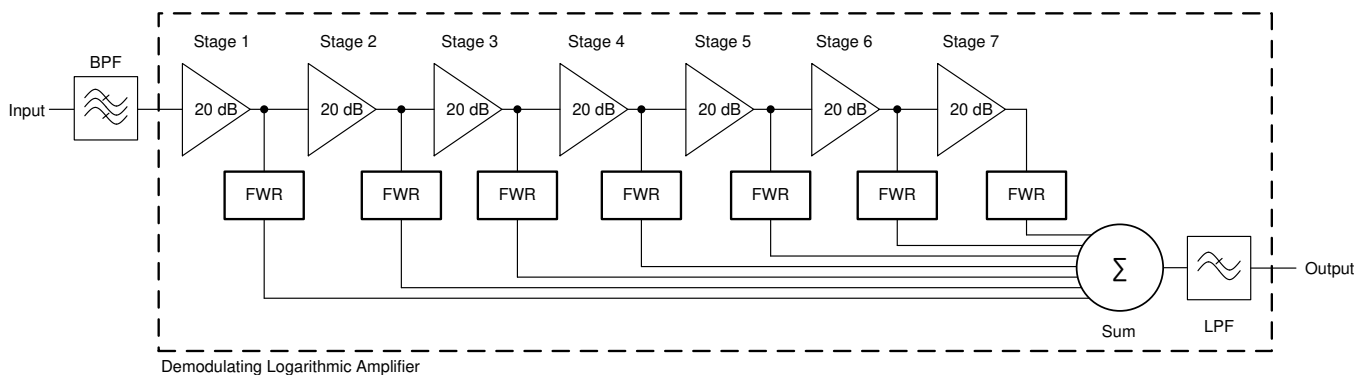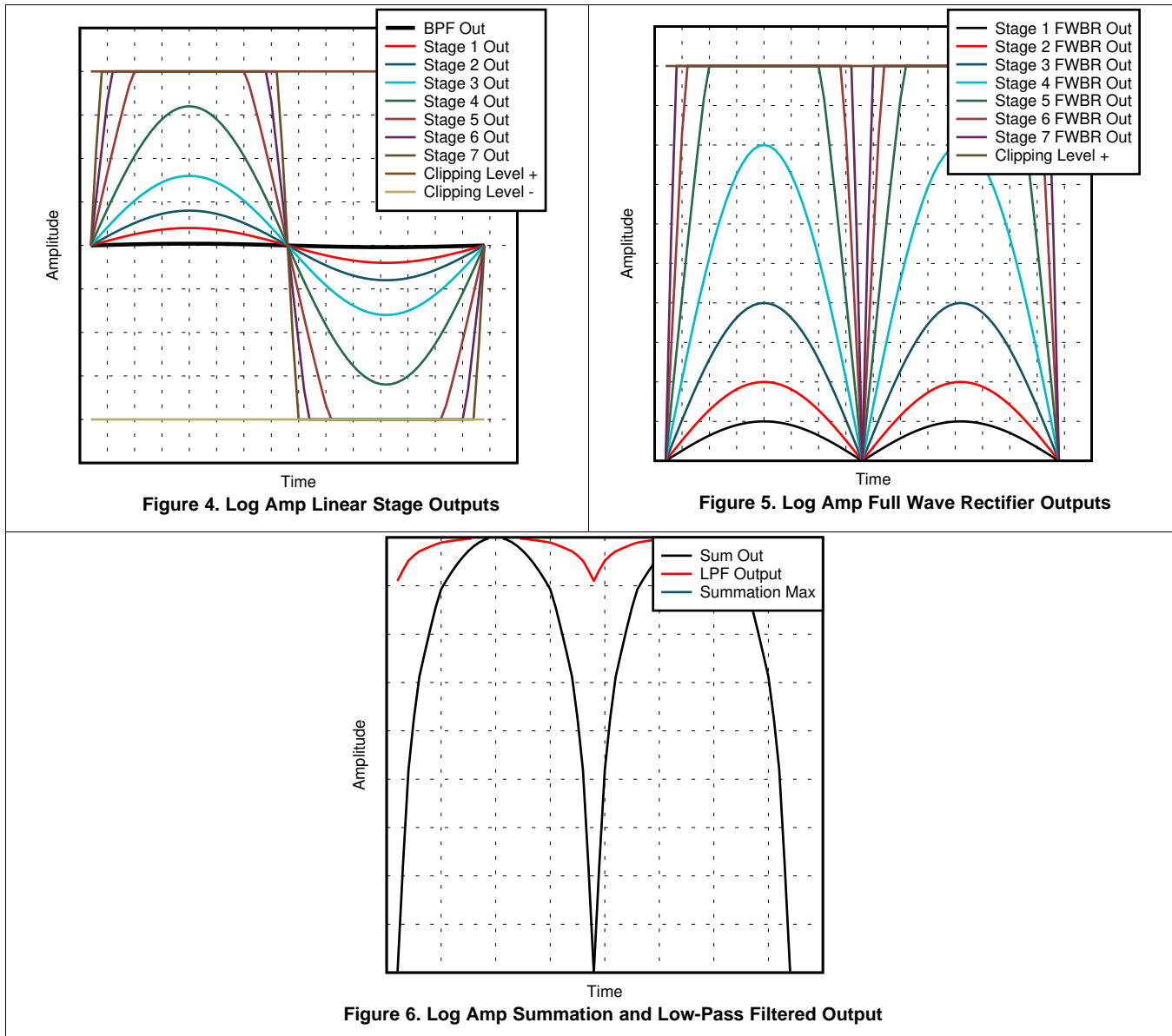

Figure 3. Log Amp Block Diagram

Figure 4. Log Amp Linear Stage Outputs

Figure 5. Log Amp Full Wave Rectifier Outputs

Figure 6. Log Amp Summation and Low-Pass Filtered Output

Eventually with a large enough peak input amplitude, the internal linear gain stages will amplify the sine wave to a point of saturation, such that the peak amplitude is clipped. The clipping level is set by the designer of the log amp so that the output of the final stage matches a desired output level for a subsequent comparator, ADC capture device, or both. For example, in the case of a 3.3-V logic level microcontroller, each of the seven internal linear amplifiers are set to have a 400-mV clipping level for maximum summation of 2.8 V (for 0.5-V margin) at the end of the signal chain if all stages are clipped. If an intermediate linear amplifier stage reaches the clipping level of 400 mV, then the clipped signal will continue to pass through each stage to maintain a 400-mV peak amplitude. Note that an already clipped input renders the subsequent linear stages less effective as the amplification becomes 0 dB for the peak value. Figure 4 shows the output of each linear stage, whereby the clipping starts to occur at stage 5 in the example. The output of each linear stage is forced to an absolute value by full wave rectification (Figure 5), summed together, and low-pass filtered to remove high-frequency ripple content to yield a smooth envelope as shown in Figure 6.

When the input is reduced or increased by a factor of the maximum amplification factor (20 dB) of an individual linear stage, the output difference is the equivalent to the clipping value (400 mV) of a single linear stage. For example, if the initial input signal is causing clipping at any point of the internal linear amplifier, then reducing the input amplitude by a factor of 20 dB will result in a maximum output difference of 400 mV. In this example, the output is changing by 400 mV for each factor of 20 dB of input amplitude, which results in a log amp slope of 400 mV per 20 dB or 20 mV/dB.

