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

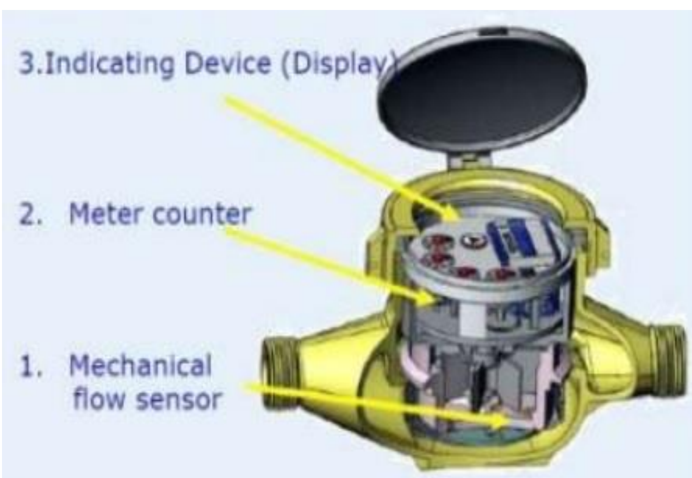
Why Ultrasonic for a Flow Meter?

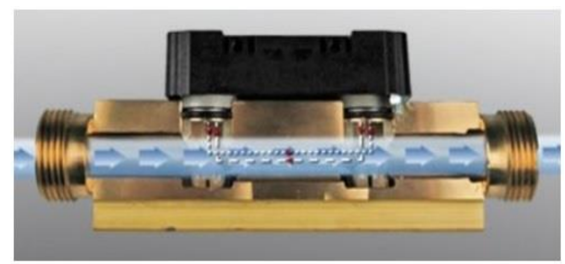
Mechanical Meter

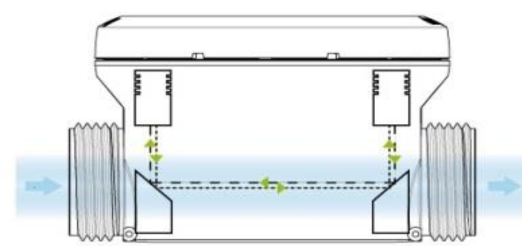
- Short life time < 7 years
- Dirt accumulated on impeller
- High minimum flow rate Qmin > 20 L/hr
- Cannot detect small flow leakage
- Low accuracy
- Need re-calibration within 6 to 7 years
- Tempering issue

Ultrasonic Meter

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

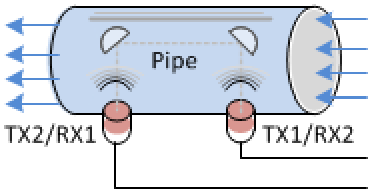






Flow Measurement Technology Comparison

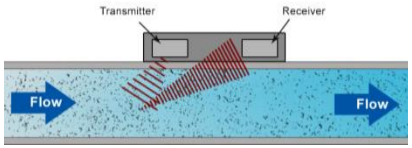
Ultrasonic (TOF)



Pros:
- No moving parts
- Good accuracy < ±1%
- Long operation life
- Detect variety of materials
- Resistant to vibration infrared radiation, EMI

Cons:
- Need clear path (proper mechanical construction for transducers)

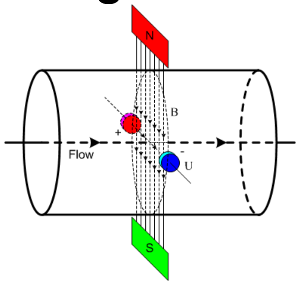
Doppler



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

Cons:
- Less accurate ±3-5%
- Requires particulates or bubbles in the flow (good for wastewater or dirty liquid)

