

# S12ZVL LIN Enabled Ultrasonic Distance Measurement

## Based on the MC9S12ZVL32 MagniV Device

by: Petr Cholasta

### 1 Introduction

This application note introduces the MC9S12ZVL32 device in ultrasonic sonar application, capable of detecting an object as well as measuring the object distance.

The MC9S12ZVL32 integrates a 16-bit microcontroller built on proven S12 technology, an automotive voltage regulator, a LIN interface, a VSUP module to sense automotive battery voltage and an HVI pin.

The measured object distance is displayed in the FreeMASTER tool. The on-board RGB LED color is smoothly changed based on the actual object distance. The application includes the RGB LED diagnostics as well.

The AMMCLIB [6] functions are used for mathematical operations.

Parts of this document is the AN4841SW.zip file containing X-S12ZVL32-USLED hardware and software files.

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## 2 Ultrasonic based measurement overview

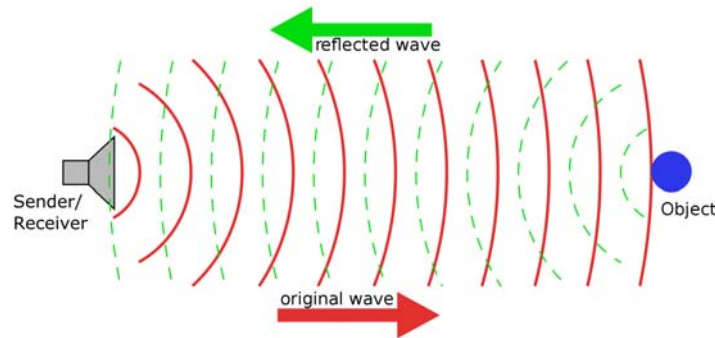
An ultrasonic based measurement is a key part of applications dealing with non-contact object distance measurement and object detection:

- Automotive safety systems
  - Parking distance sensor
  - Blind spot detection
  - Object detection
- Level measurement (e.g. fuel)
- Alarm systems
- Automatic door opener
- Electronic tape measures
- Robotics

### 2.1 Ultrasonic sensing principle

The ultrasonic waves are sounds of frequencies above 20 kHz, which can not be heard by humans.

The applied methodology is based on measuring the pulse reflection time [2]. The ultrasonic transducer emits an ultrasonic wave pulse, see [Figure 1](#). Once the pulse is emitted, the transducer becomes quite in order to receive object echoes. When the wave pulse reaches an object, the reflected wave, called an echo, is bounced back to the transducer.



**Figure 1. Ultrasonic sensing principle [1]**

The object distance is calculated by the following formula:

$$d = \frac{t \times c}{2} \tag{Eqn. 1}$$

where:

- d — object distance [m]
- t — time delay between wave emission and echo reception [s]
- c — ultrasonic sound velocity [m/s]

Metal, wood, concrete, glass, rubber and paper objects reflect the majority of the ultrasonic waves back to transducer. These objects can be easily detected. Cloth, cotton and wool absorb the majority of ultrasonic waves, so it may be difficult to detect these objects [2].

## 2.2 Required compensation

The ultrasonic sound velocity is dependent on the air temperature, see Figure 2, for the following formula [1]:

$$c = 331,3 + 0,606T \tag{Eqn. 2}$$

where:

- $c$  — ultrasonic sound velocity [m/s]
- $T$  — air temperature [°C]

It is necessary to measure the air temperature to keep the object distance calculation precise enough.

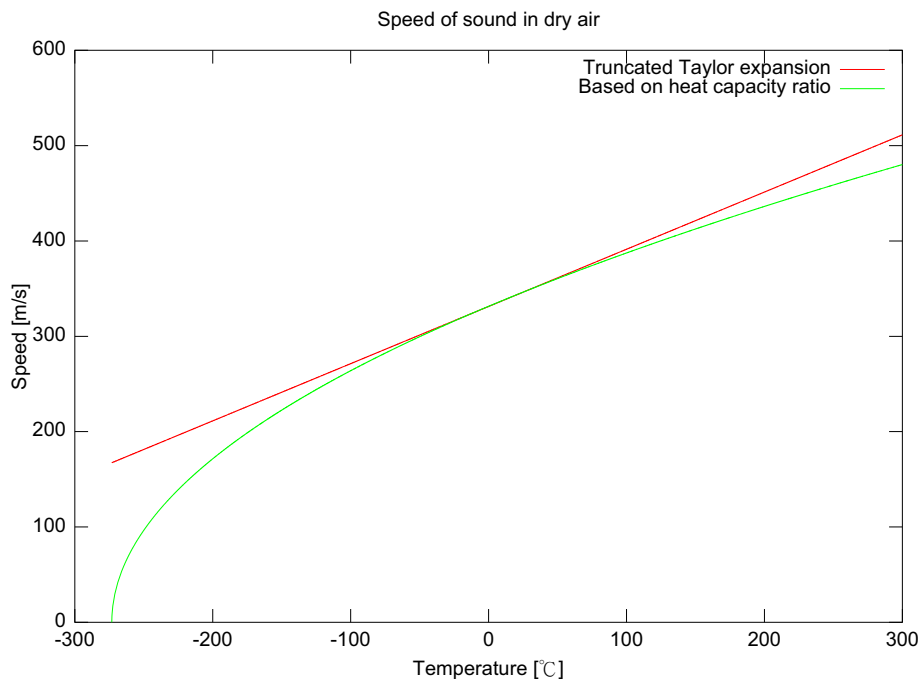
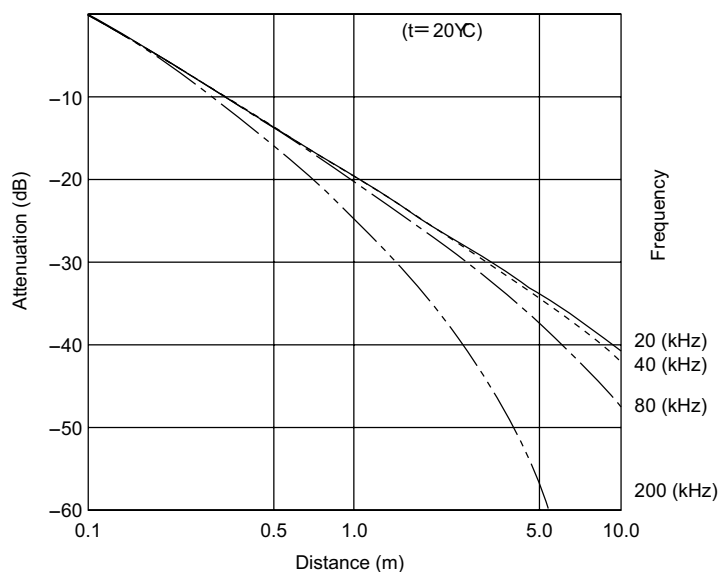


Figure 2. Sound velocity dependency on temperature in dry air [1]

### Ultrasonic based measurement overview

The strength of ultrasonic waves attenuates proportionally with object distance [2], see [Figure 3](#). During echo processing, the attenuation needs to be compensated for to properly detect the object echo.



