

**High precision & accurate sensing at  
lowest flow rate for metering applications**

# Setting The Scene

There are challenges in achieving **high precision** and **accurate sensing** at low to high flow rates in metering applications such as flow meters as well as distance measurement and level detection applications.

Ultrasonic sensing technology is outstanding at measuring flow velocity and using an integrated analog-to-digital converter (ADC) provides the ability to accurately measure flow even at the lowest rates.

This webinar will review ultrasonic sensing technology, the ADC implementation and examples using Texas Instruments MSP430 microcontrollers, tools and software.

# Abstract

## What you'll learn:

- Challenges in the target applications e.g. flow meters
- Why Ultrasonic technology is used for addressing this
- How ? Understanding ADC-based technique & its advantages
- What ? Understand how the Ultrasonic Sensing Solution (USS) module works & its value
- Understand the tools and software for the USS module
- Demo / Results with EVM430-FR6047



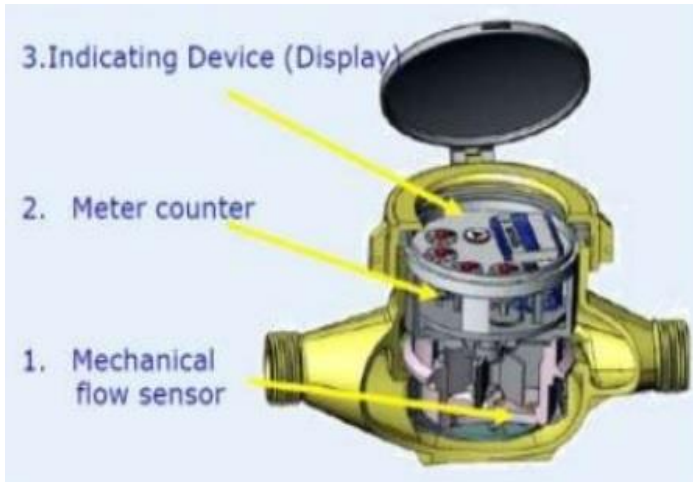
# Why Ultrasonic Sensing Technology?

[Read the whitepaper](#)

# Why Ultrasonic for a Flow Meter?

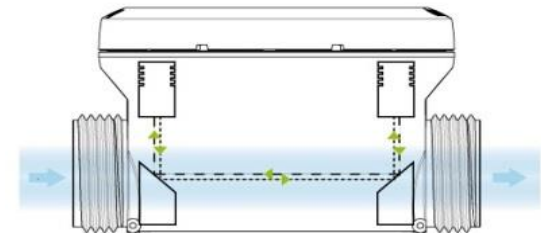
## Mechanical Meter

- Short life time < 7 years
- Dirt accumulated on impeller
- High minimum flow rate  $Q_{min} > 20$  L/hr
- Cannot detect small flow leakage
- Low accuracy
- Need re-calibration within 6 to 7 years
- Tempering issue



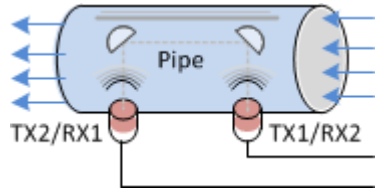
## Ultrasonic Meter

- Long life time 20 years
- No moving parts
- Low minimum flow rate  $Q_{min}$  at 5 - 10 L/hr
- Can detect small flow leakage (  $\sim 1$ L/hr )
- High accuracy
- Re-calibration >20 years
- No tampering issue
- Electronic device to enable AMR

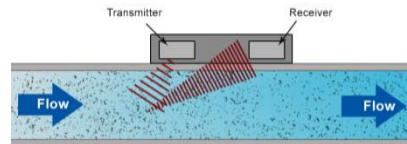


# Flow Measurement Technology Comparison

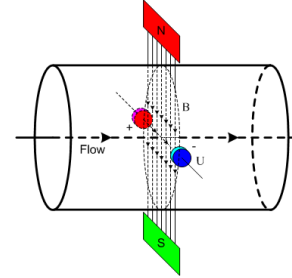
## Ultrasonic (TOF)



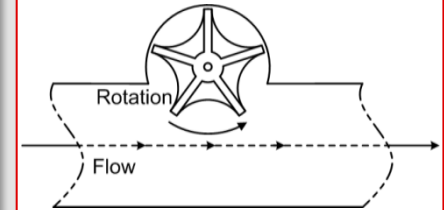
## Doppler



## Magnetic



## Mechanical



### Pros:

- No moving parts
- Good accuracy  $< \pm 1\%$
- Long operation life
- Detect variety of materials
- Resistant to vibration infrared radiation, EMI

### Cons:

- Need clear path ( proper mechanical construction for transducers )

### Pros:

- Can be installed outside the pipes
- Corrosion resistant
- Low power since takes 2-3 seconds to measure

### Cons:

- Less accurate  $\pm 3-5\%$
- Requires particulates or bubbles in the flow (good for wastewater or dirty liquid)

### Pros:

- No moving parts
- Medium cost
- Immune to impurities and flow profile
- Low flow detection

### Cons:

- Only conductive liquids
- Sensitive to sediments & chemical process
- Electrodes may wear out
- Medium power

### Pros:

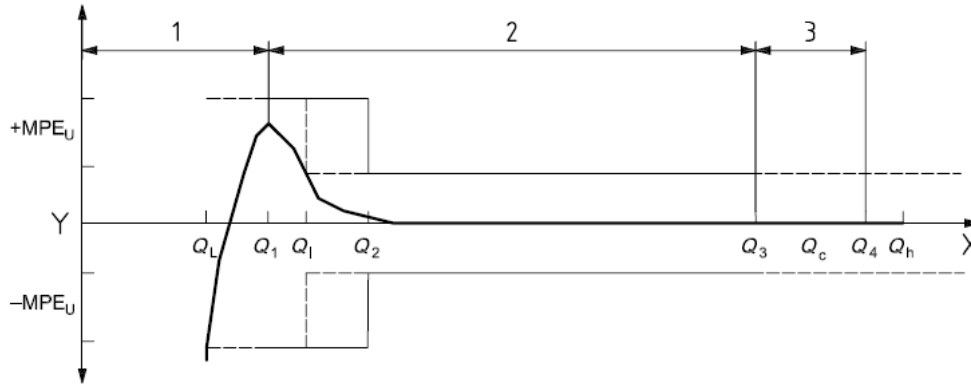
- Low cost to implement
- Accurate zero flow detection
- Works with all clean liquids

### Cons:

- Inertia and Friction
- Low flow detection
- Wears out
- Sensitive to impurities, sediments, flow profile

# Standards and requirements (driven by Europe)

- ISO 4064-1/EEC directive 75/33

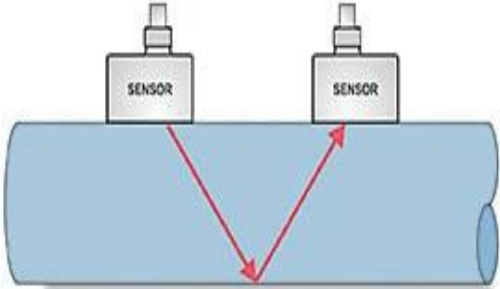
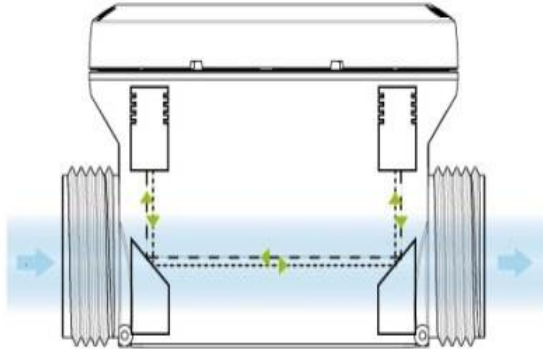
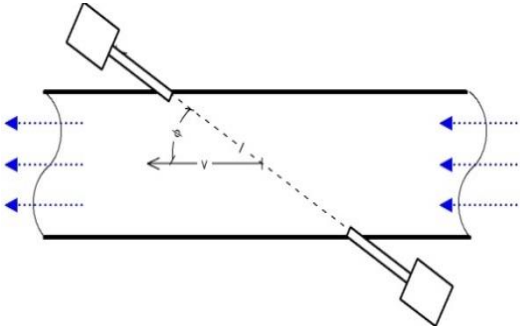


The flow rate	MPE Requirement
$Q_1$	< 5%
$Q_2, Q_3, Q_4$	< 2 % for water temperature < 30°
	< 3% for water temperature > 30°

dia (mm)	15	20	25	30	40
Q1 (L/H)	15	25	35	60	100
velocity_Q1 (m/s)	0.023569	0.022096	0.019798	0.023569	0.022096
Differential TOF T12- T21 (transducer separation = 6 cm, 25 deg C, Ultrasound vel = 1400 m/s) (ns) (flow rate Q1)	1.443	1.352816	1.212122	1.443	1.352816
Accuracy requirement (ps)	72.1500002	67.64082	60.60612	72.15	67.64082
dia (mm)	15	20	25	30	40
Q2 (L/H)	22.5	37.5	53	90	150
velocity_Q2 (m/s)	0.035354	0.033144	0.02998	0.035354	0.033144
Differential TOF T12- T21 (transducer separation = 6 cm, 25 deg C, Ultrasound vel = 1400 m/s) (ns) (flow rate Q2)	2.164530614	2.029224	1.83551	2.164531	2.029224
Accuracy requirement (ps)	43.29061227	40.58449	36.7102	43.29061	40.58449

- Accuracy requirement for leak detection, with 1 l/h water flow, 20% accuracy, 10 cm separation, is 45 ps resolution

# Ultrasonic Flow Meter Working Principle



Diagonal



Reflective

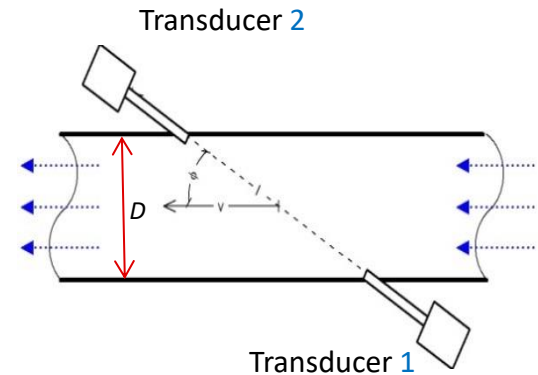


Non-Invasive



# Ultrasonic: Differential Time of Flight & Volume

- Ultrasound is described as the frequency range above human audible sound (> 20 kHz)
- Flow meters use in the range of 30 kHz to few MHz