1.3   Log Amp Slope and Intercept Configuration

The transfer function of the log amp is defined as:

$$V_{OUT} = LogAmp_{Slope} \times 20\ Log(\ V_{IN}\ /\ LogAmp_{Intercept}) \tag{1}$$

Configuration of the log amp is simplified to two variables, the log amp slope and intercept. These variables define the transfer function to set the relationship between the acceptable input amplitude range and desired output voltage. The slope is determined by the rate of change from one input amplitude value to another in terms of volts per dB. Figure 7 shows the effects of three different log amp slope values.
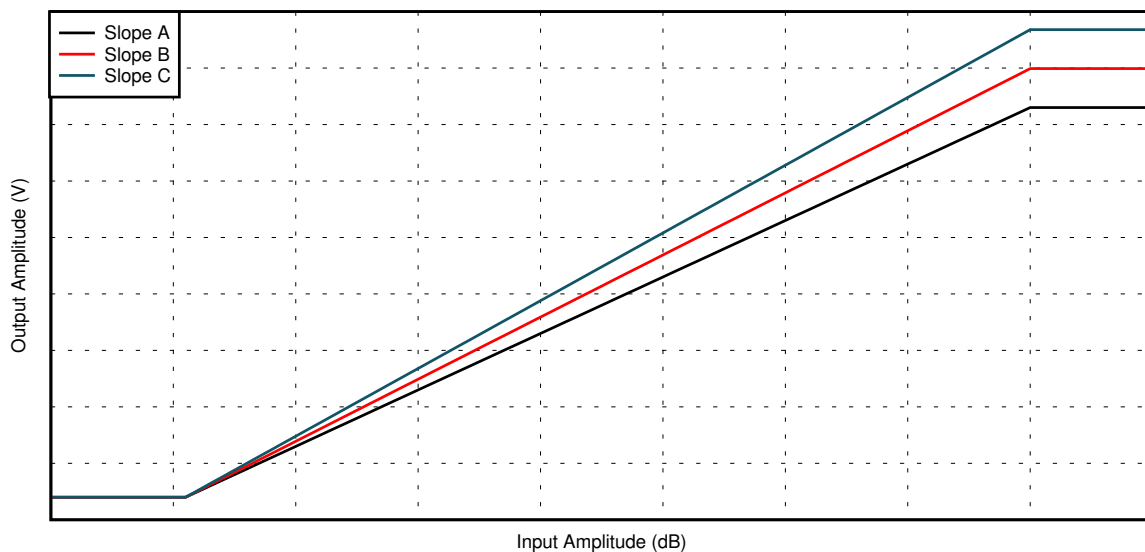

Figure 7. Log Amp Slope Effect

To determine the log amp intercept, or use the log amp intercept to approximate the transfer function with respect to the log amp slope, apply linear extrapolation to an output of 0 V. Linear extrapolation can only be used when the input amplitude is represented in linear dB terms or on a logarithmic scale if in volts. On the log scale, the log amp responds linearly to an input amplitude within a given range. Input values beyond the acceptable range yield a fixed or flat response at the output. This is because the minimum amount of amplification of the log amp at a very low input amplitude cannot drop below the reference bias noise of the circuit. This means the noise floor will always generate a consistent base line amount of noise amplification through the log amp. At the very large input amplitude, the log amp saturates due to the summation of the maximum output value set by the clipping level of each internal linear amplifier stage. The log amp intercept has an inverse effect on the output such that as the intercept value increases, the output voltage decreases. Figure 8 shows how the intercept value is determined based on the 0-V output level threshold.
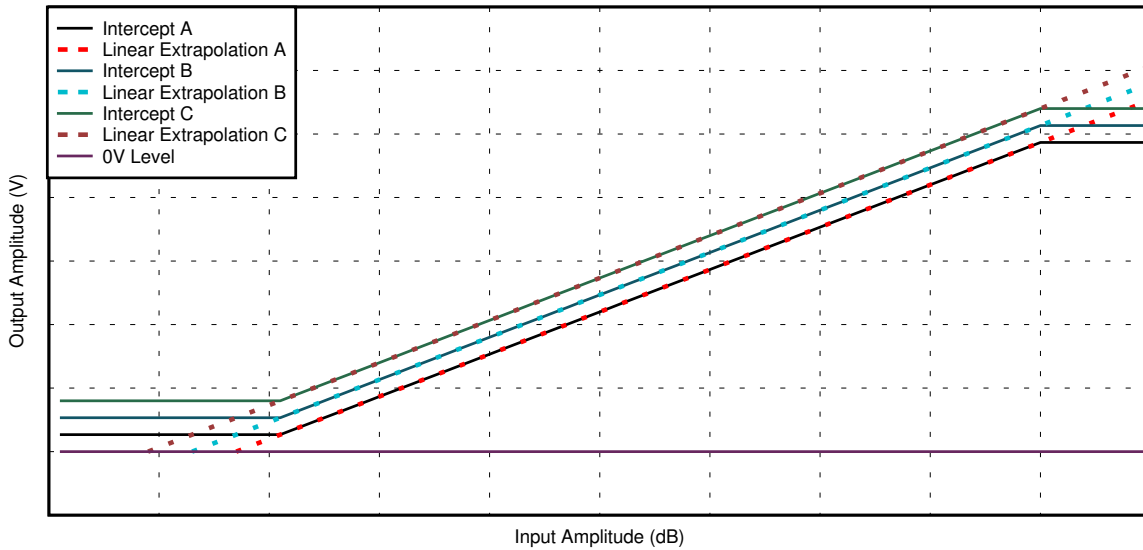
Figure 8. Log Amp Intercept Effect