**Figure 3. Ultrasonic waves strength attenuation with distance and wave frequency [2]**

### 2.3 Transducer

The transducer turns the electric pulses into mechanical vibration, and vice versa, using piezoelectric ceramics [2]. The transducer’s sensitivity is the highest at the piezoelement resonant frequency. The transducer’s pattern directivity allows detection of the object position in space. When the object hits the transducer lobe, the echo is received. The transducer directivity can be sharpened by an attached horn, see Figure 4.

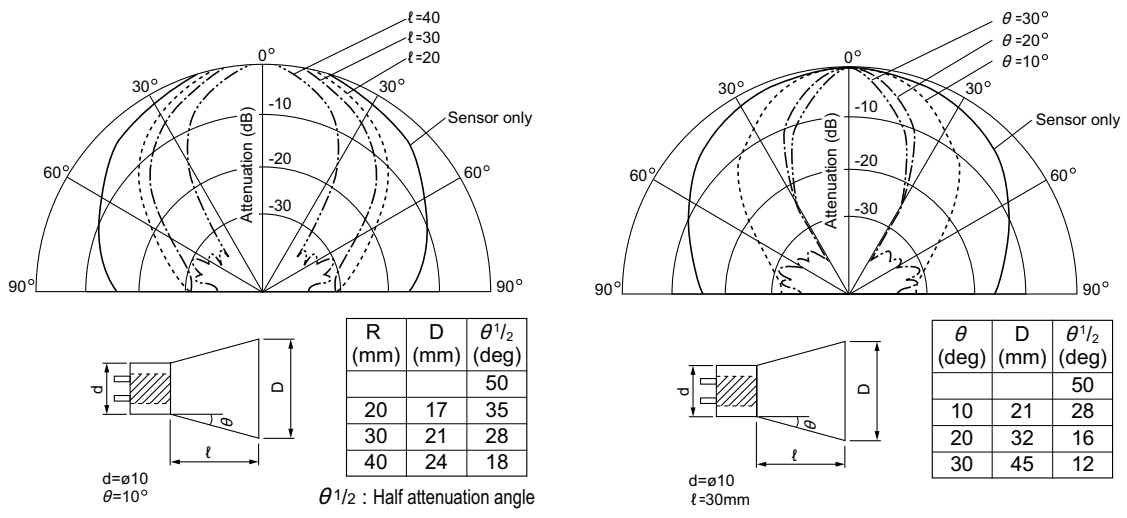
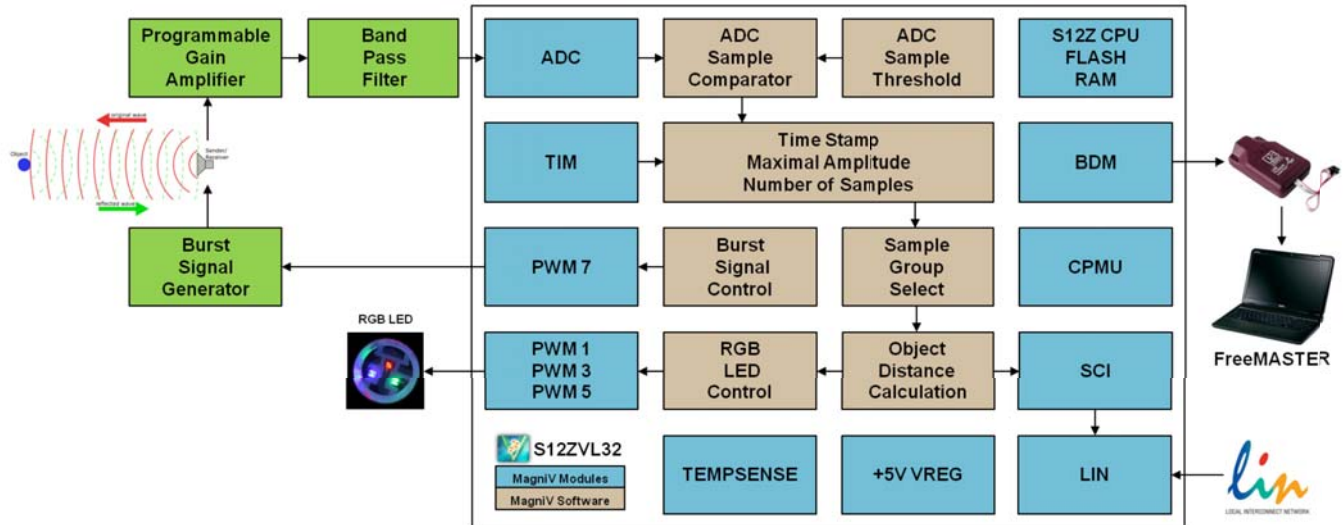


Figure 4. MA40S4R transducer receiver lobe variation with horn length and angle [2]

Transducers called “combined use types” integrate both an ultrasonic sender and receiver. These devices are used in automotive applications for object detection, e.g. parking distance sensor, blind spot detection. There are the sender and receiver transducers available separately, called “dual use types”, e.g. in alarm systems and robotics.

### 3 Ultrasonic sensing application

The [Figure 5](#) shows the Ultrasonic sensing application block diagram. The green boxes represent modules external to the MC9S12ZVL32 MCU, the blue boxes are MCU modules and the light brown boxes represent the software modules.



**Figure 5. Application block diagram**

The ultrasonic sonar unit uses dual use type transducers MA40S4S and MA40S4R operating at 40 kHz, see [3]. These transducers allow detection of an object at a distance of 20 cm to 4 m. The MA40S4S ultrasonic sender is driven by the PWM7 signal amplified by the burst signal generator. The object echo signal is received by the MA40S4R receiver transducer and amplified by the programmable gain amplifier. The band pass filter improves the echo signal to noise ratio.

The echo signal is sampled by the ADC module and processed in the digital domain. The echo signal detection is based on the ADC sample value comparison with a preset threshold.

The object distance is calculated and averaged using the AMMCLIB [6] functions and visualized in the FreeMASTER tool [5]. The measured object distance is compensated with temperature. The on-board RGB LED color control is based on the actual object distance.

For a detailed description, see the following chapters.

### 3.1 Scheduling

The [Table 1](#) shows an application scheduling. The application is running in five time slots. The time slots from 0 ms to 30 ms are used for ultrasonic signal transmission and reception. The slot starting at 30 ms and ending at 60 ms is used for data processing, object distance calculation and visualization.