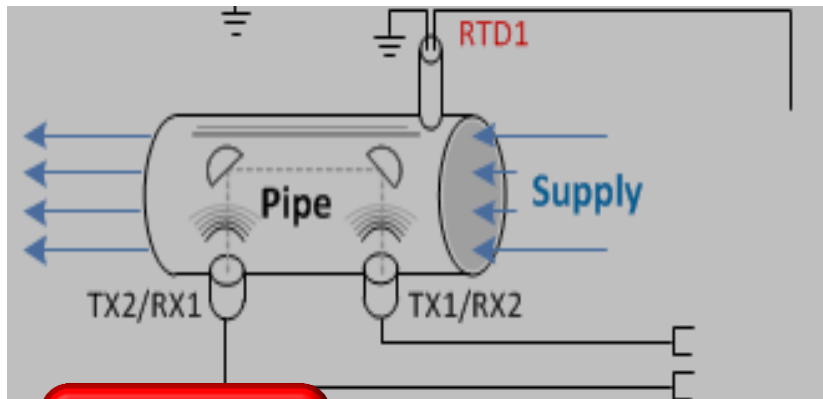


$v$  = Flow velocity of the medium  
 $L$  = Length of the acoustic path  
 $c$  = Velocity of sound in the medium  
 $D$  = Diameter of Pipe  
 $Q$  = Flow rate

$$\text{Transit time } (t) = \frac{\text{Distance}}{\text{Velocity}}$$

$$T_{12} = \frac{L}{c + v \cos \phi} \rightarrow v \cos \phi = \frac{L}{T_{12}} - c$$

$$T_{21} = \frac{L}{c - v \cos \phi} \rightarrow v \cos \phi = c - \frac{L}{T_{21}}$$



**MSP430**

# Differential Time of Flight & Volume

Formula for average flow velocity:

$$v = \frac{L}{2 \cos \phi} \left( \frac{1}{T_{12}} - \frac{1}{T_{21}} \right)$$

$$v = \frac{L}{2 \cos \phi} \left( \frac{T_{21} - T_{12}}{T_{21} T_{12}} \right)$$

$$v \propto T_{21} - T_{12} \rightarrow \Delta T$$

Calculating the Volume:

$$Q = \frac{\pi D^2}{4} \frac{L}{2 \cos \phi} \left( \frac{\Delta T}{T_{21} T_{12}} \right)$$
$$= \underbrace{\frac{\pi D^3}{4 \sin(2\phi)}}_{\text{Area}} \underbrace{\left( \frac{\Delta T}{T_{21} T_{12}} \right)}_{\text{Flow velocity}}$$

Measure difference in upstream vs. downstream TOF to calculate flow rate

In addition to dTOF, we also measure the AbsTOF ( T21, T12 ) for UPS ( upstream ) and DNS ( downstream )

Final volume is based on the area of the flow tube ( meter constant )

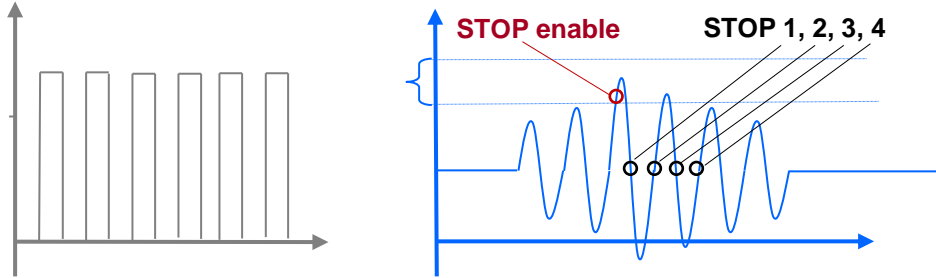
- Temperature and Pressure are constant within few ms of measurements
- Medium density, velocity of sound do not impact measurement

# ADC-Based Technique

[www.ti.com/product/MSP430FR6047](http://www.ti.com/product/MSP430FR6047)

# Techniques for differential TOF estimation

1) Zero crossing detection: detect arrivals of upstream  $r_1(t)$  and downstream  $r_2(t)$  signals & estimate  $\Delta T$  (Time of flight difference) *based on averaging of zero crossings*.



$$r_1(i) = s_1(i) + n_1(i)$$

$$r_2(i) = s_2(i) + n_2(i)$$

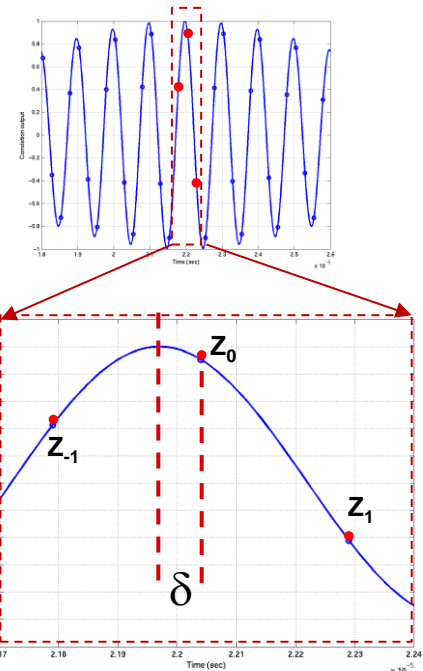
$$s_2(i) = a s_1(i - \Delta T)$$

$a$  is the amplitude difference up/downstream - Ideally  $a \approx 1$

2) ADC based Algorithm: Cross-correlation Method for  $\Delta T$  estimation:

a) Fold  $r_1(t)$  &  $r_2(t)$  =

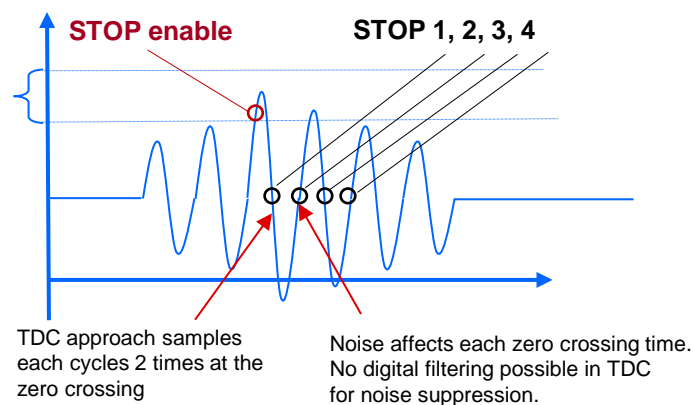
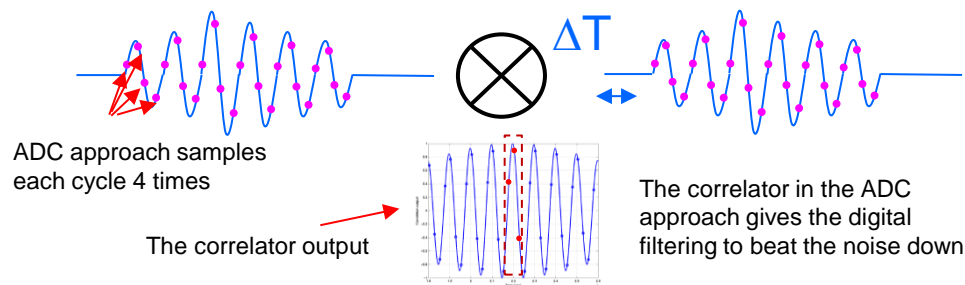
$$corr(k) = \sum_{i=1}^{N-k} r_1(i+k)r_2(i) \quad Z_n = corr(\hat{k} - n) \quad n = (-1,0,1)$$



b) Interpolate time offset for maximized correlation at 3 points

# Features of ADC based processing

- Fundamental Difference : **Signal processing**



- **Performance**

- Best in class Zero flow drift across temperature and enables low flow detection (<1L/h )
- The correlation acts as digital filter to suppress noise
  - Benefit of ~3-4X noise lower standard deviation. Can also suppress other interference like line noise etc.
- Allows use of lower voltage driving (0-3V only) for gas applications

- **Robustness**

- Robust to signal amplitude variations
  - The algorithm is insensitive to the received signal amplitude as in high flow rates, transducer to transducer variation, temperature variation, different gas compositions (air, methane)