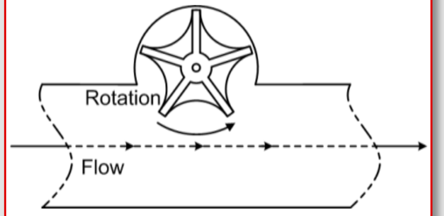
Magnetic



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

Mechanical

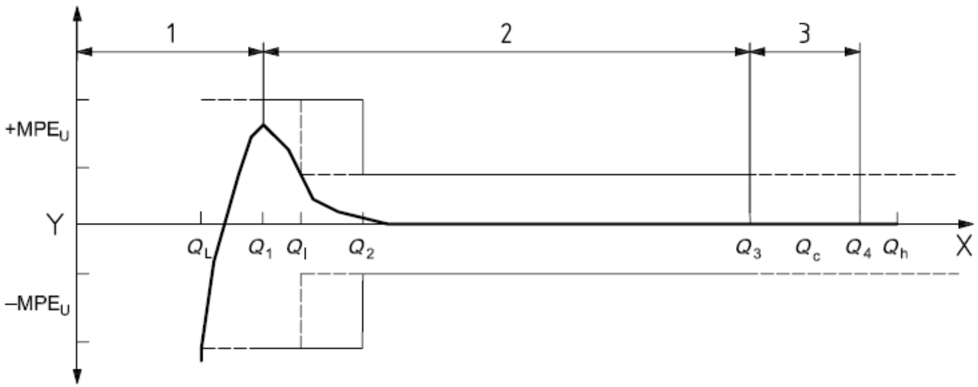


Pros:
- Low cost to implement
- Accurate zero flow detection
- Works with all clean liquids

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

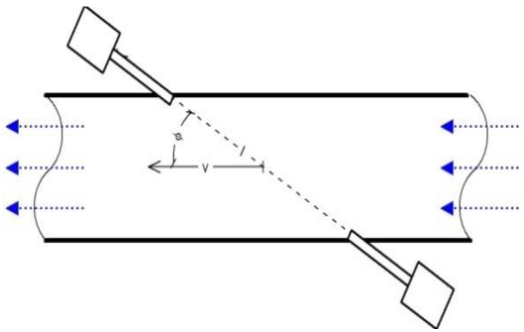


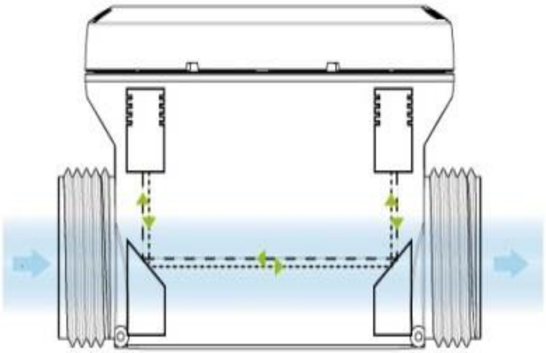
The flow rate	MPE Requirement
Q_1	< 5%
Q_2, Q_3, Q_4	< 2 % for water temperature < 30º
	< 3% for water temperature > 30º

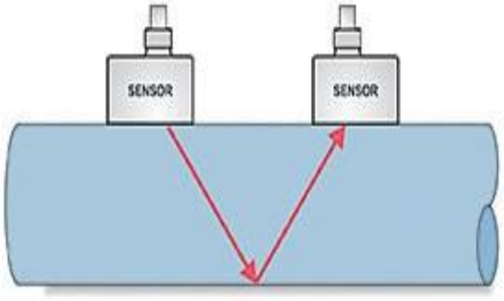
` dia (mm)	15	20	25	30	40
Q1 (L/H)	15	25	35	60	100
velocity_Q1 (m/s)	0.023569	0.022096	0.019798	0.023569	0.022096
Differential TOF *T12- T21* (transducer separation = 6 cm, 25 deg C, Ultrasound vel = 1400 m/s) (ns) (flow rate *Q1)*	1.443	1.352816	1.212122	1.443	1.352816
Accuracy requirement (ps)	72.15000002	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