**Table 1. Application scheduling**

Time [ms]	Burst generator	Echo receiver	Echo signal sampling and processing	Object distance calculation	Temperature measurement	RGD LED control and diagnostics
0 - 0,135	ON	-	-	-	-	-
0,135 - 1,135	-	-	-	-	-	ON
1,135 - 30	-	ON	ON	-	-	-
30 - 59	-	-	-	ON	ON	ON
59 - 60	-	-	-	-	ON	ON

**Note:** Symbol “-” represents a module not operating.

Transducers MA40S4S and MA40S4R [3] allow measurement of a maximal distance of 4 m. An echo reception minimal period, see [Eqn. 1](#), is given by the measured maximal distance and sound velocity, see [Eqn. 2](#), at the minimal air temperature,  $T = -40^{\circ}\text{C}$ :

$$c = 331,3 \frac{m}{s} + 0,606T = 331,3 - 24,24 = 307,06 \frac{m}{s} \quad \text{Eqn. 3}$$

$$t = \frac{2 \times d}{c} = \frac{2 \times 4m}{307,06 \frac{m}{s}} = 26ms \quad \text{Eqn. 4}$$

Once the burst signal is transmitted, the echo receiver transducer is saturated for a 1ms period, see [Figure 6](#). The minimal measured distance using [Eqn. 1](#), calculated at maximal air temperature  $T = 85^{\circ}\text{C}$ :

$$d = \frac{t \times c}{2} = \frac{1,135ms \times 382,81 \frac{m}{s}}{2} = 21,8cm \quad \text{Eqn. 5}$$

The [Figure 6](#) shows the ultrasonic burst signal (yellow colored) waveform and the transducer receiver signal amplified by the PGA (blue colored) waveform. The PGA gain is changed proportionally with time, i.e. with object distance. The pink colored waveform displays the PGA gain change on the waveform signal edge.

Ultrasonic sensing application

In Figure 6 can be seen the object reflection at a distance of 2.2 m (blue colored waveform) at 25°C:

$$d = \frac{t \times c}{2} = \frac{12,8ms \times 346,45 \frac{m}{s}}{2} = 2,2m \quad \text{Eqn. 6}$$



Figure 6. Signal overview



## 3.2 Burst generator

The PWM module channel 7 generates the burst signal, see [Figure 7](#), the pink colored signal.

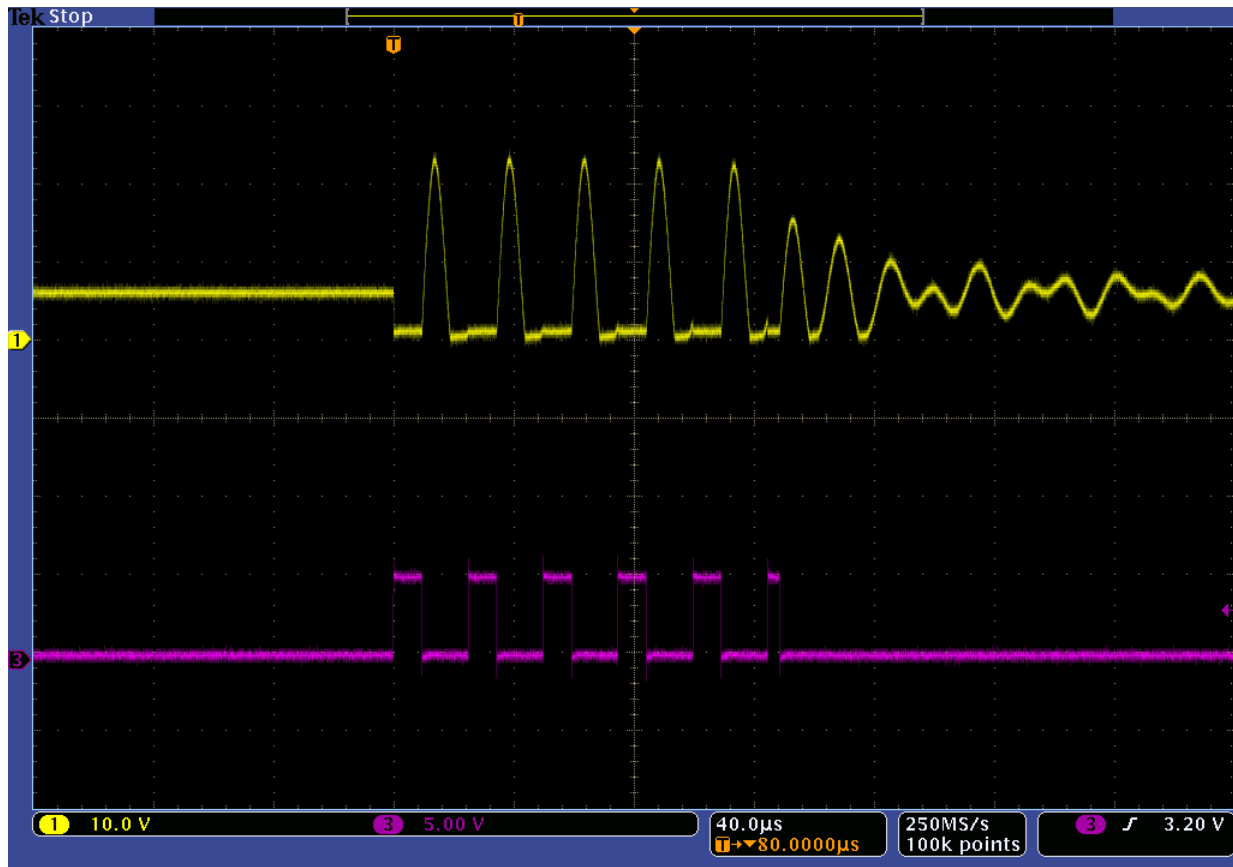


Figure 7. Burst signal

The burst signal drives the ultrasonic burst circuitry to generate pulses with an amplitude of 20 V<sub>pp</sub>, see [Figure 7](#), the yellow colored signal. The signal amplitude is given by the PWM signal duty cycle, set to 38%, and the L/C tank circuit ratio, see [Figure 8](#). The MA40S4S ultrasonic transducer sender emits an ultrasonic wave pulse into the air.

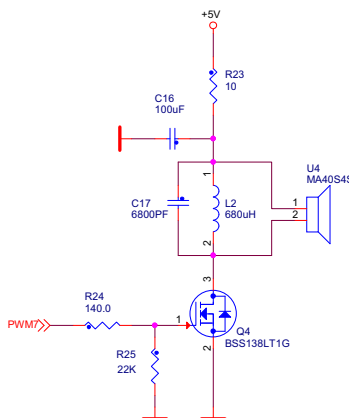


Figure 8. Burst generator

### 3.3 Echo receiver

When the ultrasonic wave hits the object, the echo is sent back to the MA40S4R transducer receiver, see Figure 9. The echo signal is amplified using the Programmable Gain Amplifier (PGA) to compensate the ultrasonic waves strength attenuation that is proportional to the object distance.