The reliability of a log amp to maintain accuracy throughout the transfer function can be impacted across temperature. The deviation for the ideal output performance is referred to as log conformance, quantified in terms of ± dB error. As the dynamic range of log amp is reduced, the log conformance improves. Figure 9 shows how temperature effects the log amp conformance error.
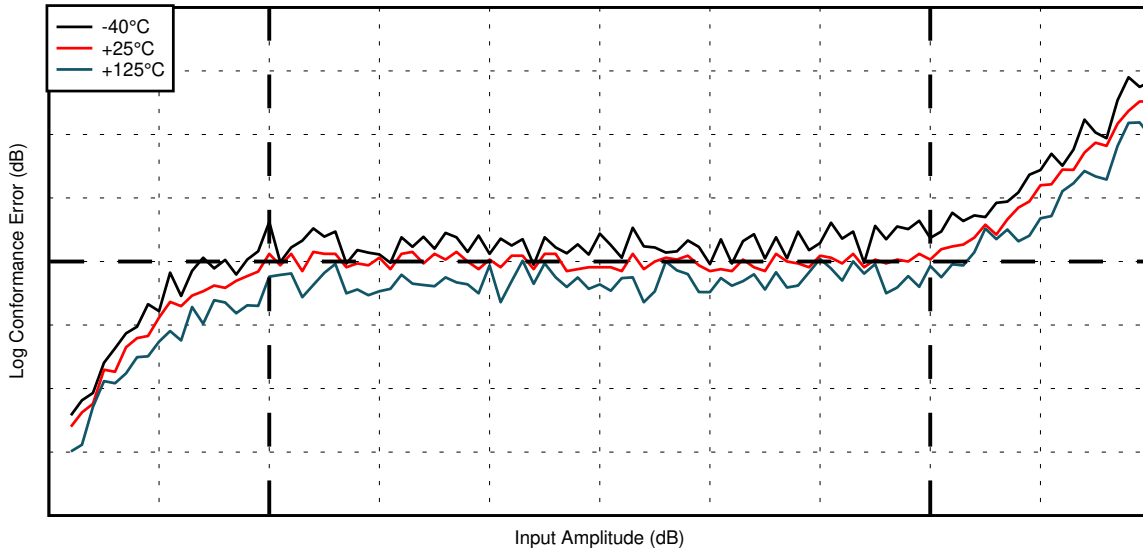

Figure 9. Log Amp Conformance Error

1.4   Log Amp Output Stage Low-Pass Filter

To enable post-processed envelope detection or thresholding of the log amp output, or both, select the corner frequency of the low-pass filter of the log amp such that the ripple of the rectified input frequency is normalized to a smooth curve, but also be able to respond to short and fast changing signals. The RC time constant of the low-pass filter can be calculated based on the worst-case rise time and input duration requirements of the log amp output envelope. A corner frequency that is too low will prevent the log amp from detecting fast changing input signals, while a corner frequency that is too high will result in more ripple from the full wave rectification stage of the log amp to remain unfiltered and visible at the output envelope. Figure 10 shows how various low-pass filter cut-off frequency values effect the final output stage of the log amp.
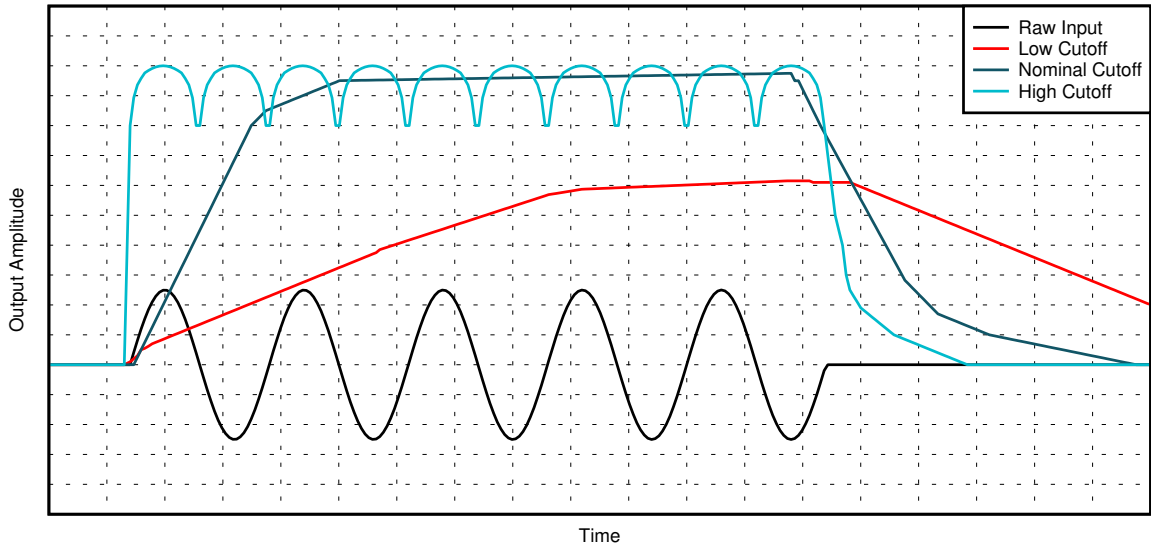
Introduction to Logarithmic Amplifier (Log Amp)