- **Envelope of signal is obtained naturally in ADC based processing.**

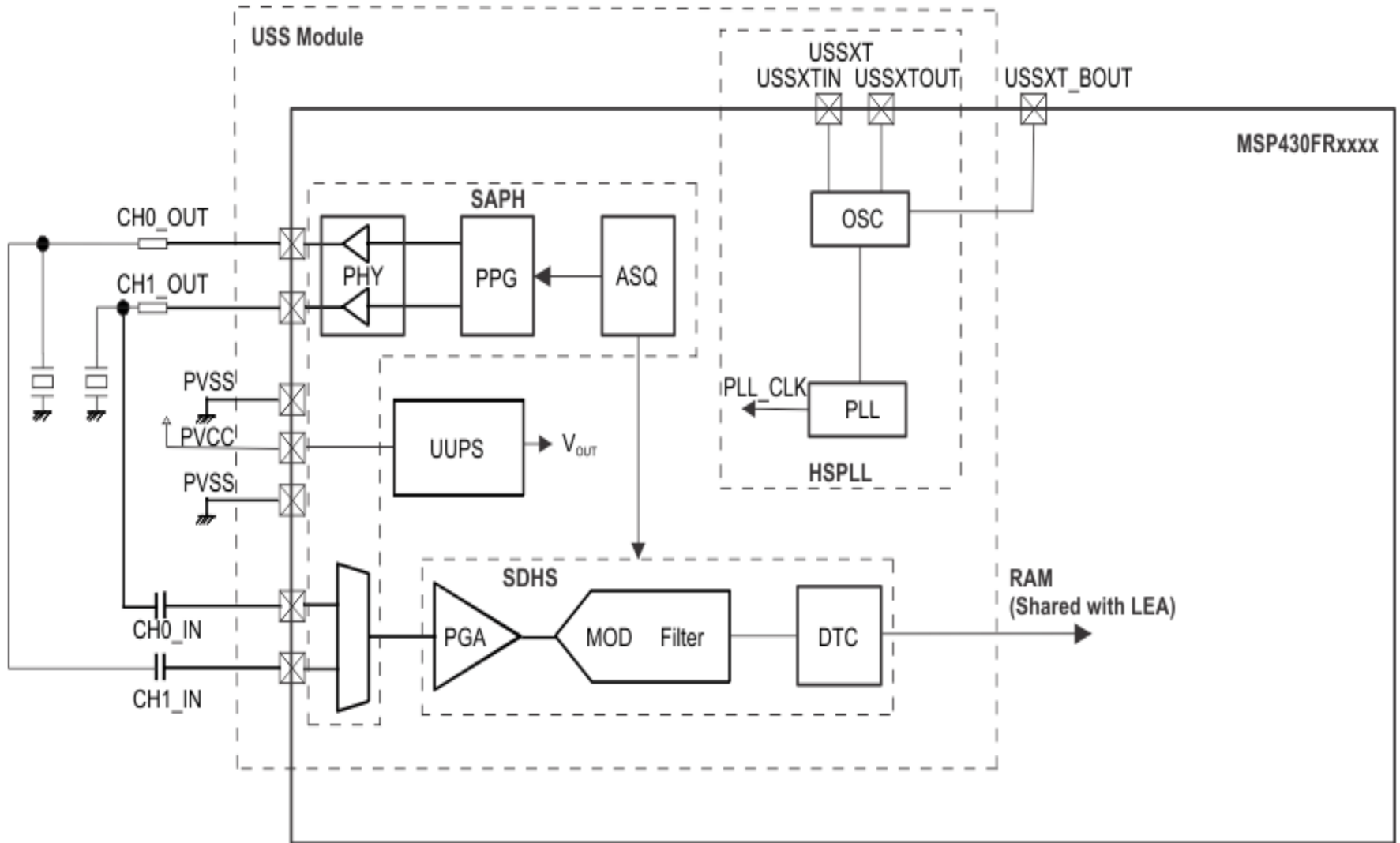
- Enables tuning to the transducer frequencies
- Slow variations in envelope across time can be used for detection of aging of transducers/meter

# **MSP430FR6047**

## **Ultrasonic Sensing Analog Front End Detailed Module Description**

**[Read the whitepaper](#)**

# USS IP Block Diagram I (Signal Path)



## PPG (Programmable Pulse Generator)

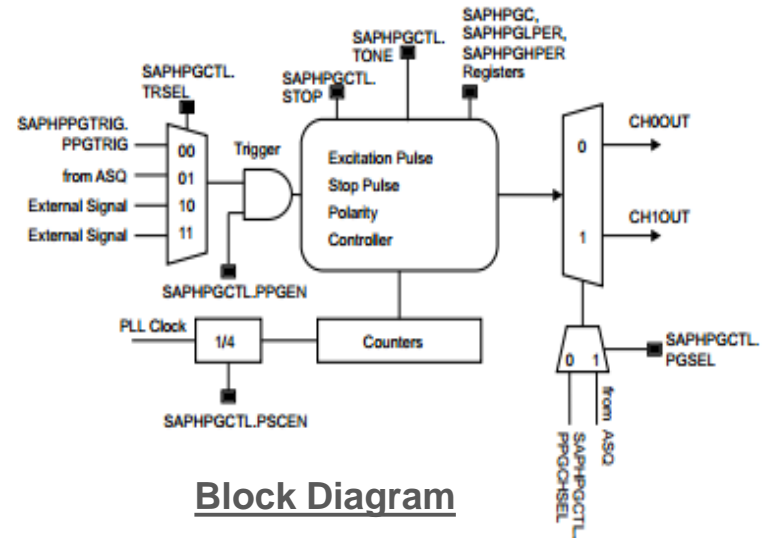
- Generate Excitation Pulses
  - # of pulses:
    - In phase: 1 ~ 127
    - Stop phase: 0 ~ 15
- Frequency Range: 33KHz ~ 2.5MHz
- Test tone generation for continuous pulses ( Debug/Analysis )
- Resolution is dependent on the nominal transducer frequency & HSPLL frequency

$$\Delta F = \frac{HSPLL\_Frequency}{HPER + LPER} - \frac{HSPLL\_Frequency}{HPER + 1 + LPER}$$

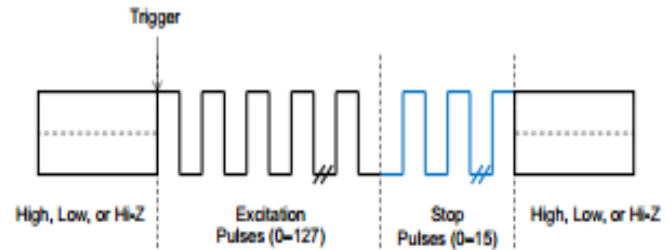
HPER : High period of pulse

LPER : Low period of pulse

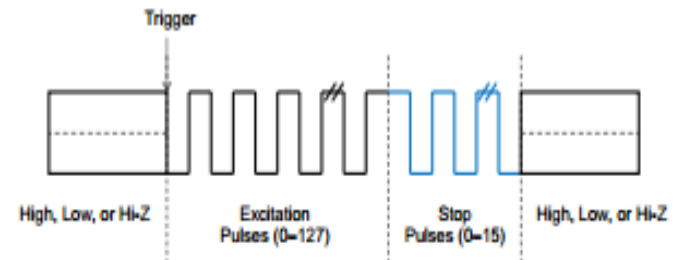
- Examples:
  - For 1 MHz pulses with 80 MHz PLL,  $\Delta F \sim 13$  kHz
  - For 2 MHz pulses with 80 MHz PLL,  $\Delta F \sim 51$  kHz



**Block Diagram**



**PPG Outputs With SAPHPGC.PPOL = 0 (Starts With High Polarity)**

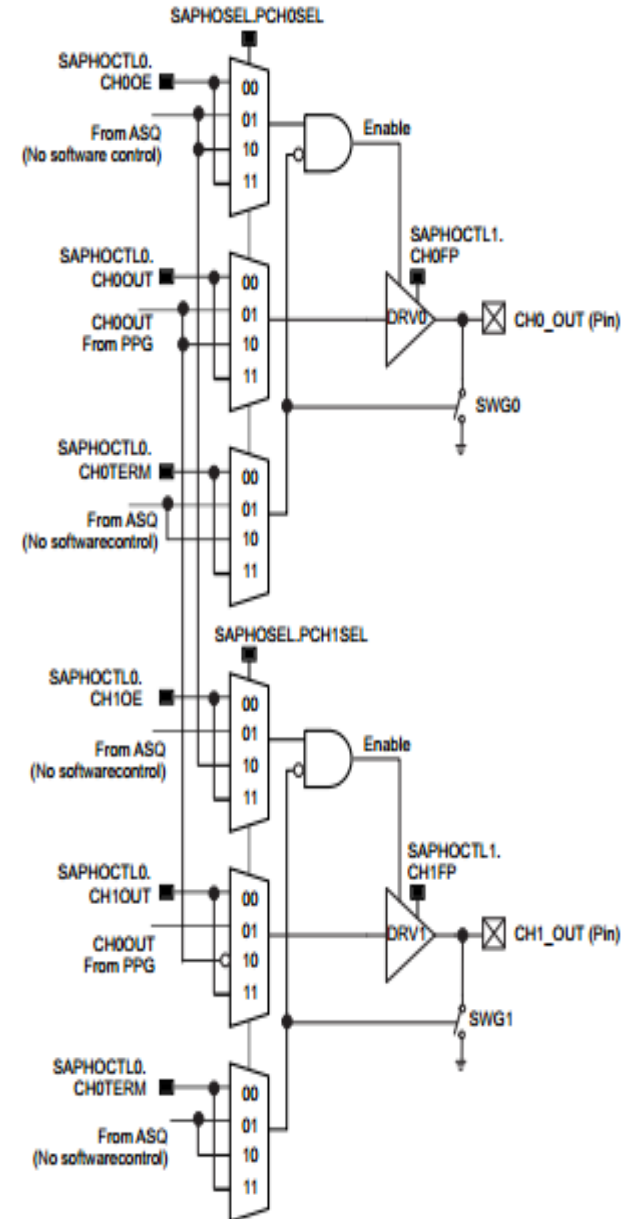


**PPG Outputs With SAPHPGC.PPOL = 1 (Starts With Low Polarity)**



# PHY

- 2ch. to control Input & Output of the USS Module
- Impedance Matching for best ZFD performance
  - Device specific ATE Trimmed values
  - Internal Multi-plexing feature
- Dedicated Low Impedance drivers
  - $\leq 4 \Omega$  (Typ), 120 mA (Typ) x 2
- Operating voltage range 2.2V – 3.6V



# 12-bit 8MSPS ADC

## PGA

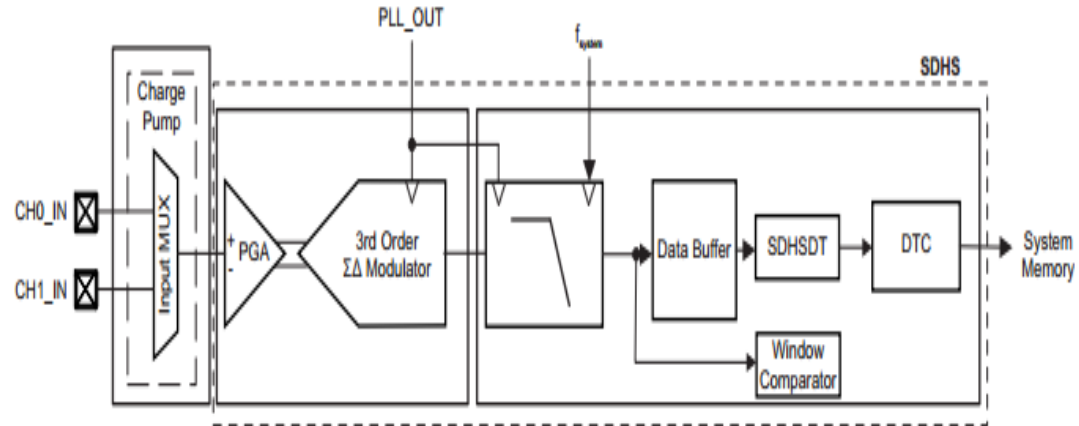
- Input Voltage: 35mV ~ 760mV (<2.5V)
- Input Voltage: 35mV ~ 1000mV ( $\geq 2.5V$ )
- Gain: -6 ~ 19dB with ~1dB step