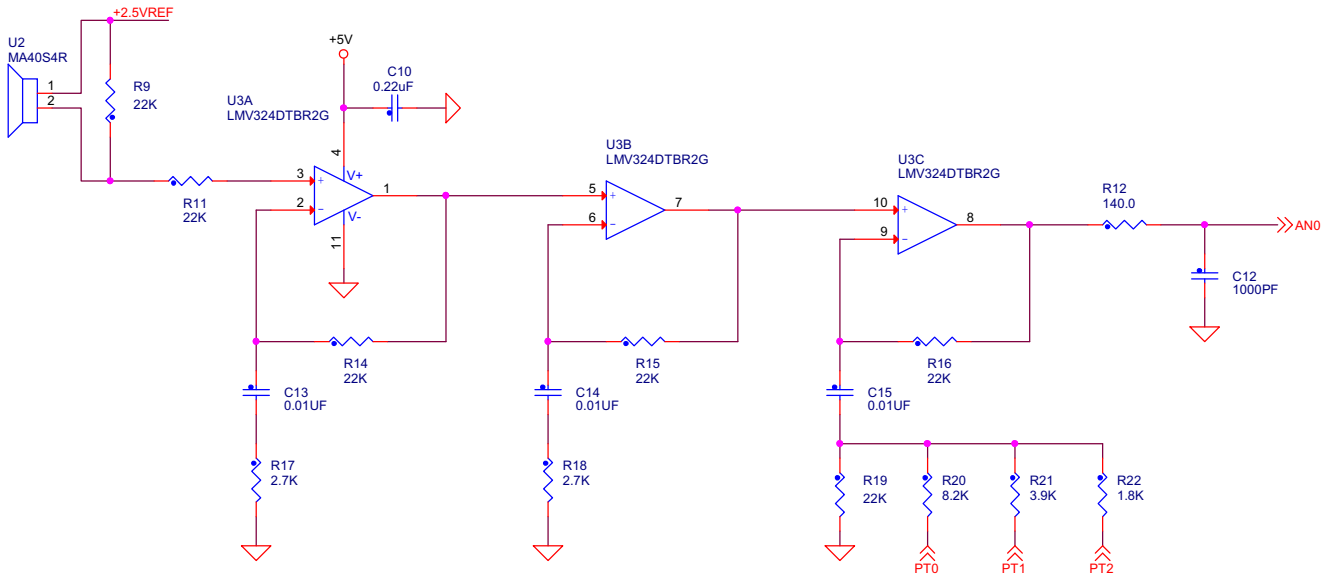


Figure 9. Programmable gain amplifier circuitry

The PGA gain control is based on the actual time measurement, see Table 2.

Table 2. Programmable gain amplifier gain control

Distance [cm]	Time [ms]	Gain [-]	PT0	PT1	PT2
0 - 20	0	184	Input	Input	Input
20 - 30	1,135	184	Input	Input	Input
30- 60	1,765	376	Output low level	Input	Input
60 - 80	2,941	600	Input	Output low level	Input
80 - 110	4,706	784	Output low level	Output low level	Input
110 - 140	6,471	1040	Input	Input	Output low level
140 - 170	8,235	1248	Output low level	Input	Output low level
170 - 400	10	1600	Output low level	Output low level	Output low level

The integrated band-pass filter improves the echo signal-to-noise ratio and acts as an ADC anti-aliasing filter as well.

The band-pass filter design combines passive components and a relatively low U3 transition frequency to obtain the required band pass filter characteristic, with a center frequency of 40 kHz, see Figure 9.

### 3.4 Echo signal sampling and processing

The object echo signal is sampled using the ADC module. The ADC module samples the data with an 8-bit resolution and a sampling speed of 2.2 us per one sample. When using the 40 kHz ultrasonic transducer, approximately eleven ADC samples are taken per single signal period, see Figure 10.

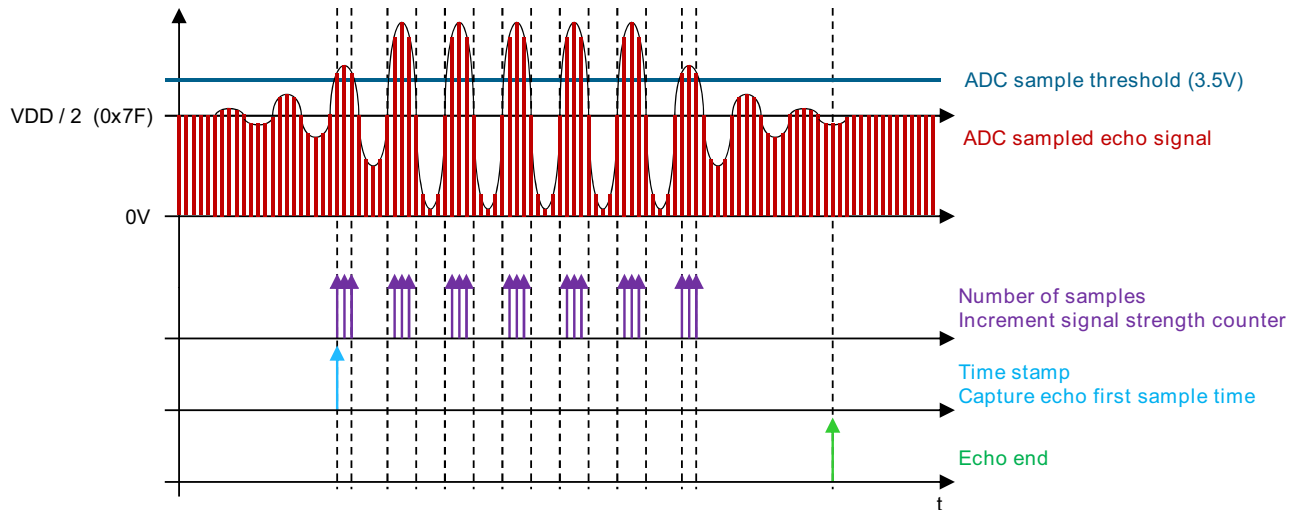


Figure 10. Echo signal sampling and processing

The ADC sampled data processing is software-based. The ADC data is compared with the ADC sample threshold, which is set to 3.5 V. Where there is software comparator first match, the first pulse time is captured (time stamp). From now on, each software comparator match increments the signal strength counter (number of samples) and the signal maximal amplitude is worked out. When there is no software comparator match for a maximum period of 68 us, the echo end is promoted.

The echoes parameters are sorted into a three dimensional array capturing:

- First sample time
- Number of samples
- Maximal amplitude

### 3.5 Object distance calculation

The echo reception is finished when a 30 ms period has expired, starting from the burst signal transition.

As the first step, the echo with the maximal amplitude is singled out. Echoes with an amplitude below 80% of this maximal amplitude are discarded.

As the next step, the echo with the maximal number of samples is singled out. Echoes with a number of samples below 25% of this maximal number of samples are discarded.

The described filtering process allows elimination of weak object reflections, that appear at the sides of the transducer's lobe and disturb the desired object distance measurement.

## Ultrasonic sensing application

As the last step, the echoes are sorted by value of the first sample time. The echo with the shortest period is promoted as the desired object echo.