Figure 10. Low-Pass Filter Cutoff Responses of the Log Amp Output

2 Logarithmic Amplifier in Ultrasonic Sensing

2.1 System Architecture

The block diagram of an ultrasonic sensor system comprises of two primary blocks, the driver and receiver. The driver block includes an H-bridge or transformer driver to excite the transducer in direct-drive mode at a single frequency by a digital pulse generator to achieve maximum voltage across the transducer. Maximizing driver voltage across the transducer ensures the maximum sound pressure level is generated. The receiver block includes the analog front end (AFE) to receive and amplify a returning in-band ultrasonic echo. The received echo is amplified with a fixed-gain linear low-noise amplifier, followed by a band pass filter to remove out-of-band noise. After filtering, the signal enters the log amp for input level dependent amplification to enable high sensitivity for weak signals and wide dynamic range over full signal range without causing saturation of the AFE. The output of the log amp is low-pass filtered, and buffered on to the V_{OUT} pin as an input for an external comparator, ADC, or MCU for additional post-processing. Figure 11 shows an example block diagram for the ultrasonic sensing system.
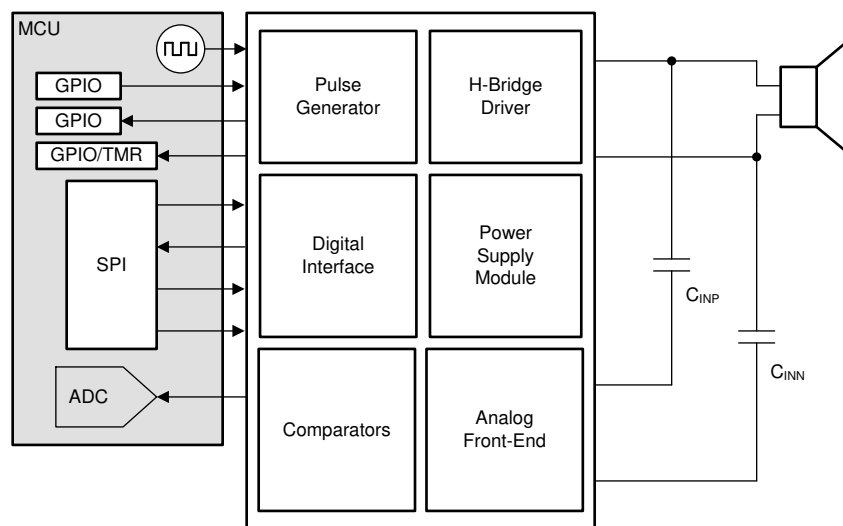
Figure 11. Simplified Ultrasonic Sensing System Block Diagram

2.2 Analog Front End (AFE)

The AFE is designed to condition ultrasonic frequency transducer signals from a few microvolts RMS to tens of millivolts RMS. To enable to widest possible dynamic range for the log amp, the input referred noise level of the AFE must be lower than the minimum expected input signal level of a few microvolts RMS. The maximum gain of the internal linear amplifier stages of the log amp is set with a clipping level such that the log amp output is not saturated at the maximum input signal level of tens of millivolts for margin. Figure 12 shows the analog front-end receiver path in block diagram form.
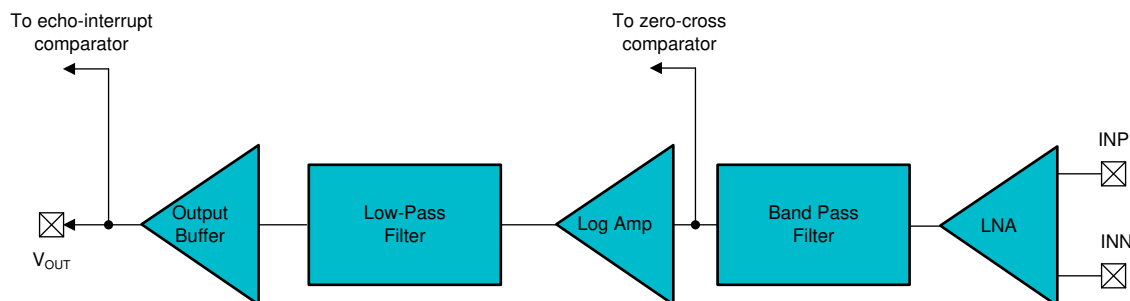
Figure 12. Block Diagram of Analog Front-End Receiver

2.2.1 Low Noise Amplifier (LNA)

The LNA is a single-ended input non-inverting amplifier with a low fixed gain output. As the first stage of the AFE, the TUSS44x0 device implements internal protection from the large driver voltages reaching upwards of hundreds of volts during burst. AFE protection from these large driving voltages is dependent on the external AC-coupling capacitor (C_{INP}) to limit current flow at input pin INP. In addition, the external capacitor C_{INN} at INN is used to provide high-pass filtering to remove 1/f noise and DC offset voltage.