## SDHS (Sigma Delta High Speed ADC)

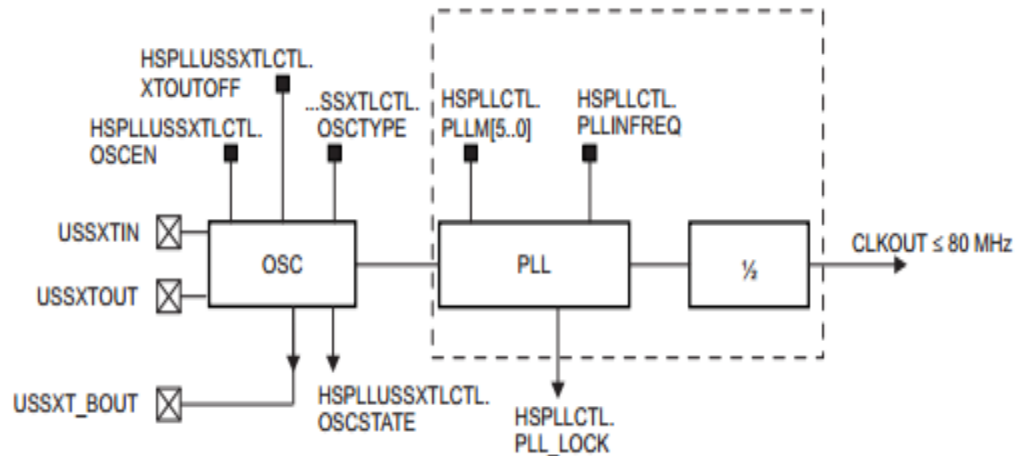
- 12 bit , SNR – 63dB ( typ) upto 1.5MHz BW
- Input Voltage max. 600mVpp
- Modulator Frequency: 68MHz ~ 80 MHz
- Output Data Rate: up to 8MSPS
- OSR Ratio: 10, 20, 40, 80, 160
- Stand alone mode

## HSPLL (High Speed PLL)

- Input: 4-8MHz
- Output: 68-80MHz



SDHS Block Diagram



HSPLL Block Diagram

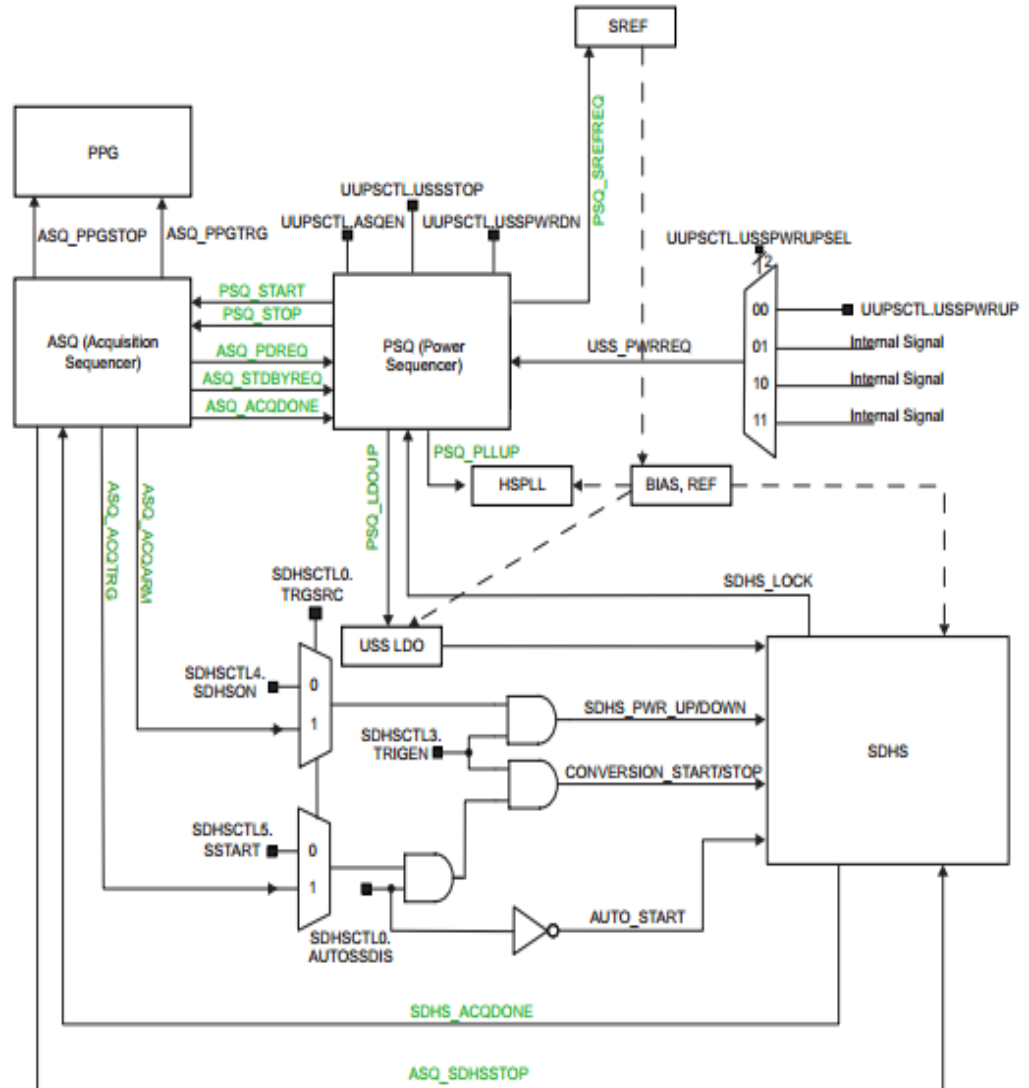
# USS IP Block Diagram II (Control Path)

## PSQ (Power SeQuencer)

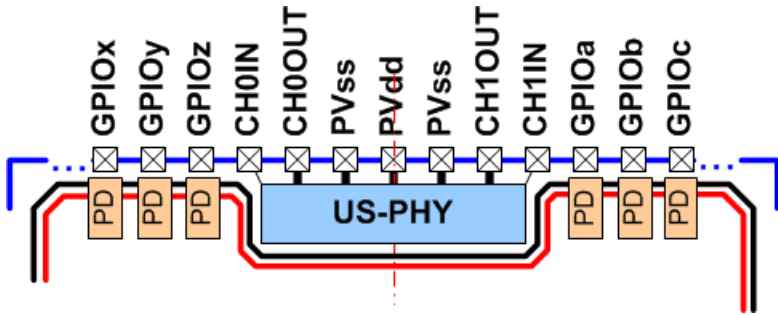
- Detect "Start" signal
- Control Power Up/Down Sequence
- Detect Debug Mode

## ASQ (Acquisition SeQuencer)

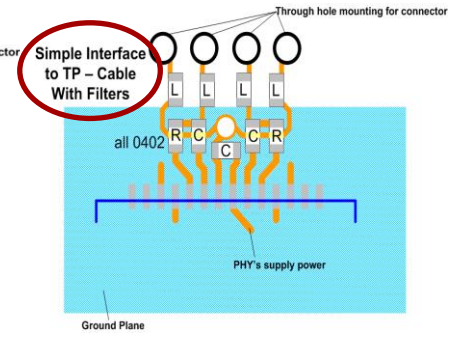
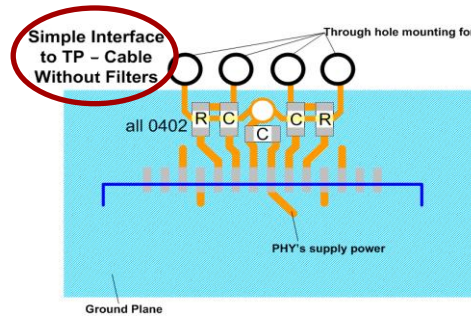
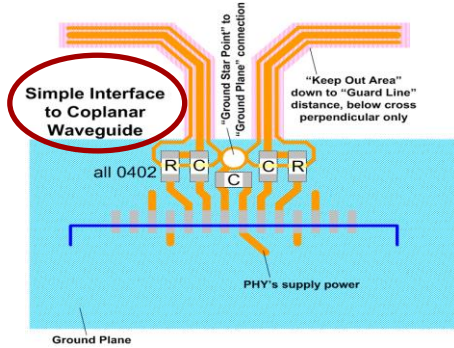
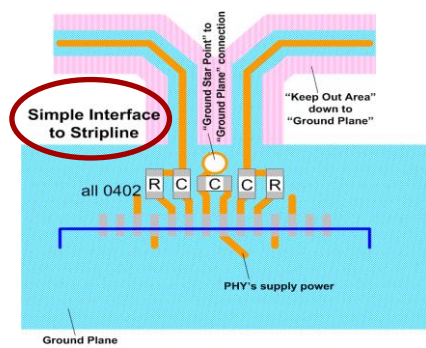
- Control measurement sequence
- Start/Stop PPG & SDHS
- Programmable events



# Application Section Pinout/PCB



The USS terminals on the device are **symmetric** to the package axis, thus allow to easily maintain symmetry on the PCB