The object distance is calculated, see [Eqn. 1](#), with sound velocity compensated for by the actual temperature, see [Eqn. 2](#). Calculation is proceed in 16-bit fractional arithmetic using AMMCLIB [6]. The actual temperature is measured by the on-chip temperature sensor.

The calculated object distance value is then averaged using a digital 2nd order IIR low-pass filter with a 2 Hz transition frequency. The IIR filter is part of the AMMCLIB [6].

The object distance is measured in millimeters and reported, as depicted in [Table 3](#).

**Table 3. Object distance reporting**

Object distance [mm]	Measured distance	RGB LED color	RG LED color
0 - 199	0	Red	Red
200 - 349	Object distance	Red and Green	Red and Green
350 - 499	Object distance	Green and Blue	
500 - 4000	Object distance	Blue	Green
more than 4000	65535 (0xFFFF)		

## 3.6 RGB LED control and diagnostics

The on-board RGB LED color control is based on the measured object distance, as depicted in [Table 3](#). The PWM module drives the LED with a 16-bit resolution, enabling a smooth change of the LED color.

The RGB LED diagnostics module reports the actual LED average current, calculated using the LED voltage and applied PWM duty cycle.

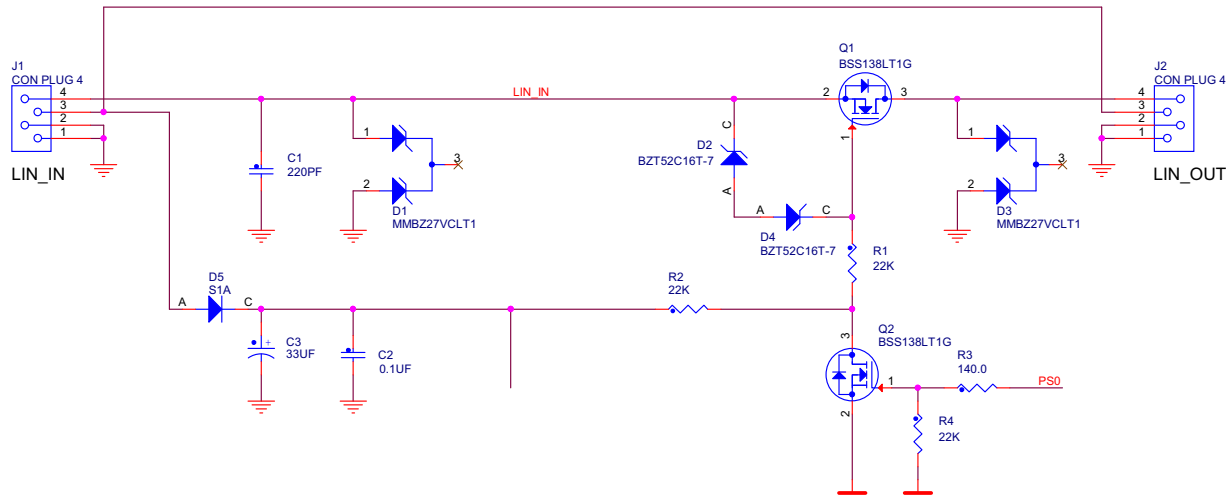
The actual LED voltage is sampled by the ADC when the LED is turned ON, approximately 3 us for red, 6 us for green and 9 us for the blue diode after the PWM signal falling edge. The sampled value is used to calculate the diode resistor voltage. As the resistor voltage and its resistance is known, the diode peak current is calculated. The average current value is calculated using the known PWM duty cycle, and the diode peak current during a 1ms time slot from 0.135 ms to 1.135 ms, see [Table 1](#).

The calculation is carried out in 16-bit fractional arithmetic using the AMMCLIB [6].

More information can be found in AN4842 [7].

### 3.7 LIN Slave node position detection

The on-board LIN switch hardware is designed to support LIN Slave node auto-addressing and daisy-chaining, see [Figure 11](#). The LIN\_IN and LIN\_OUT LIN signal lines are either connected or disconnected based on the MCU PS0 output pin logic level, see [Table 4](#).



**Figure 11. LIN signal line switch**

When the system is powered-up, the LIN\_IN (J1) and LIN\_OUT (J2) LIN signal lines (pin 4) are disconnected. The LIN Master unit communicates to the closest LIN Slave unit only. The LIN Master unit sends the LIN configuration frame. Once the LIN Slave address is configured, the LIN\_IN and LIN\_OUT node LIN signal lines are connected and the LIN Slave configuration is repeated for the following node in the line. The cycle is repeated until the configuration of the LIN network slaves is not finished.

**Table 4. LIN signal line switch control**

MCU PS0 pin	LIN_IN and LIN_OUT
High level	Disconnected
Low level	Connected

## 4 MC9S12ZVL32 modules configuration

The Ultrasonic sensing application uses the following set of peripheral modules:

1. Clock, Reset and Power Management Unit (CMPU)
2. Timer module (TIM)
3. Pulse Width Modulator (PWM)
4. Analog-to-Digital Converter (ADC)
5. Port Integration Module (PIM)
6. Interrupt (INT)

The modules' configuration and usage is described in the following chapters. Detailed information on the MCU modules can be found in the MC9S12ZVL32 reference manual [4].

The application software is developed to meet the following specification:

- Object distance ultrasonic measurement in the range of 20 cm to 4 m at 25°C
- Object distance measurement compensation for the temperature
- Echo signal processing in the digital domain
- RGB LED control and diagnostics
- FreeMASTER enabled

For detailed info, see [Section 5, “Ultrasonic sensing application demo”](#)

### 4.1 Clock, Reset and Power Management Unit

The Clock, Reset and Power Management Unit (CMPU) sets the CPU clock to 64 MHz and the bus clock to 32 MHz using the Internal 1 MHz clock signal.

The Internal 1 MHz reference clock is selected as the source clock for the PLL (CPMUREFDIV\_REFDIV = 0, CPMUREFDIV\_REFFRQ = 0).

The PLL VCOCLK frequency is set to 64 MHz (CPMUSYNR\_SYNDIV = 31):

$$VCOCLK = (2 \times (SYNDIV + 1)) \times 1MHz \quad \text{Eqn. 7}$$

The VCOCLK signal frequency is divided by 1 (CPMUPOSTDIV\_POSTDIV = 0). This is used as the 64 MHz core clock ECLK2X signal and the 32 MHz bus clock ECLK signal.

The chip temperature sensor is enabled (CPMUHTCTL\_HTE = 1).

### 4.2 Timer Module

The TIM channel 0 is running as an application scheduler time base. The TIM channel 0 compare output is configured as no action on a channel compare event (TIM0TCTL2\_OL0 = 0, TIM0TCTL2\_OM0 = 0). The TIM channel 0 interrupt is enabled (TIM0TIE\_COI = 1).

The timer single tick is configured to 1us (TIM0TSCR2\_PR = 5).