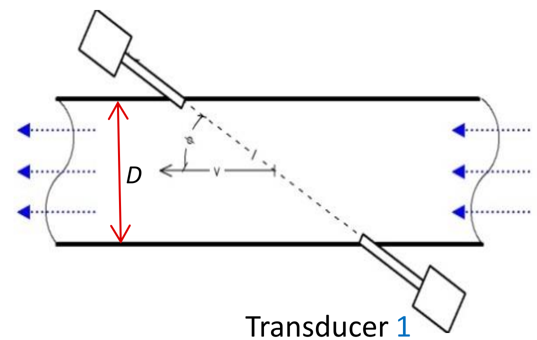
Diagonal

Reflective

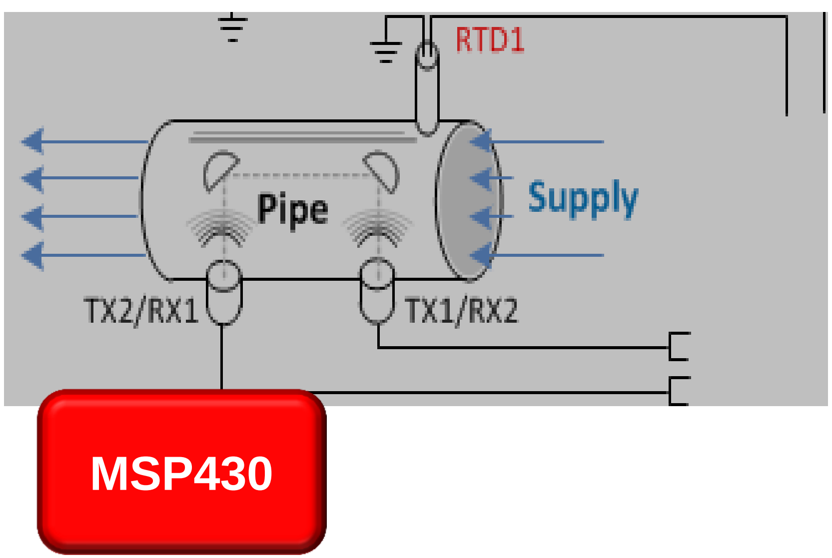
Non-Invasive

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



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

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

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

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:

$$Q = \frac{\pi D^2}{4}\frac{L}{2\cos\phi}\left(\frac{\Delta T}{T_{21}T_{12}}\right)$$

$$= \frac{\pi D^3}{4\sin(2\phi)}\left(\frac{\Delta T}{T_{21}T_{12}}\right)$$

Area — 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)

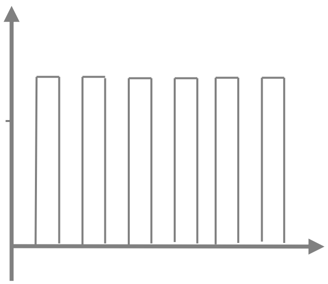
- Temperature and Pressure are constant within few ms of measurements
- Medium density, velocity of sound do not impact measurement

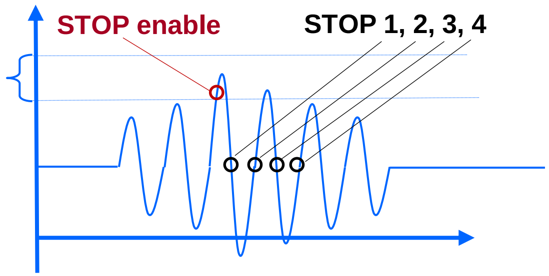
ADC-Based Technique

www.ti.com/product/MSP430FR6047

Techniques for differential TOF estimation

<u>1) Zero crossing detection:</u> detect arrivals of upstream $r_1(t)$ and downstream $r_2(t)$ signals & estimate ΔT (Time of flight difference) *based on averaging of zero crossings*.





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

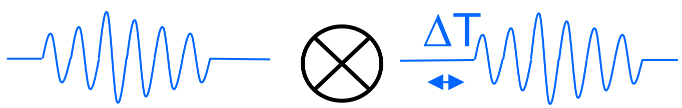
$$r_2(i) = s_2(i) + n_2(i)$$

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

a is the amplitude difference up/downstream - *Ideally a* ≈ 1

2) ADC based Algorithm: Cross-correlation Method for ΔT estimation:

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



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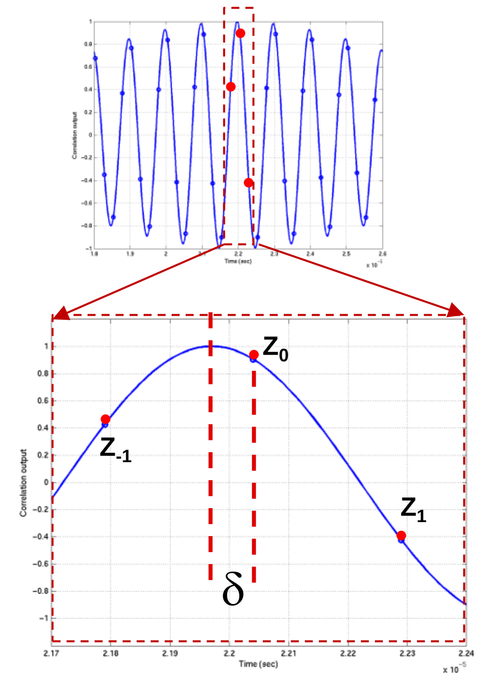
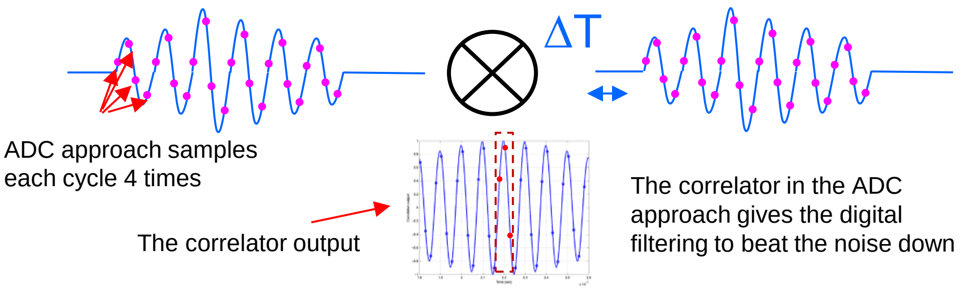


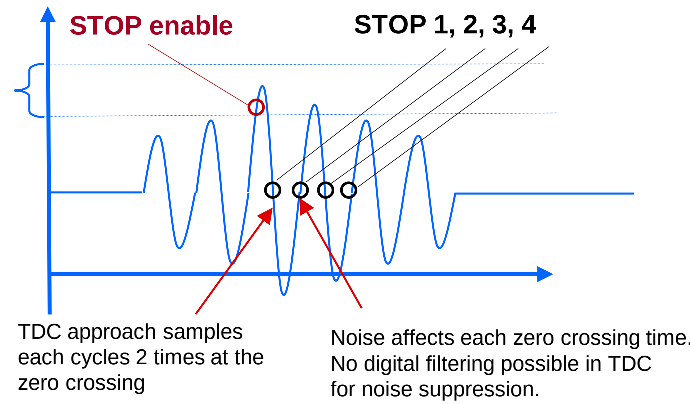
$$corr(k) = \sum_{i=1}^{N-k} r_1(i+k) r_2(i) \qquad Z_n = corr(\hat{k} - n) \qquad n = (-1, 0, 1)$$