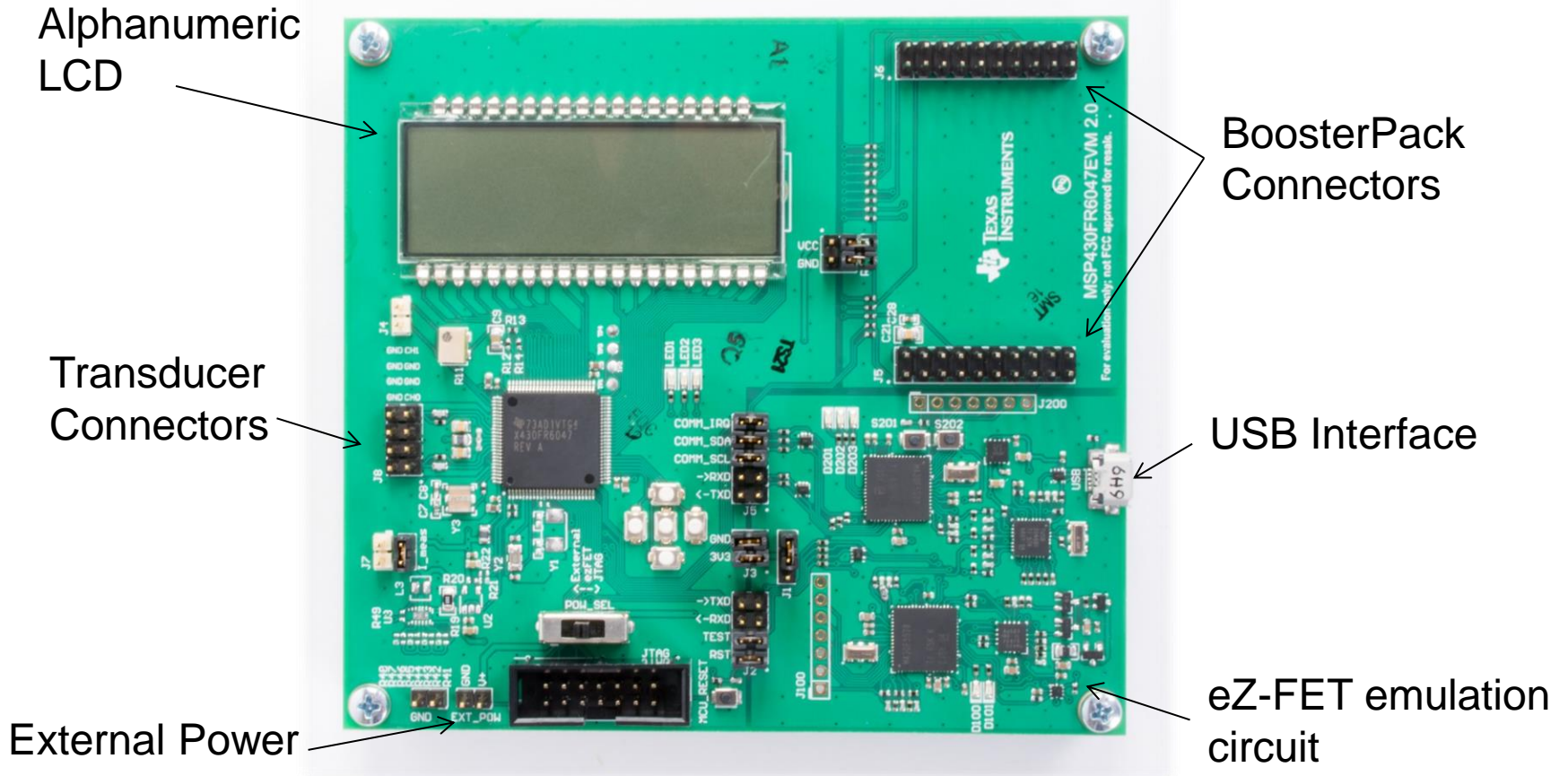


TI will provide, guidelines on how to connect the Transducers via cable or PCB via App Notes

# MSP430FR6047 Evaluation Module

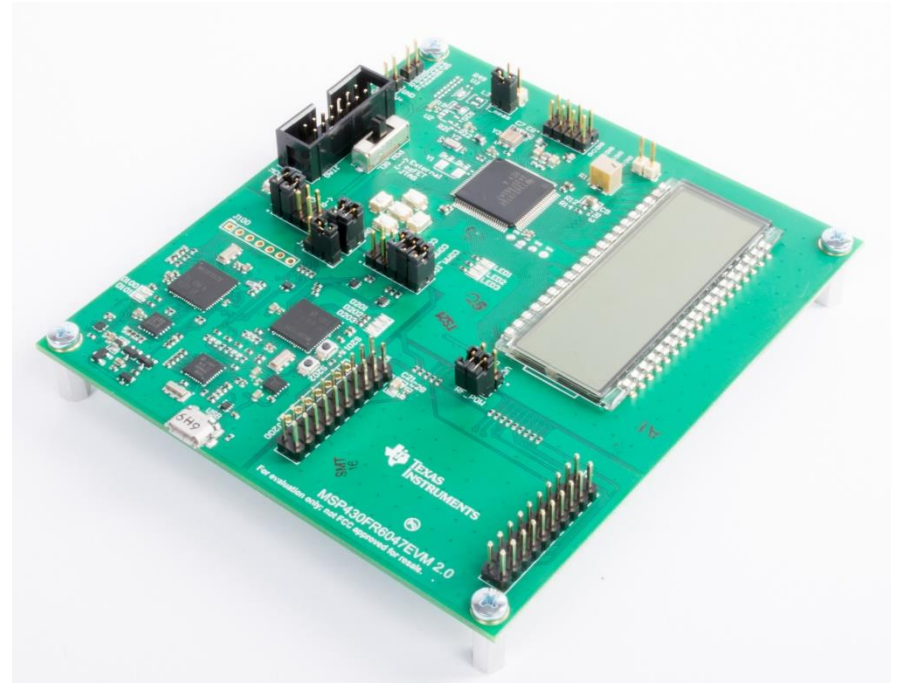
[www.ti.com/tool/EVM430-FR6047](http://www.ti.com/tool/EVM430-FR6047)

# EVM430-FR6047 Key Components



# EVM430-FR6047 Features

- External/USB Power Options
- On-board eZ-FET for programming/debug
- Header available to measure current consumption
- USB HID interface to PC GUI
- Alphanumeric LCD for stand-alone operation
- Two transducers can be connected
- Booster-Pack Connectors for additional functionality such as RF
- Compatible with USS Software Library

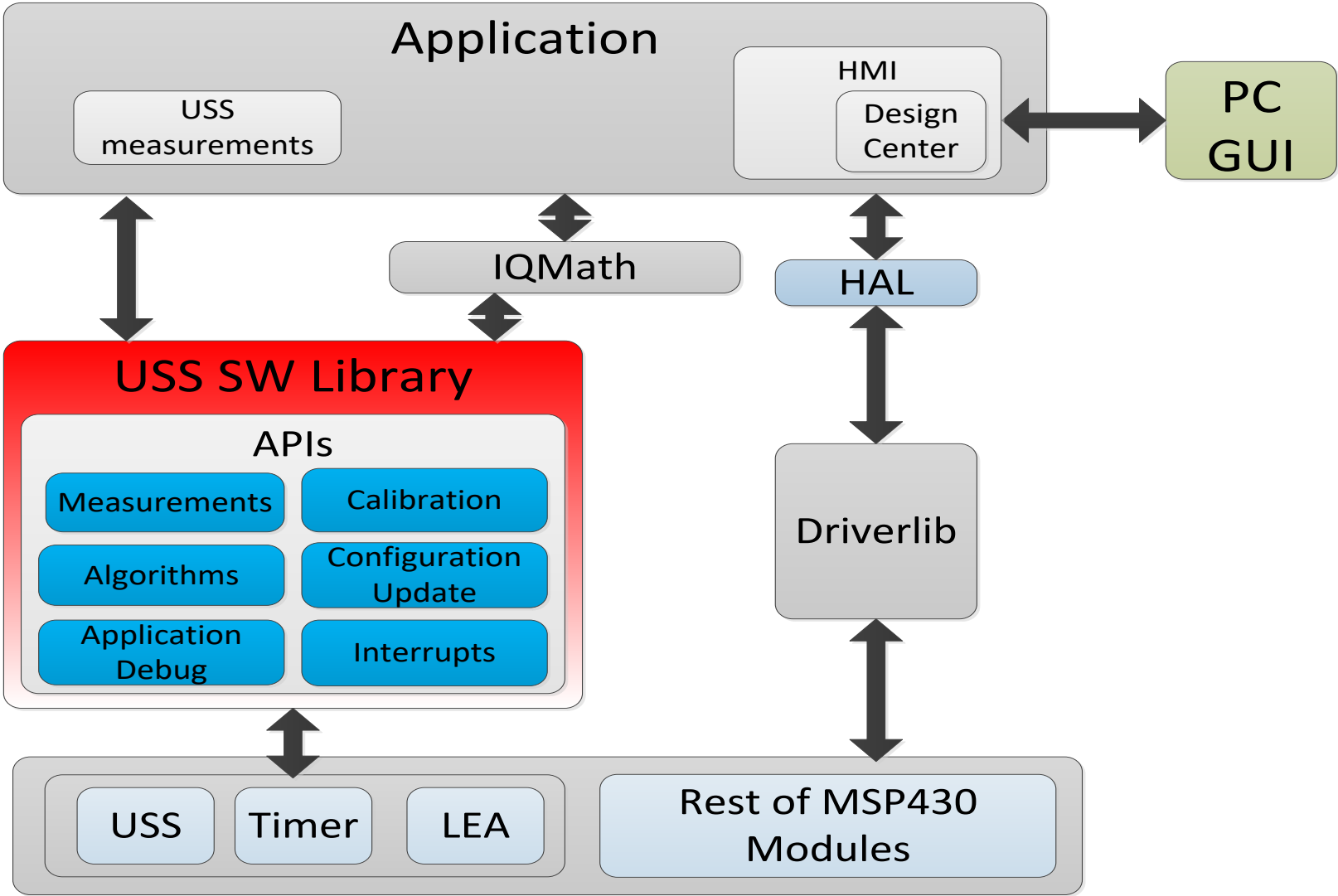


# Application Software and USS SW Library

[www.ti.com/tool/MSP-USSSWLIB](http://www.ti.com/tool/MSP-USSSWLIB)