## 4.3 Pulse Width Modulator

The Pulse Width Modulator module generates the ultrasonic sensor burst signal and controls the on-board RGB LED.

The PWM module channels operate in 16-bit resolution mode (PWMCTL\_CON01 = 1, PWMCTL\_CON23 = 1, PWMCTL\_CON45 = 1, PWMCTL\_CON67 = 1). The PWM clock A equals the 32MHz bus clock (PWMPRCLK\_PCKA = 0) and the PWM clock B equals 16 MHz (PWMPRCLK\_PCKB = 1).

The channels PWM1, PWM3, PWM5 generate a 244 Hz PWM starting with a low-level polarity (PWMPOL1 = 0, PWMPOL3 = 0, PWMPOL5 = 0) to control the RGB LED. As a clock source, clock B is selected.

The channel PWM7 generates a 40 KHz PWM starting with a high-level polarity (PWMPOL7 = 1) and a duty cycle of 38% to control the ultrasonic transducer sender. As a clock source, clock A is selected.

The PWM1, PWM3, PWM5 channels are enabled (PWME\_PWME1 = 1, PWME\_PWME3 = 1, PWME\_PWME5 = 1). The PWM7 channel is enabled only to generate the burst, see [Section 3.1, “Scheduling”](#).

## 4.4 Analog-to-Digital Converter

The Analog-to-Digital Converter is used to sample the echo signal and LED voltage.

The ADC clock is set to 8MHz (ADC0TIM = 1). The ADC module is configured to access mode via the data bus (ADC0CTL\_0\_ACC\_CFG = 2). The ADC is running in trigger mode (ADC0CTL\_0\_MOD\_CFG = 1). The end-of-list interrupt is enabled (ADC0CONIE\_1\_EOL\_IE = 1).

Based on the application scheduler described in [Section 3.1, “Scheduling”](#), the ADC module is periodically reconfigured every 30 ms.

In the first 30 ms period, the ADC module samples the echo signal using the single command sequence list (ADC0CTL\_1\_CSL\_BMOD = 0) and the two result value list (ADC0CTL\_1\_RVL\_BMOD = 1) with 8-bit resolution (ADC0FMT\_SRES = 0). The command sequence list drives the ADC to convert 15 consecutive samples of the echo signal. With an ADC 8-bit resolution, an end-of-list interrupt arises every 34us and sampled data is processed. The double buffer mode allows a continuing echo signal sampling, while the sampled data from the other list is processed.

The following 30 ms period, the ADC module samples LED voltage and on-chip temperature sensor voltage using the single command sequence list (ADC0CTL\_1\_CSL\_BMOD = 0) and the single result value list (ADC0CTL\_1\_RVL\_BMOD = 0) with 10-bit resolution (ADC0FMT\_SRES = 2). The LED voltage is recalculated to the LED average current, see [Section 3.6, “RGB LED control and diagnostics”](#).

## 4.5 Port Integration Module

The Port Integration Module is used to drive the RGB LED, see [Section 3.6, “RGB LED control and diagnostics”](#), control the PGA, see [Section 3.3, “Echo receiver”](#), and control the LIN switch, see [Section 3.7, “LIN Slave node position detection”](#).

The port pins PT3, PT4 and PT5 can be used to debug the application by enabling either the ULTRASONIC\_APPLICATION\_DEBUG or LED\_APPLICATION\_DEBUG macros, see [Table 5](#). The pins share SCI and TIM modules as well.

**Table 5. Application debug**

MCU pin	ULTRASONIC_APPLICATION_DEBUG	LED_APPLICATION_DEBUG
PT3	ADC end-of-list interrupt	-
PT4	PGA gain changed	ADC end-of-list interrupt
PT5	Time slot expired	PWM falling edge generated

## 4.6 Interrupt

The Interrupt module sets the interrupt priorities as follows, starting with the highest priority:

1. The ADC0 end-of-list - samples are ready for processing
2. The TIM channel 0 - time slot expired
3. The PIM Port P - PWM module signal falling edge captured



## 5 Ultrasonic sensing application demo

The ultrasonic sensing application demo can be build using attached AN4841SW.zip file containing X-S12ZVL32-USLED board hardware and software files.

### 5.1 Hardware

The X-S12ZVL32-USLED board, see [Figure 12](#), is built using the AN4841SW.zip hardware files. These files include the board schematic, bill of materials, gerber files and an instruction for board manufacturing.

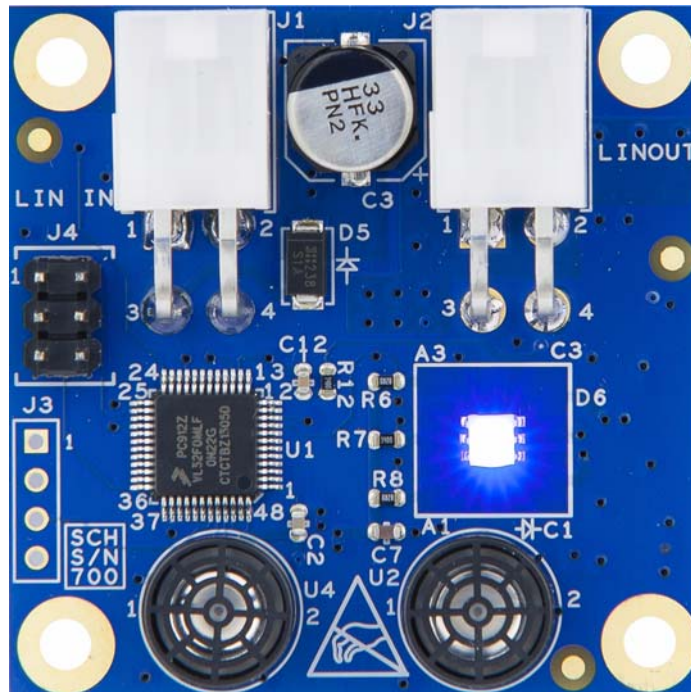


Figure 12. The X-S12ZVL32-USLED board

The X-S12ZVL32-USLED board contains, see [Section Appendix A, “X-S12ZVL32-USLED board schematic”](#):

- MC9S12ZVL32 LQFP32 MCU, see [4]
- LIN Slave node position detection hardware
- Ultrasonic sensing circuitry:
  - Burst module
  - Programmable gain amplifier
  - Sender and receiver transducers
- RGB LED with diagnostics hardware
- Reverse battery protection
- BDM enabled

## 5.2 Software

The software files are packed as the MC9S12ZVL32\_UDSD\_REV1.exe file available in AN4841SW.zip file. The application is developed using the CW10.3 environment. The MC9S12ZVL32\_UDSD\_0N22G\_AMMCLIB\_v\_1\_0\_0.elf file can be found in the project FLASH folder. For code download, the P&E USB Multilink Interface is used.