2.2.2 Band Pass Filter (BPF)

Given transducers are high-Q components, a BPF is required to limit the bandwidth of the AFE to only further amplify a narrow frequency range centered at the resonant frequency of the transducer. The BPF is able to reduce noise from the LNA stage and external noise sources. The center frequency of the BPF is configurable in the TUSS44x0 device. The Q-factor is selectable but constant after selection of the TUSS44x0 BPF is constant, so the bandwidth increases as the center frequency increases, resulting in an increase of integrated noise. In the TUSS44x0 device, using the alternate high-pass filter becomes favorable for center frequencies above 500 kHz to limit the amount of 1/f noise.

2.2.3 Logarithmic Amplifier

Log amps are used as an alternative to automatic gain control circuits in applications requiring large dynamic range of operation, fast settling time, and high bandwidth such as an ultrasonic sensing system. The TUSS44x0 device implements a demodulating type of log amp to calculate and detect the logarithm of the input envelope signal. As the input signal from the echo amplitude of the log amp increases, the internal linear stages of the log amp start to clip the output. The amplifier stages of the TUSS44x0 device provide a total gain of 88 dB with a 3 dB cut-off at 1 MHz. Each stage uses an LPF in a feedback loop to attenuate the DC offset, which would otherwise saturate the log amp. Two range extension stages are included in addition to handle input signals larger than 300 mV, hence the standard case output voltage margin from the maximum output level (3.3 V or 5.0 V), and extend the dynamic range upward.

3 Logarithmic versus Time Varying Linear Amplifier

Though the logarithmic amplifier eliminates the need for users to manually configure the ultrasonic gain levels of the AFE, there are still some limitations to consider when selecting a logarithmic amplifier. Table 1 lists the advantages and disadvantages of a logarithmic gain amplifier compared to a time-varying linear gain amplifier.
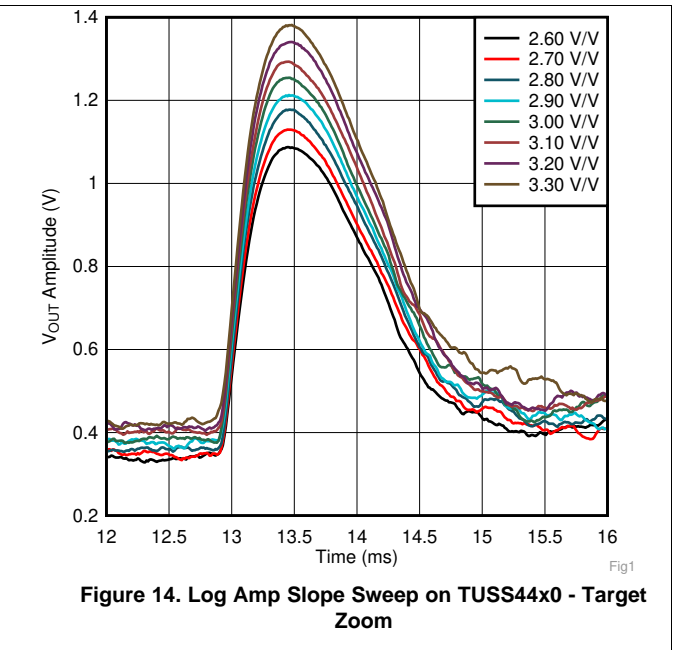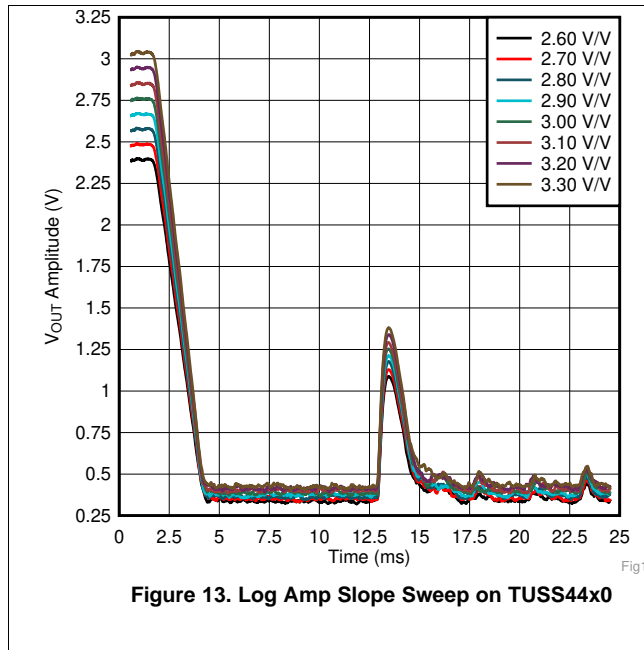
Table 1. AFE Type Comparison

| Amplifier Type	Advantage	Disadvantage	TI Devices
Logarithmic	1. Wide dynamic input range is able to normalize the SNR of the output envelope regardless of the distance or radar cross section of the targeted object. Radar cross section is calculated based on the object shape and size. 2. Strong return echoes do not saturate the front end, maximizing SNR scaling. 3. Data compression enables binary level of object detection. This is because the noise is held at a constant gain level, a single fixed-level threshold slightly above the noise floor can be used to simplify the thresholding implementation. 4. Configurability of the log amp slope and intercept options still give users the ability to prioritize the output scaling of short- or long-range measurements.	1. Unable to mask unwanted points of amplification, such as the burst energy or staggered time -of-flight windows known to create false-positive results. 2. In bi-static mode, the internal driver block noise couples onto the AFE, and is amplified to create the unwanted envelope equivalent of a mono-static transducer network with weak drive voltage signature.	TUSS4440, TUSS4470
Time-varying linear	1. For an application where external variables have been ideally accounted, controlled, and compensated for, such as worst-case targeted object parameters and presence of foreign noise sources, the linear gain settings can be optimized for best-case SNR scaling. 2. Ability to force AFE gain to be a low value during the driver phase to attenuate and prevent saturation of driving pulses coupling onto the AFE. 3. Ability to mask unwanted windows of noise or known regions in the time-of-flight measurement creating false positives.	1. In the case of a ramping time varying gain, the noise floor also ramps, preventing the ability to use a single fixed-level threshold. 2. In the case where a large variety of targets are to be detected, very large objects may saturate the AFE, while very small objects may barely register. These outlier object-cases degrade SNR scaling and detection reliability.	PGA460

4   Performance of Log Amp in Ultrasonic Systems

4.1   *Effect of Slope and Intercept*

To demonstrate the effects of the log amp intercept and slope settings, consider the following case for a fixed object and distance.