# Software Architecture – Ultrasonic Application



# Ultrasonic Software Library

## USS SW Library

### APIs

Measurements

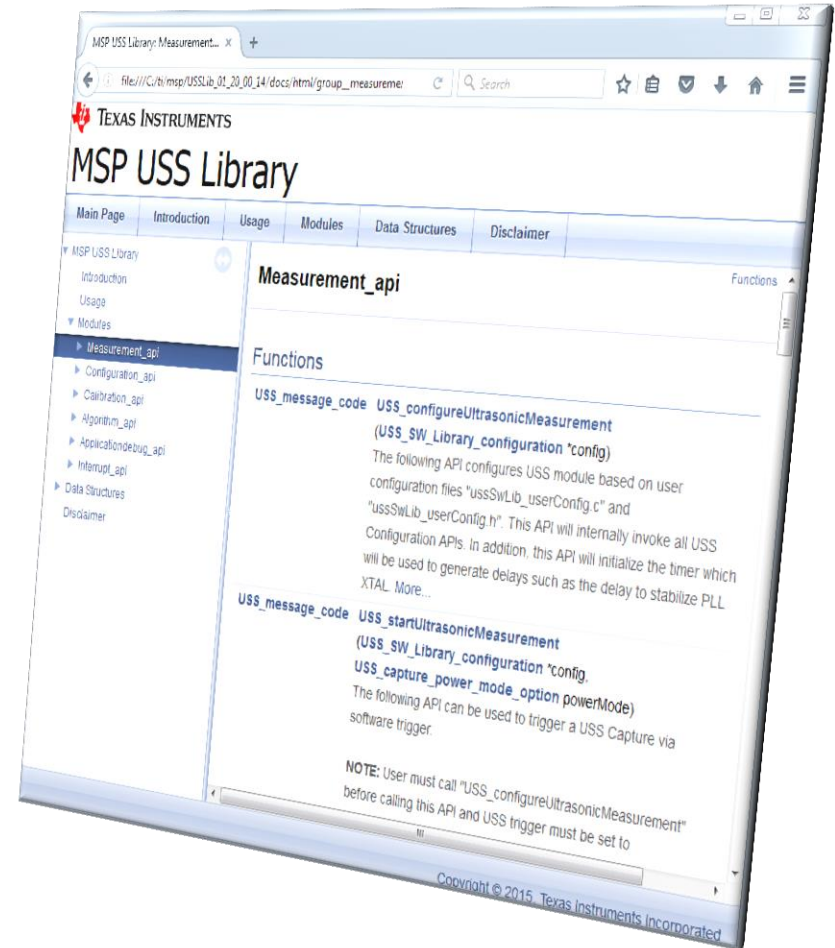
Calibration

Algorithms

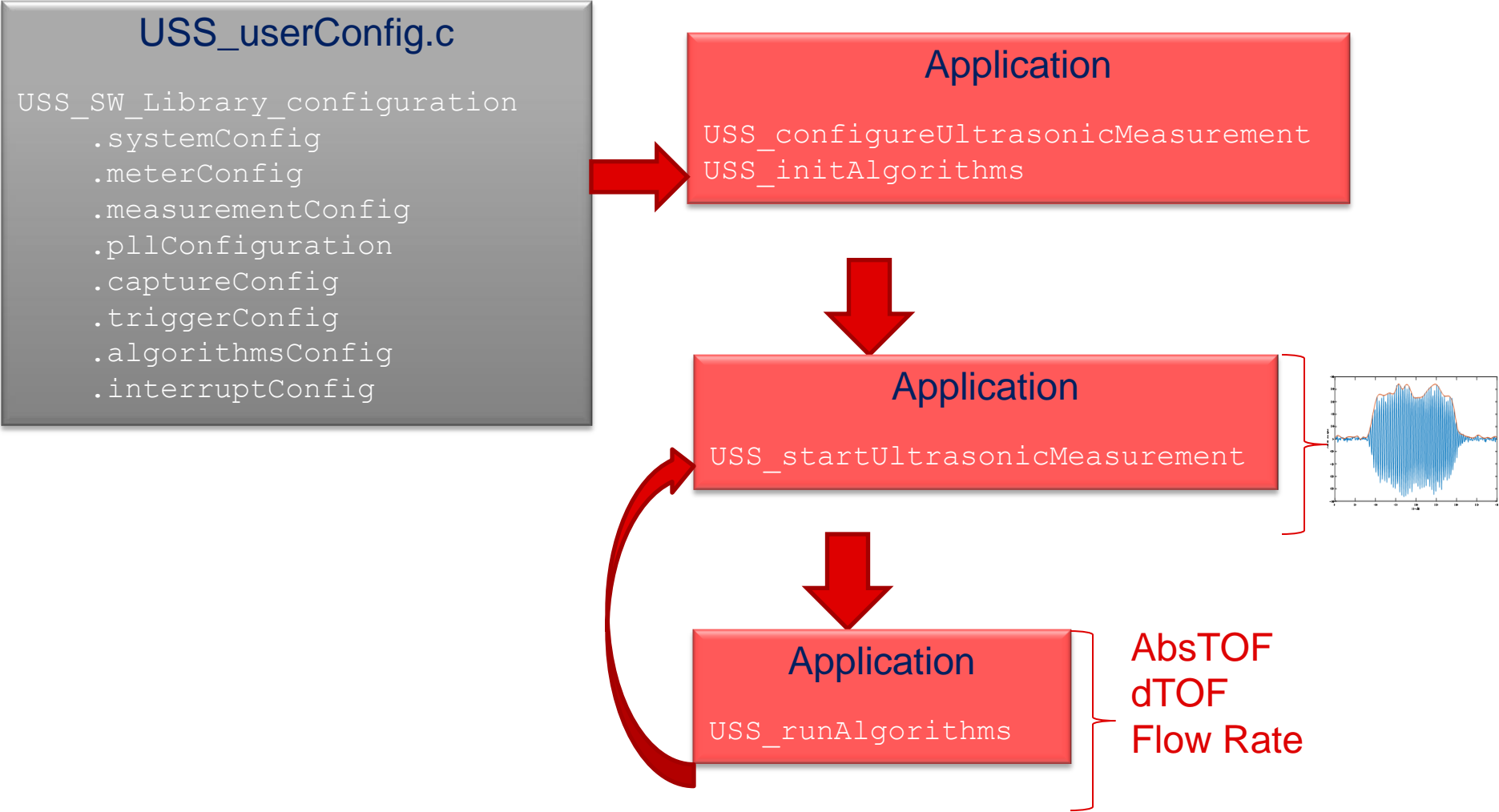
Configuration  
Update

Application  
Debug








Interrupts



# Ultrasonic Software Library - Implementation



# USS Software Library offering

	TI – MSP430FR6047 with USS
dToF	
AbsTOF	
Flow Rate	
Filtering / Post processing	
Averaging	
Waveform capture	
Automatic Gain Control	

# Ultrasonic Design Center

[www.ti.com/tool/msp-ultrasonic-design-center](http://www.ti.com/tool/msp-ultrasonic-design-center)

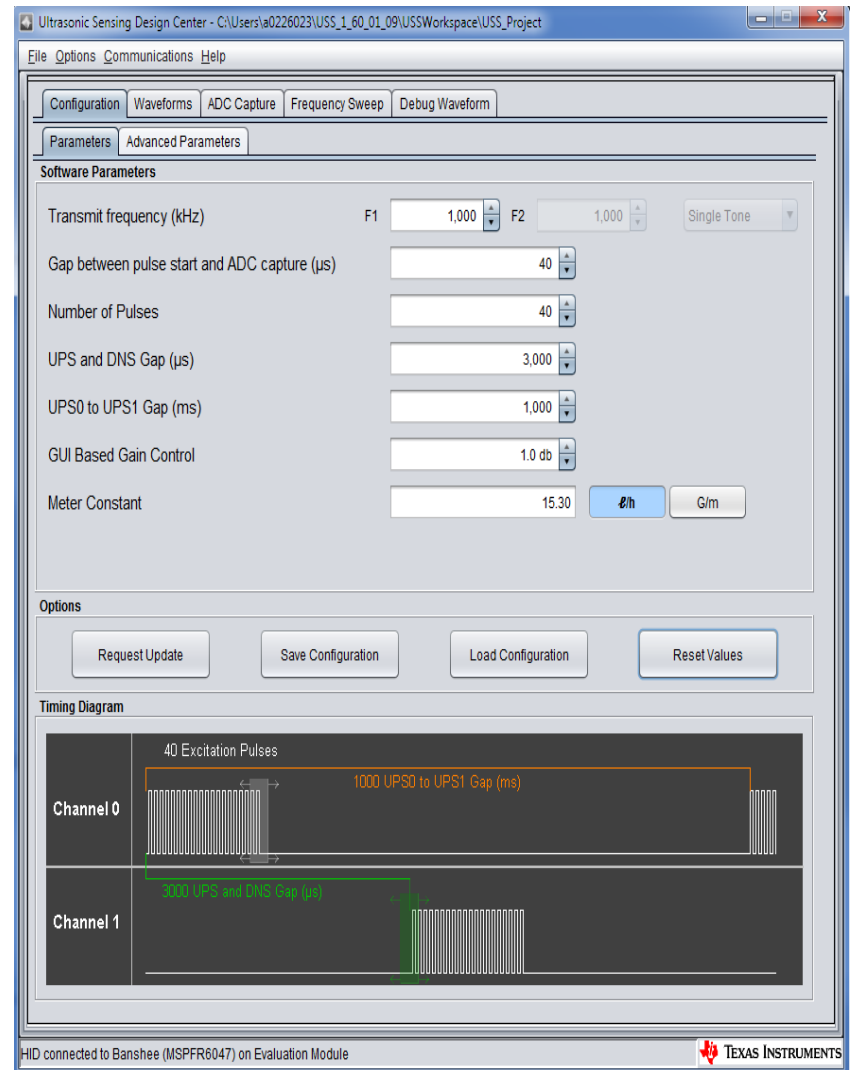
# Ultrasonic Design Center GUI

The Design Center (DC) GUI provides an easy and quick solution to get started with the MSP430FR4067 Ultrasonic Sensing Library and begin experimental water flow measurements.

The GUI equips the user with the ability to easily modify key USS Library members with a variety of input parameters.