b) Interpolate time offset for maximized correlation at 3 points

Features of ADC based processing

- Fundamental Difference : **Signal processing**





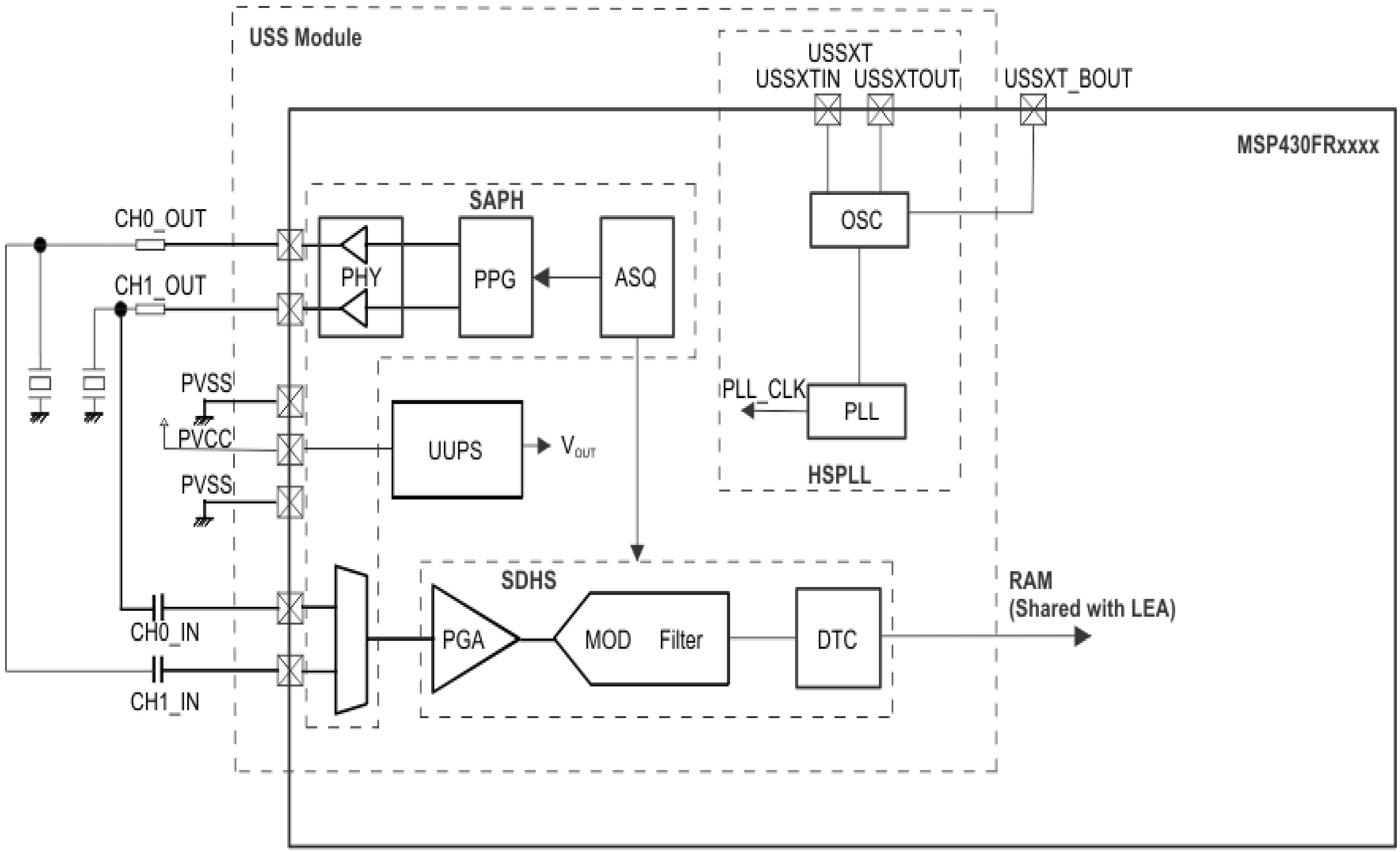
- **Performance**
  - Best in class Zero flow drift across temperature and enables low flow detection (<1L/h)
  - The correlation acts as digital filter to suppress noise
    - Benefit of ~3-4X noise lower standard deviation. Can also suppress other interference like line noise etc.
  - Allows use of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

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)

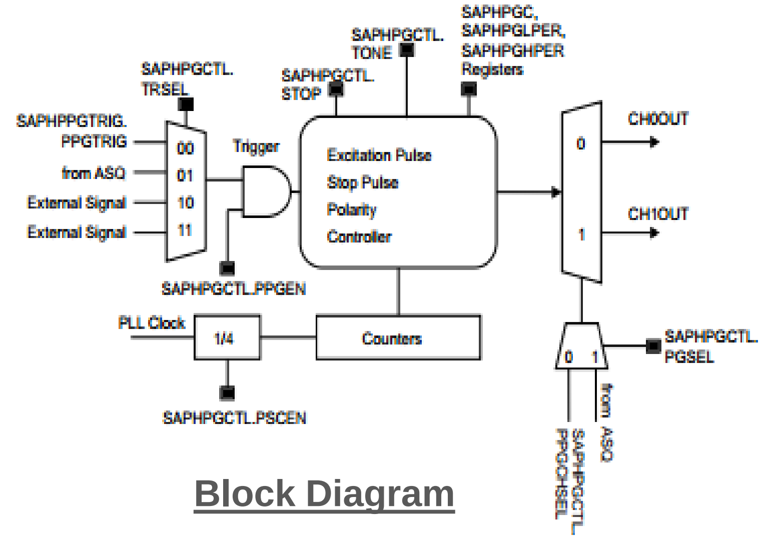
- Resolution is dependent on the nominal transducer frequency & HSPLL frequency