Figure 13. Log Amp Slope Sweep on TUSS44x0

Figure 14. Log Amp Slope Sweep on TUSS44x0 - Target Zoom

As the log amp slope increases, so does the noise and peak amplitude. Where short ranging performance is a priority, minimize the log amp slope value. Where long ranging performance is a priority, maximize the log amp slope value. Figure 13 and Figure 14 show the TUSS44x0 V_{OUT} results of a log amp slope value sweep.

Figure 15. Log Amp Intercept Sweep on TUSS44x0

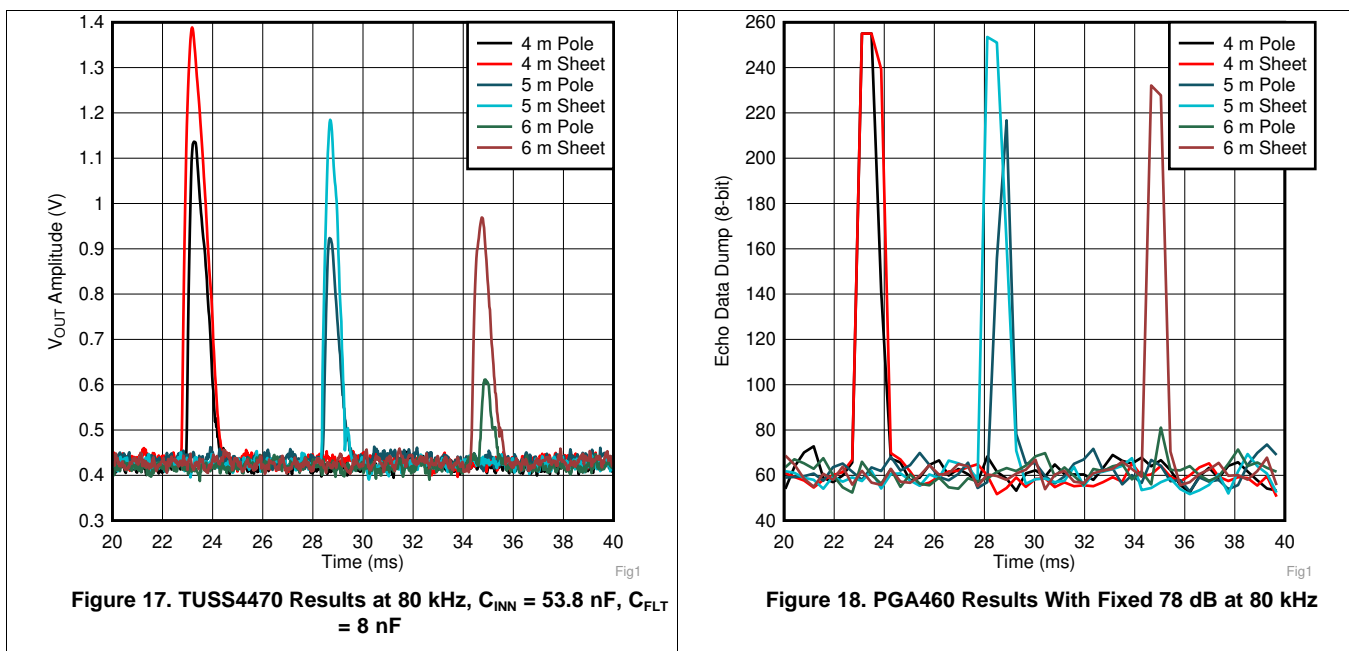**Figure 16. Log Amp Intercept Sweep on TUSS44x0 - Target Zoom**
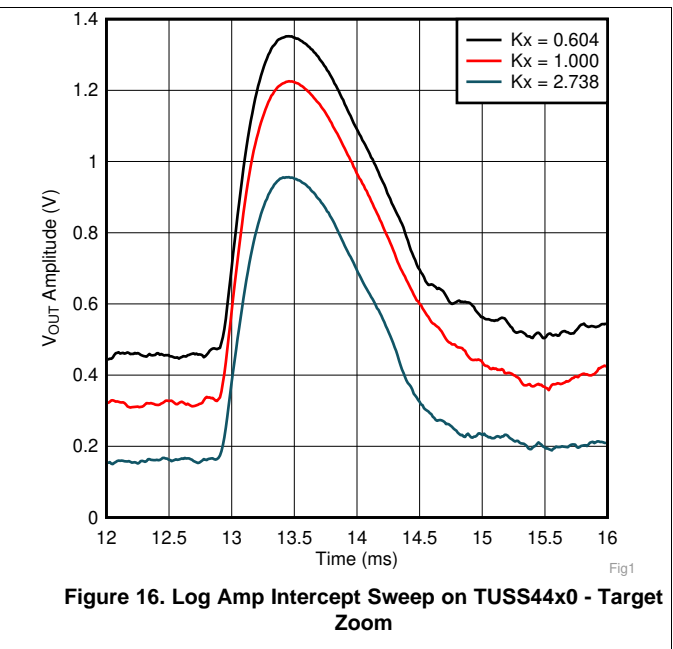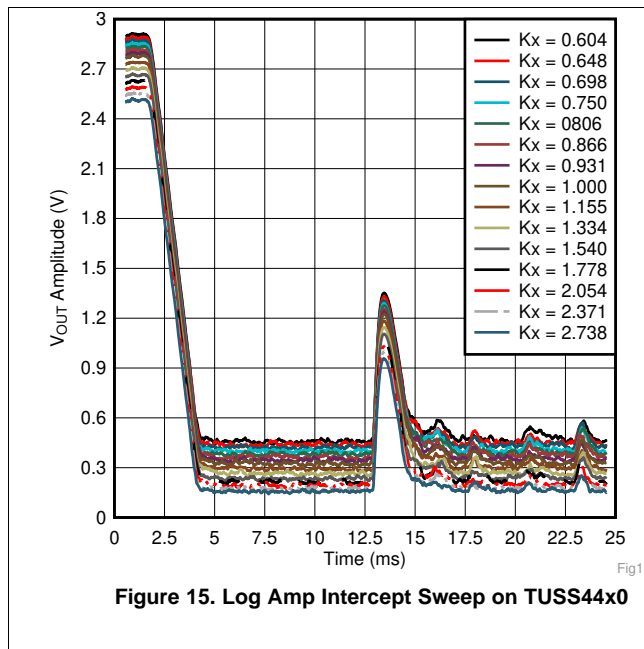
As the log amp intercept increases, the noise and peak amplitude decreases. Where short ranging performance is a priority, maximize the log intercept slope value. Where long ranging performance is a priority, minimize the log amp intercept value. Figure 15 and Figure 16 show the TUSS44x0 V_{OUT} results of a log amp intercept value sweep.