The ultrasonic sensing application demo shows:

- Object distance measurement in the range of 20cm to 4m at 25°C
- Object distance measurement compensation for the temperature
- Smooth RGB LED color control based on the actual object distance
- RGB LED diagnostics
- FreeMASTER tool displays:
  - Actual object distance
  - RGB LED average current
- Integrating the AMMCLIB [6].

## 5.3 Demo set-up

The demo set-up is depicted in [Figure 13](#). The demo is designed to be able to run either with or without the FreeMASTER tool. The demo user chooses the actual object distance visualization.



Figure 13. Demo Set-up

Follow the instructions for a complete demo set-up:

1. Install the FreeMASTER tool [5] on the PC used
2. Connect the +12 V/100 mA DC power supply to the X-S12ZVL32-USLED board at J1, LIN\_IN:
  - a) GND to J1 pin 1
  - b) +12 V to J1 pin 3
3. Turn ON the power supply
4. Connect the P&E USB Multilink Interface to the X-S12ZVL32-USLED board at J4
5. Open the “MC9S12ZVL32\_UDSD\_LED.pmp” file, available in the project AN4841SW.zip file
6. Go to the FreeMASTER file Project/Options folder and check the settings as depicted in [Figure 14](#) and [Figure 15](#)
7. Run FreeMASTER communication by File/Start Communication
8. Put an object (e.g book, paper, etc.) in front of the ultrasonic transducers U2 and U4. The RGB LED color will change smoothly based on the actual object distance, see [Section 3.6, “RGB LED control and diagnostics”](#):
  - a) Red - object closer than 20 cm
  - b) Red and Green combination - object distance between 20 cm and 35 cm
  - c) Green - object distance 35 cm
  - d) Green and Blue combination - object distance between 35 cm and 50 cm
  - a) Blue – object distance more than 50 cm
9. The object distance is displayed on the FreeMASTER page, see [Figure 16](#)
10. The RGB LED average current is displayed on the FreeMASTER page, see [Figure 17](#)
11. The RGB LED can be controlled, see [Figure 17](#):
  - a) OFF
  - b) Red and Green combination
  - c) Red, Green and Blue combination