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

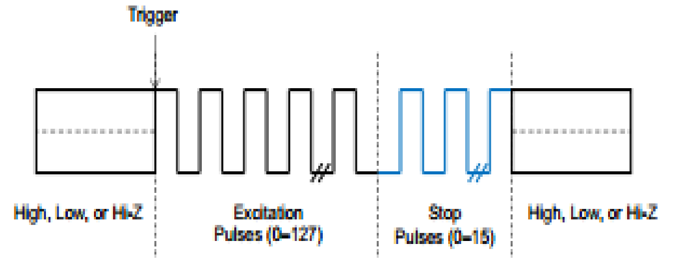
HPER : High period of pulse

LPER : Low period of pulse

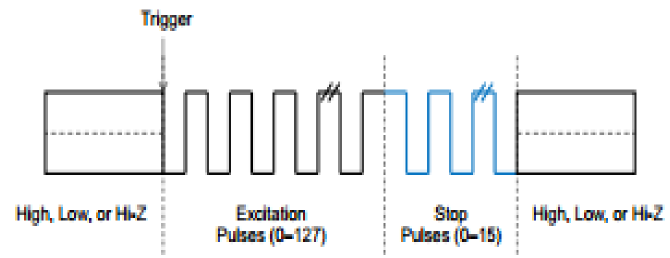
- Examples:
  - For 1 MHz pulses with 80 MHz PLL, ΔF ~ 13 kHz
  - For 2 MHz pulses with 80 MHz PLL, ΔF ~ 51 kHz



Block Diagram



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

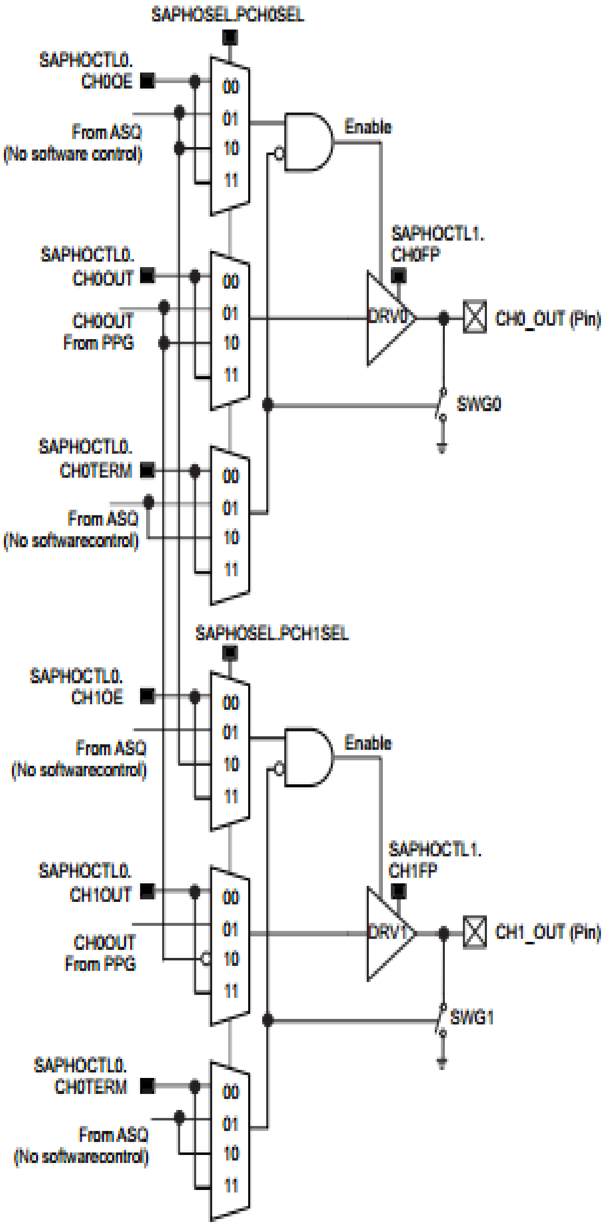


PPG Outputs With SAPHPGC.PPOL = 1 (Starts With Low Polarity)

Texas Instruments

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
  - <=4 Ω (Typ), 120 mA (Typ) x 2
- Operating voltage range 2.2V – 3.6V