Some of the modifiable Parameters and Advance Parameters include:

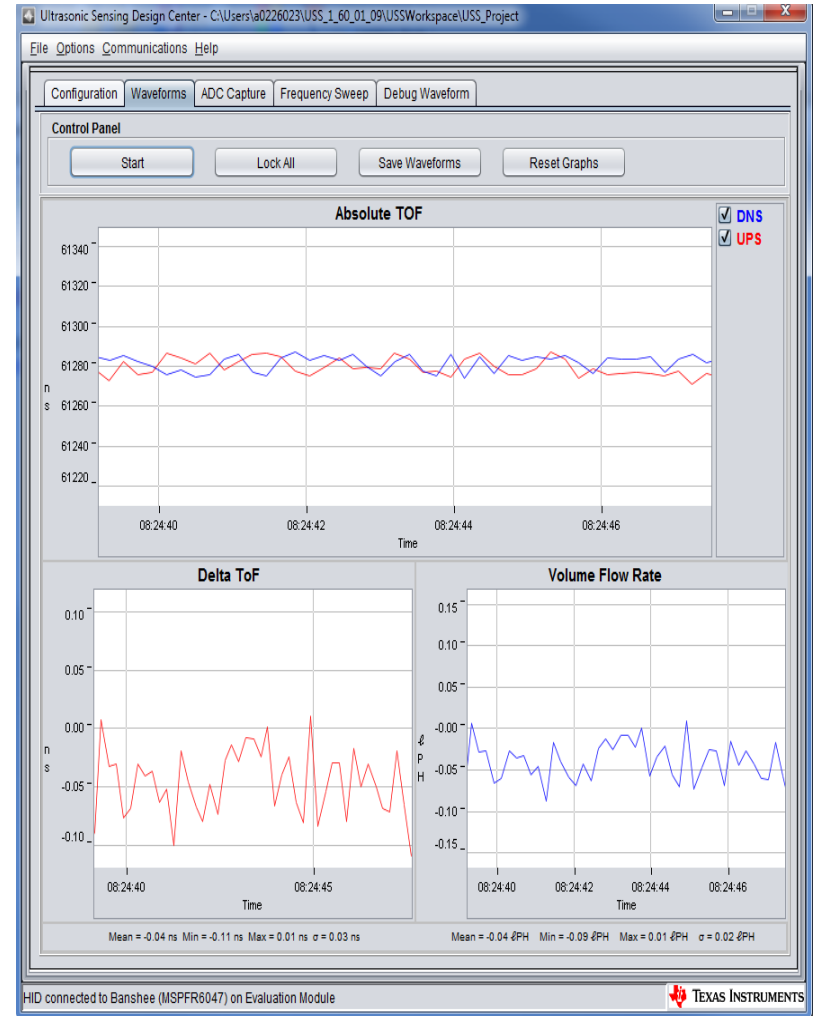
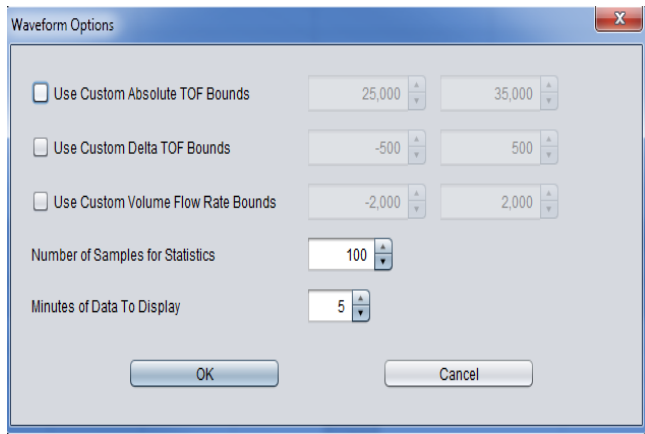
- The excitation frequency of the ultrasonic pulse (F1)
- Number of excitation pulses
- Gap between pulses (UPS0 – UPS1 Gap)
- ADC Sampling Frequency
- USS crystal settling time
- ... Much more



# Ultrasonic Design Center GUI

In addition to the ability to modify major USS Library Members, the DC GUI also provides visual data results in real time through the graphs in the “Waveforms” panel.

Each of these graphs provide editable options, giving an expanded control of the data that is visualized through the GUI. These options are editable through a ‘Waveforms Options’ pop-up window.

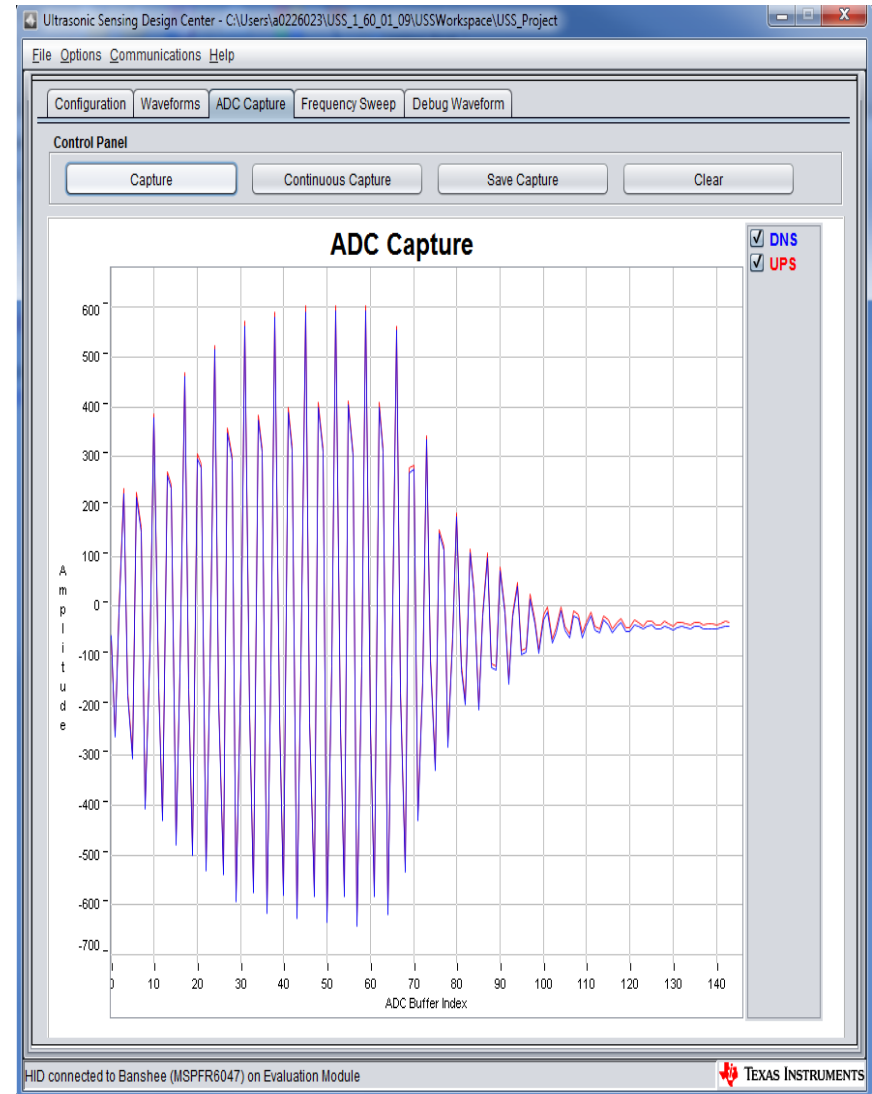


<http://www.ti.com/tool/msp-ultrasonic-design-center>

# Ultrasonic Design Center GUI

The DC GUI further has the capacity to perform three crucial actions:

1. ADC Capture
  - Capture a single ADC waveform from an excitation pulse and display it the ADC Capture graph.
2. Continuous Capture
  - Continuously capture the ADC waveform from consecutive excitation pulses, display and log the data in a .csv file.
3. Frequency Sweep
  - Sweep through a selectable range of frequencies for the excitation pulse allowing the user to obtain an optimal excitation frequency for best performance.





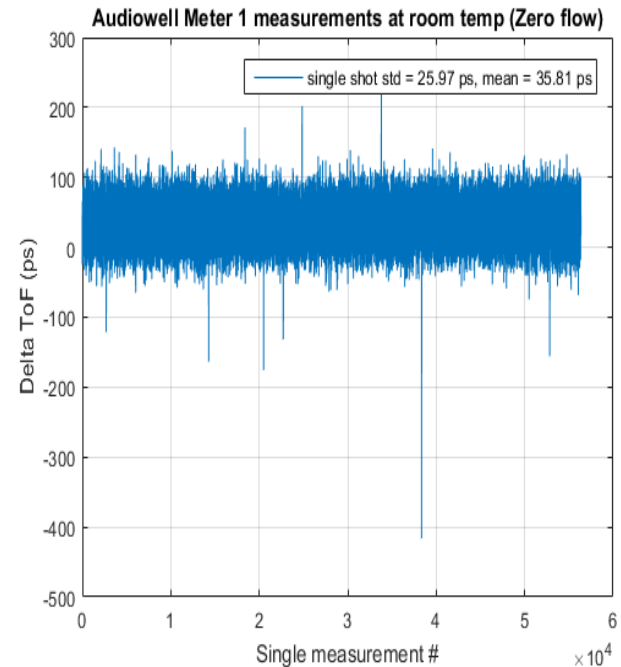
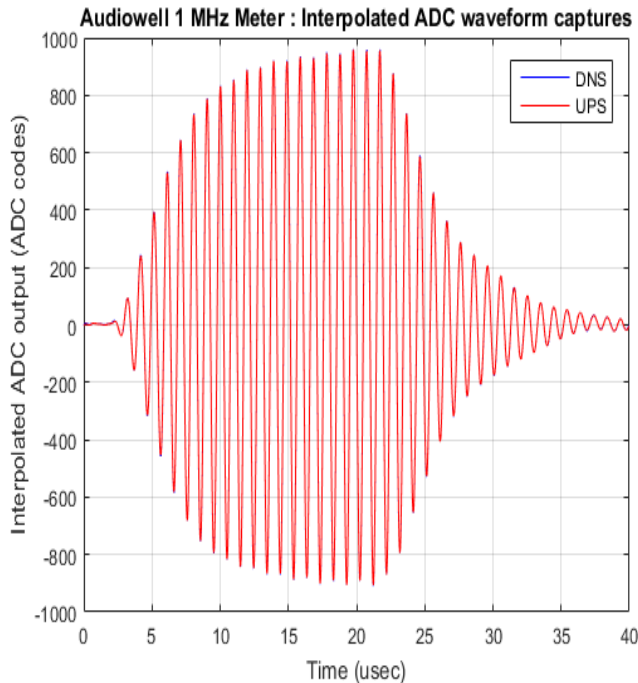
# EVM430-FR6047 Test Results

[www.ti.com/tool/EVM430-FR6047](http://www.ti.com/tool/EVM430-FR6047)

# ADC Waveform & TOF captures

- Transducer excitation frequency = 1.03 MHz
- Sampling rate: 3.6 MHz
- Capture duration: 40 us