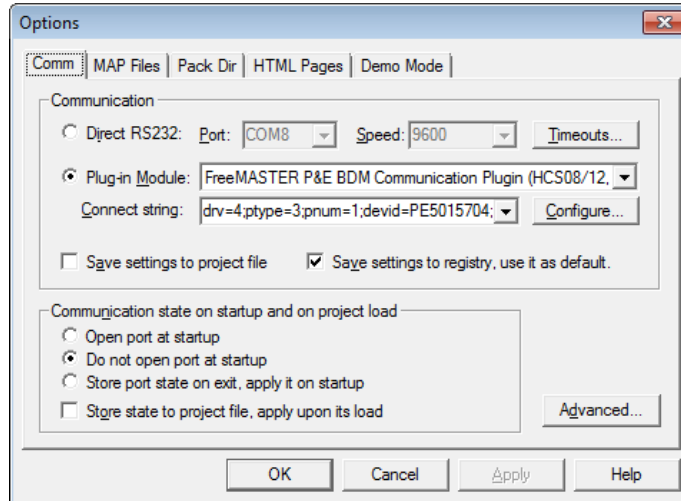


Figure 14. FreeMASTER Communication configuration

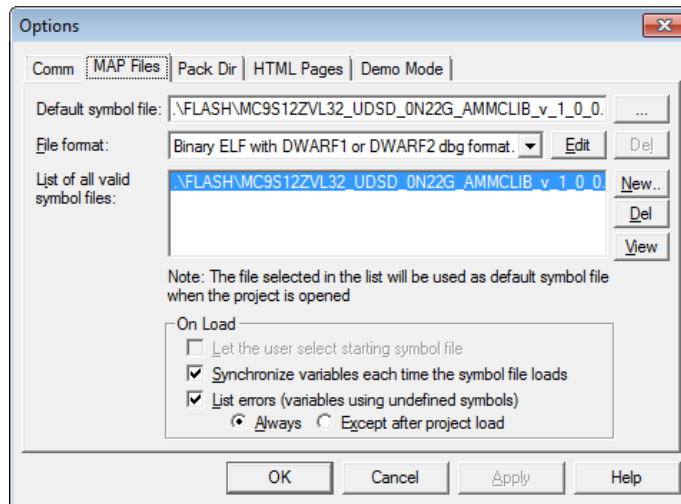


Figure 15. FreeMASTER MAP Files configuration

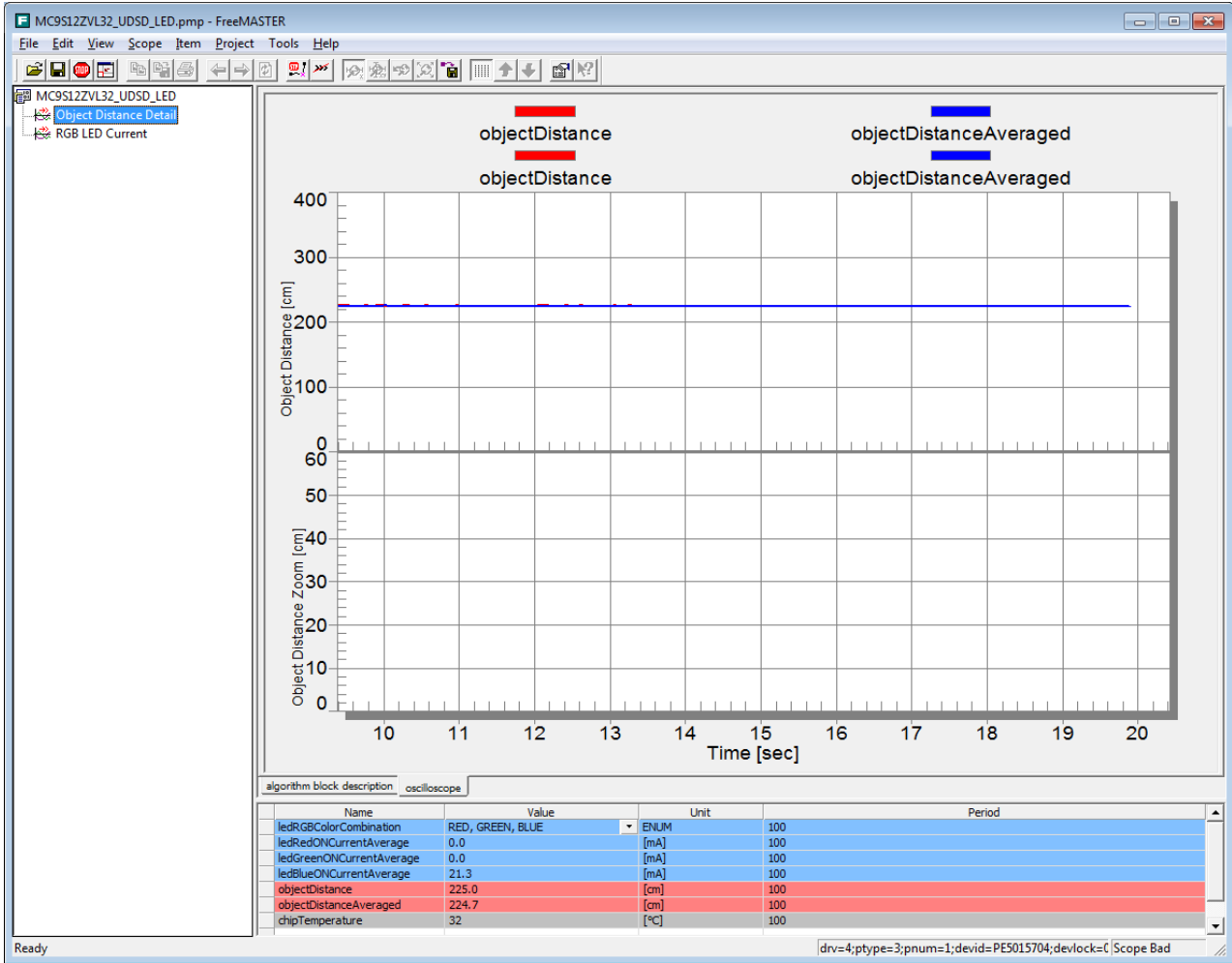


Figure 16. FreeMASTER object distance display

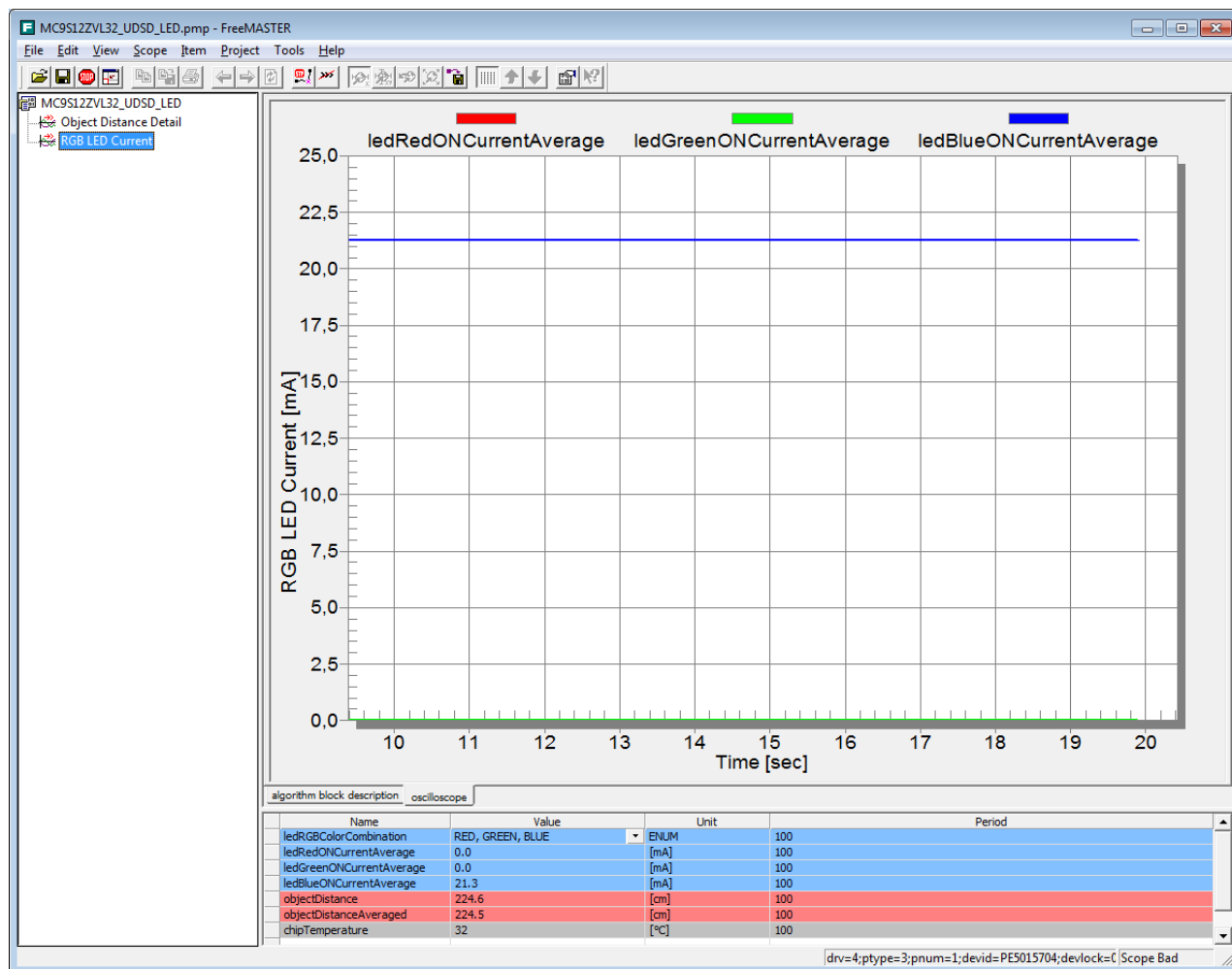


Figure 17. FreeMASTER RGB LED average current

## 6 References

1. Wikipedia, [www.wikipedia.com](http://www.wikipedia.com)
2. Ultrasonic Sensor Application Manual S15E-5, [www.murata.com](http://www.murata.com)
3. MA40S4S and MA40S4R Datasheet, [www.murata.com](http://www.murata.com)
4. MC9S12ZVL Family Reference Manual, available at [freescale.com](http://freescale.com)
5. FreeMASTER Run-Time Debugging Tool, available at [freescale.com/freemaster](http://freescale.com/freemaster)
6. Automotive Math and Motor Control Library Set, available at [freescale.com/AutoMCLib](http://freescale.com/AutoMCLib)
7. AN4842, S12ZVL LIN Enabled RGB LED Lighting Application, available at [freescale.com](http://freescale.com)

## 7 Acronyms

ADC	Analog-to-Digital Converter
AMMCLIB	Automotive Math and Motor Control Library Set
BDM	Background Debug Module
CMPU	Clock, Reset and Power Management Unit
DC	Direct Current
HVI	High Voltage Input
IIR Filter	Infinite Impulse Response Filter
INT	Interrupt
ISR	Interrupt Service Routine
LIN	Local Interconnect Network
MCU	Microcontroller Unit
PC	Personal Computer
PGA	Programmable Gain Amplifier
PIM	Port Integration Module
PWM	Pulse Width Modulation
RGB LED	Red, Green, Blue Light Emitting Diode
TIM	Timer Module
USB	Universal Serial Bus
VSUP	Voltage Supply



## Appendix A X-S12ZVL32-USLED board schematic

For this schematic, please refer to “X-S12ZVL32-USLED.pdf”, attached with the pdf of this Application Note.

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Document Number: AN4841

Rev. 1.0

3/2014