12-bit 8MSPS ADC

PGA

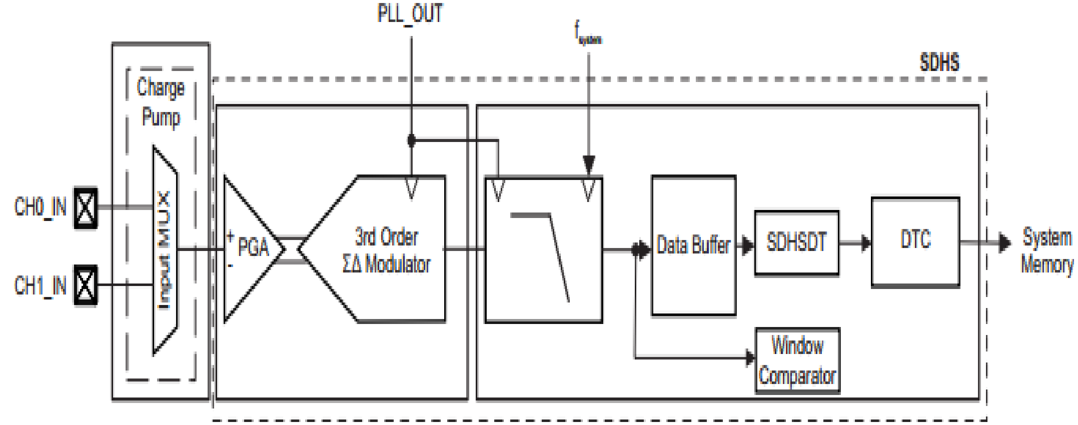
- Input Voltage: 35mV ~ 760mV (<2.5V)
- Input Voltage: 35mV ~ 1000mV (>=2.5V)
- Gain: -6 ~ 19dB with ~1dB step

SDHS (Sigma Delta High Speed ADC)

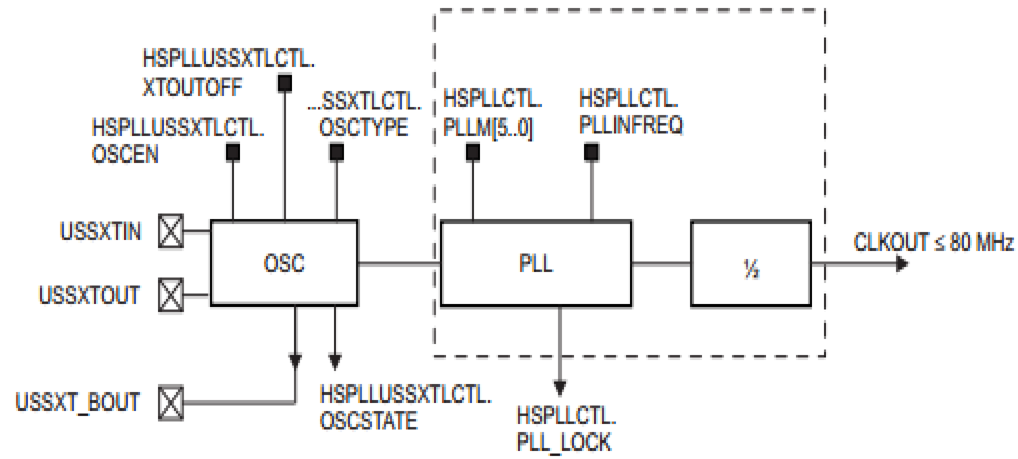
- 12 bit , SNR – 63dB (typ) upto 1.5MHz BW
- Input Voltage max. 600mVpp
- Modulator Frequency: 68MHz ~ 80 MHz
- Output Data Rate: up to 8MSPS
- OSR Ratio: 10, 20, 40, 80, 160
- Stand alone mode

HSPLL (High Speed PLL)