4.2 *Log versus Time Varying Linear Gain Amplifier*

To demonstrate the performance differences between an ultrasonic AFE that is logarithmic based versus linear, consider the following where the same driver, transducer, targets, and distances are used in each case for device AFE comparison. Each data series is the average of ten repeated measurement cycles to represent a stable and average representation of the result.
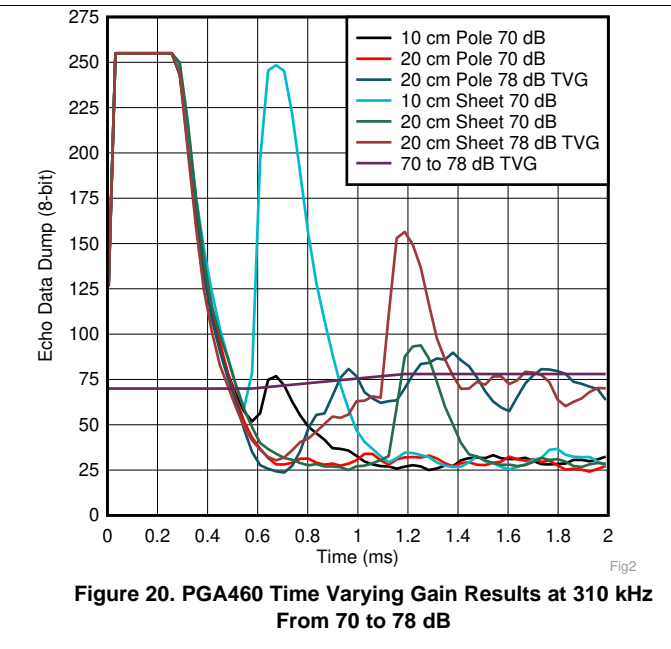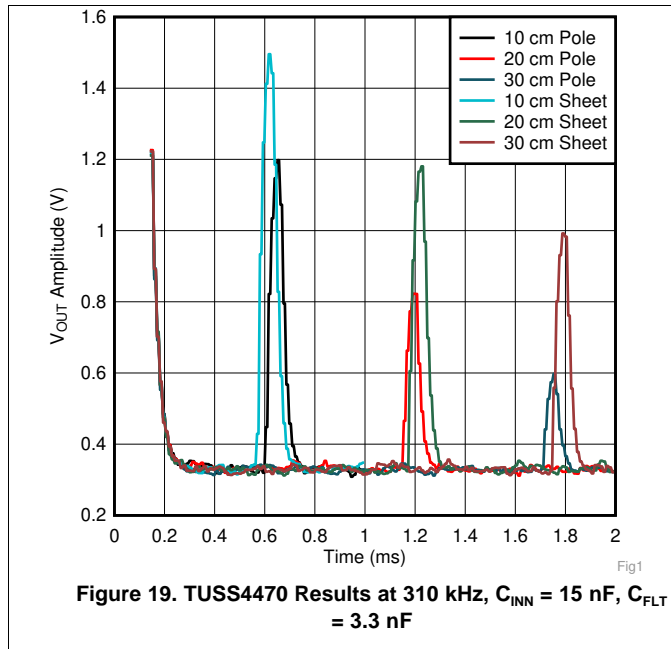
4.2.1 Fixed Gain at Long Range

Figure 17 and Figure 18 were generated under the following test conditions: 80-kHz transducer, air-coupled, 75-mm pole and 40 × 40-cm steel sheet targets at 4, 5, and 6 m.

Figure 17. TUSS4470 Results at 80 kHz, C_{INN} = 53.8 nF, C_{FLT} = 8 nF

Figure 18. PGA460 Results With Fixed 78 dB at 80 kHz

Summary: The TUSS4470 device is able to provide a non-saturated result for both objects at all distances, while the PGA460 either saturates the sheet amplitude, or is unable to provide sufficient SNR for the pole at long range. Referring to the 6-m Pole measurement, the TUSS4470 is able to provide clear distinction between the peak amplitude of the object and the noise floor, while the PGA460 shows the noise floor nearly reaching the same level as the peak amplitude of the object.