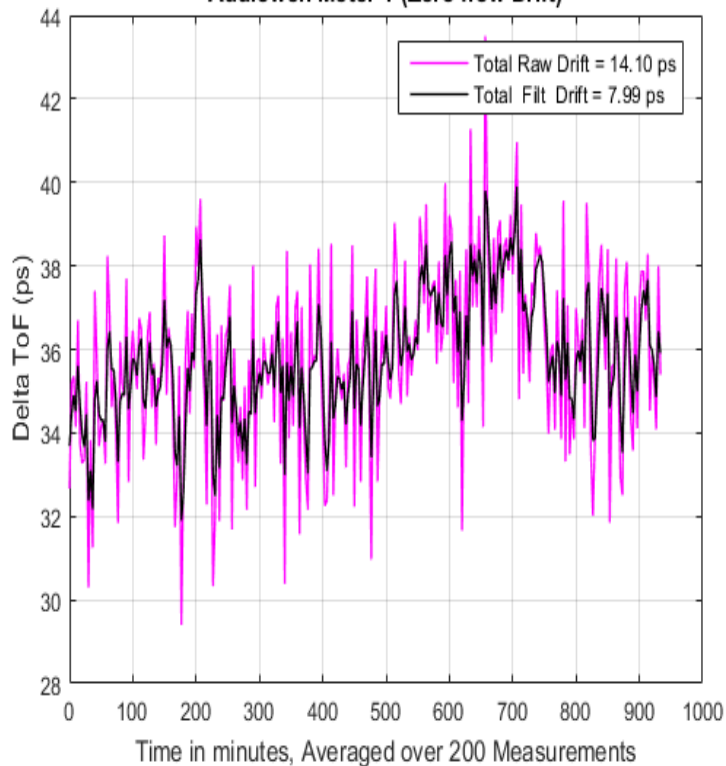
- Measurements at room temperature over 15 ½ hours
  - TOF Single shot standard deviation = 26 ps
  - TOF Mean = 36 ps



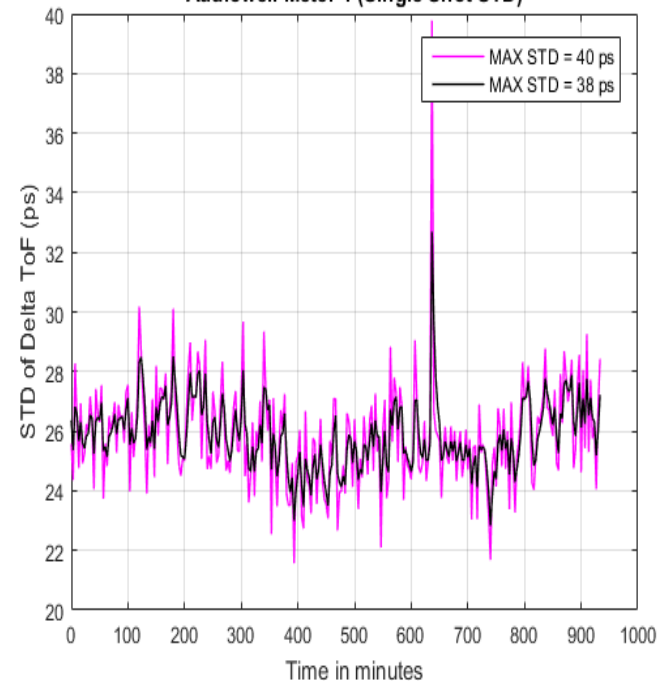
# Zero Flow Drift: Room Temp (Overnight)

- Overnight Room Temp ZFD Test
  - Measurement Rate: 1 Hz
- Zero Flow Drift (ZFD): **8 ps** (15 ½ hours run) (32ps : 40ps)
- Single shot standard deviation (STD): 26 ps

Audiowell Meter 1 (Zero flow Drift)

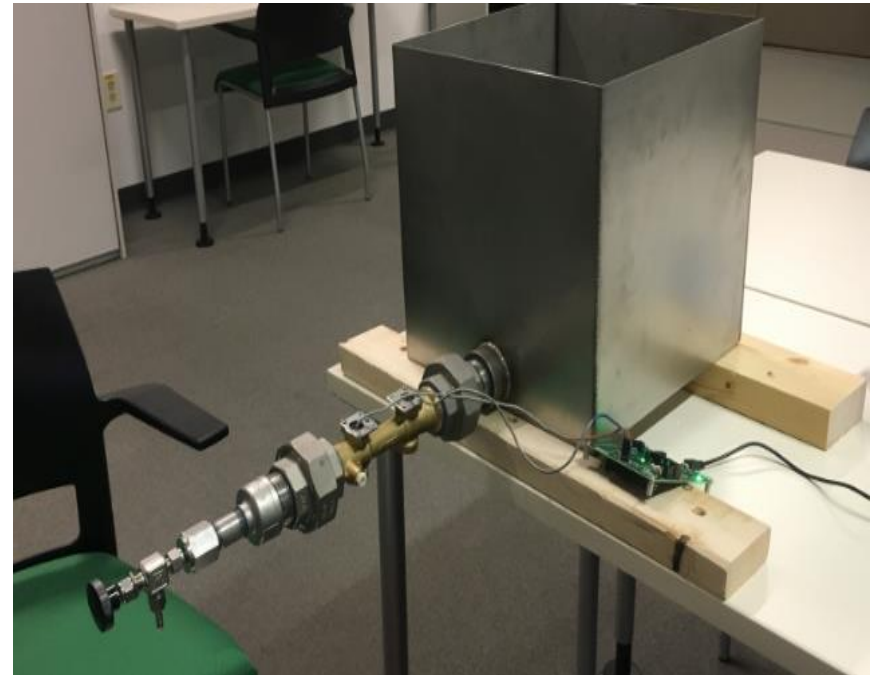
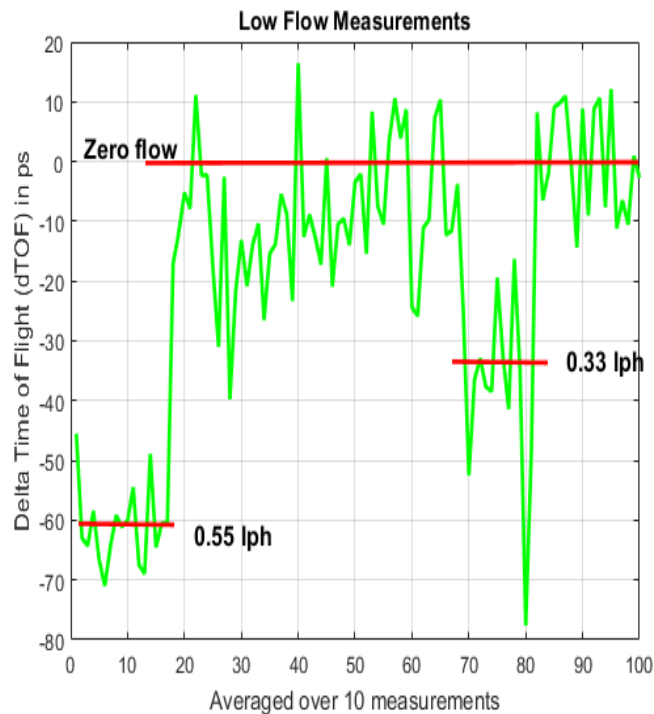


Audiowell Meter 1 (Single Shot STD)



# Low Flow Detection

- Setup allows for testing very low flow rates:
  - $< 1$  drop / sec
  - Equivalent to  $< 0.2$  lph
- Test results for  $< 1$  L/h



# Results from EVM430-FR6047

Parameter	Value
Std. Deviation for single shot measurement	<32 ps
Zero Flow Drift Over Temp. (5°C – 85°C)	<25 ps <sup>1</sup>
Min. Timing Resolution	5 ps
Average current consumption @ 1Hz	4.29 $\mu\text{A}^2$

1. has transducer / pipe dependency
2. Current Silicon performance – will be improved to ~3uA with the final silicon

# MSP430FR6047

The next level of performance for Ultrasonic Sensing Solutions

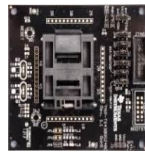
## Features/Benefits

- **First Single Chip solution with the best performance**
  - ~ 25ps Zero Flow Drift
  - ~ 32ps Standard Deviation
  - ~ 3uA measurement current
- **Ultrasonic Sub-system** ( Integrated High Performance SD-ADC, Pulse Position Generator & Integrated PHY ) **with Software Library Support**
- **LEA ( Low Energy Accelerator )** for optimizing power
- **MTIF ( Metering Test Interface Module )** running in Sleep Mode

## Tools



Flow Meter EVM



100-pin Target Socket Board



USS SW & GUI

## Software

- [Code Composer Studio™ IDE](#)
- [EnergyTrace++™ Technology](#)
- [DSPLib](#)
- [USS Software Library](#)
- [ULP Advisor](#)

## MSP430FR6047

Temperatures: -40 °C to 85 °C

**16-bit RISC**  
16 MHz

1.8 to 3.6V

### Debug

Real Time JTAG

Embedded Emulation

Boot Strap Loader

EnergyTrace++  
Technology

### Timers

Up to 6 x 16-bit  
Timers with up to 7  
Captures/Compare  
Registers

Real-time Clock  
(RTC) and Calendar

### Ultrasonic

Ultrasonic Sensing  
Solution

### Memory

256KB FRAM

8KB SRAM

Direct Memory  
Access Controller  
6 Channels

### Comms Peripherals

4 X USCIA  
(UART/SPI/IrDA/LIN)

2 X USCIB

### Data Protection

AES 256

CRC16

True Random  
Number Seed

### Data Processing

LEA

### Display

LCD-C (up to 265S)

### Power & Clocking

Brown-out Reset  
(BOR)

Supply-voltage  
Supervisor (SVS)

Power-on Reset  
(POR)

External Clock Fail  
Safe

### Analog

16ch 12-bit  
Differential ADC  
(integrated window  
comparator)

Comparator

### Other

32x32 Hardware  
Multiplier

### Packages

100 LQFP

## Target Applications

- Ultrasonic Flow Meter
- Liquid Level Sensing
- Occupancy Monitoring System
- Security Sensing
- Distance Measurement System

# Summary

- Industry's first integrated SOC for Ultrasonic Sensing
  - High Accuracy, High Precision measurements
  - Low power ( ~ 3uA ) for 1meas/ sec
  - Low flow rate detection ( <1L/h )
- Ultrasonic Design Center with Software Library, GUI for ease of development
- FR6047 EVM for hardware evaluation
- Documentation – App Notes and User Guides with Links
- Training Videos - Coming Shortly.....

[www.ti.com/product/msp430fr6047](http://www.ti.com/product/msp430fr6047)



© Copyright 2018 Texas Instruments Incorporated. All rights reserved.

SWMP003



## IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to TI's Terms of Sale ([www.ti.com/legal/termsofsale.html](http://www.ti.com/legal/termsofsale.html)) or other applicable terms available either on [ti.com](http://ti.com) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265  
Copyright © 2020, Texas Instruments Incorporated