4.2.2 Time-Varying Gain

Figure 19 and Figure 20 were generated under the following test conditions: 310-kHz transducer, air-coupled, 27-mm pole, and 10-cm × 10-cm steel sheet targets at 10, 20, and 30 cm.

Figure 19. TUSS4470 Results at 310 kHz, C_{INN} = 15 nF, C_{FLT} = 3.3 nF

Figure 20. PGA460 Time Varying Gain Results at 310 kHz From 70 to 78 dB

Summary: While the time-varying gain feature of the PGA460 scales the peak amplitude of the object, so does the intensity of the peak noise amplitude variation. Referring to the 20-cm pole measurement, the peak amplitude of the object is not detectable in either the 70- or 78-dB settings. Because the field-of-view of the transducer is very narrow, and the radar cross section of the pole section is small, the PGA460 requires the alignment of the pole to be forward facing with little to no angular error to faintly register as detectable, even when as close as the 10 cm in distance. The TUSS4470 device is less susceptible to SNR loss or error created by transducer or object angle offset from the forward facing reference.

4.2.3 Fixed Gain at High Frequency

Figure 21 and Figure 22 were generated under the following test conditions: 1-MHz transducer, liquid-coupled, water level target at 30, 67, 106 mm from the base of the tank.
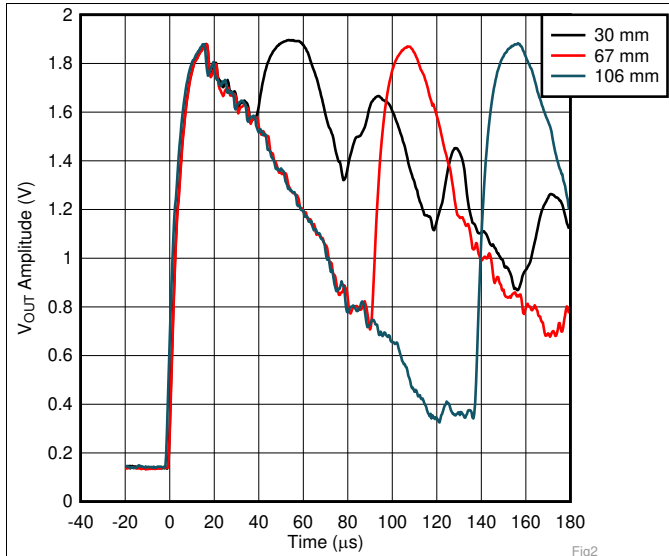
Figure 21. TUSS4470 Results at 1 MHz - No Damping Resistor, C_{INN} = 4.7 nF, C_{FLT} = 0.68 nF

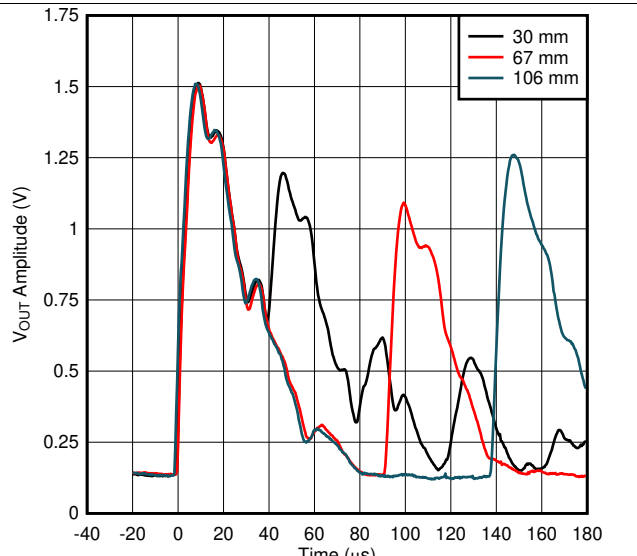**Figure 22. TUSS4470 Results at 1 MHz - 10-Ω Damping Resistor, C_{INN} = 4.7 nF, C_{FLT} = 0.68 nF**
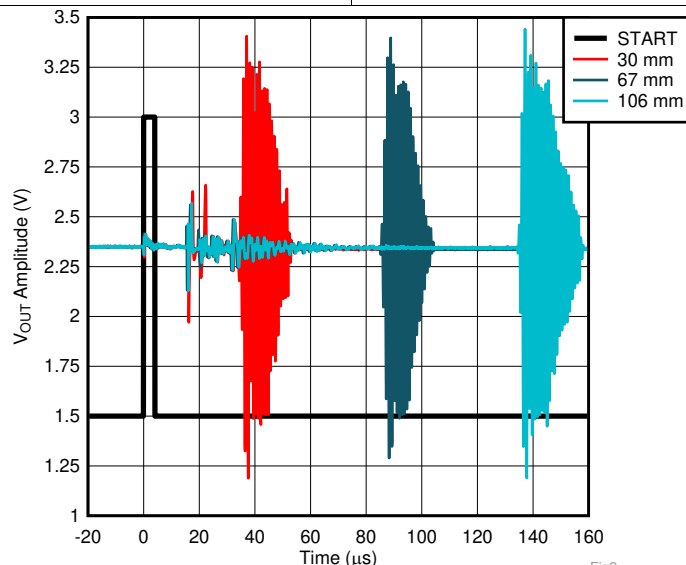

Figure 23. TDC1000 Result at 1 MHz - COMP_IN Pin

Summary: The TUSS4470 can operate up to 1 MHz in transducer operation. To achieve a decay time comparable to the TDC1000 device, place a parallel damping resistor in parallel to the transducer to attenuate the transducer during the post-burst decay phase. By attenuating the decay signal, the ring down time is reduced to enable very short range measurements with a lower threshold level, such as the 30-mm level-sensing measurement.

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