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



SDHS Block Diagram



HSPLL Block Diagram

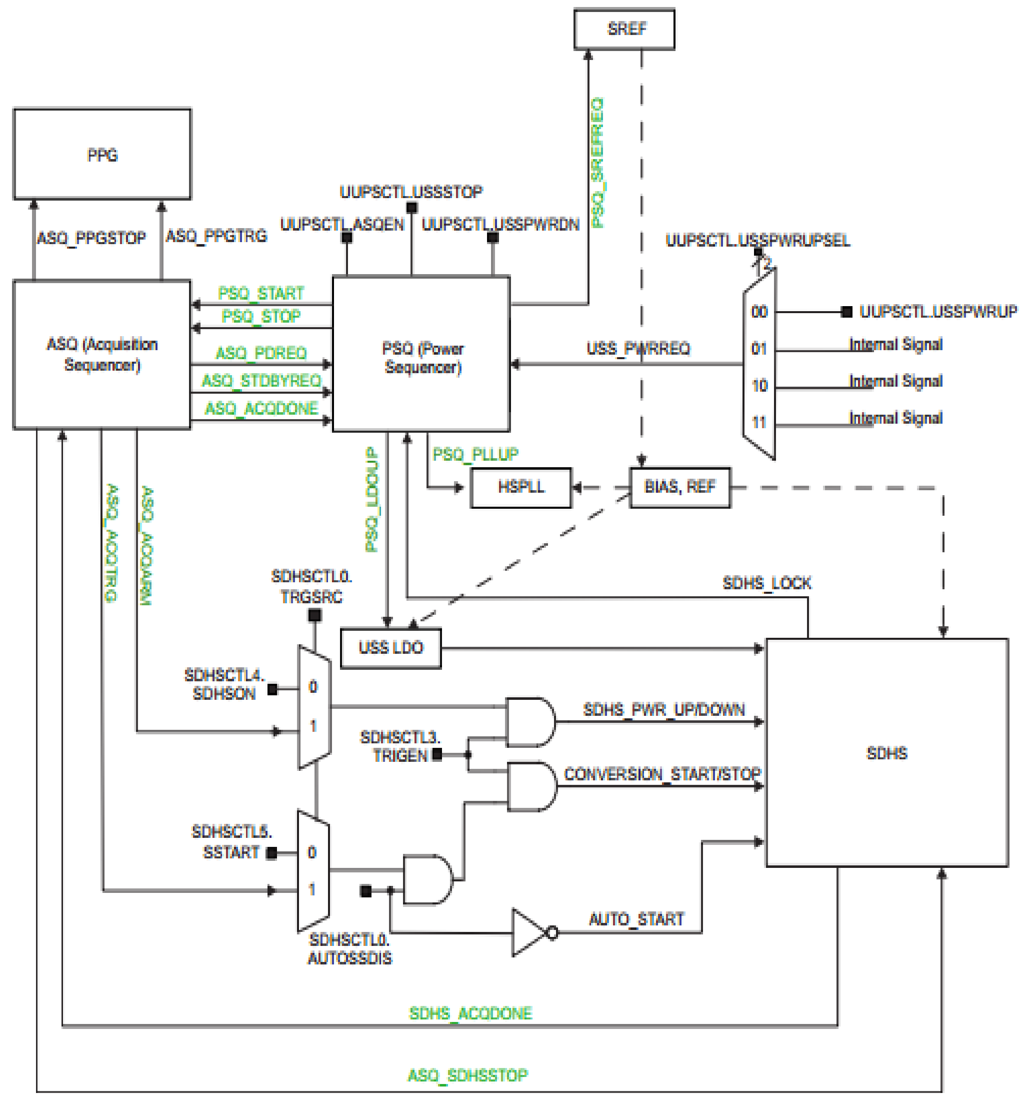
USS IP Block Diagram II (Control Path)

PSQ (Power SeQuencer)

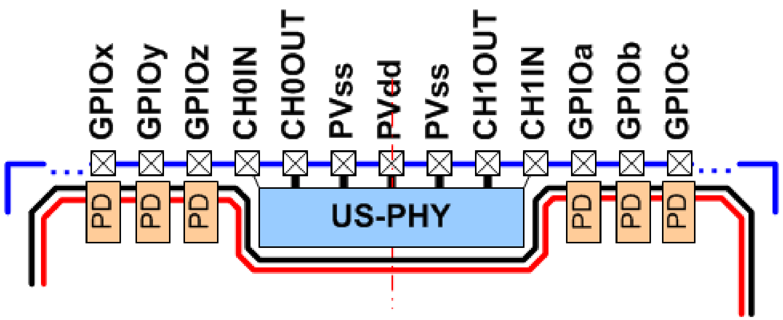
- Detect “Start” signal
- Control Power Up/Down Sequence
- Detect Debug Mode

ASQ (Acquisition SeQuencer)

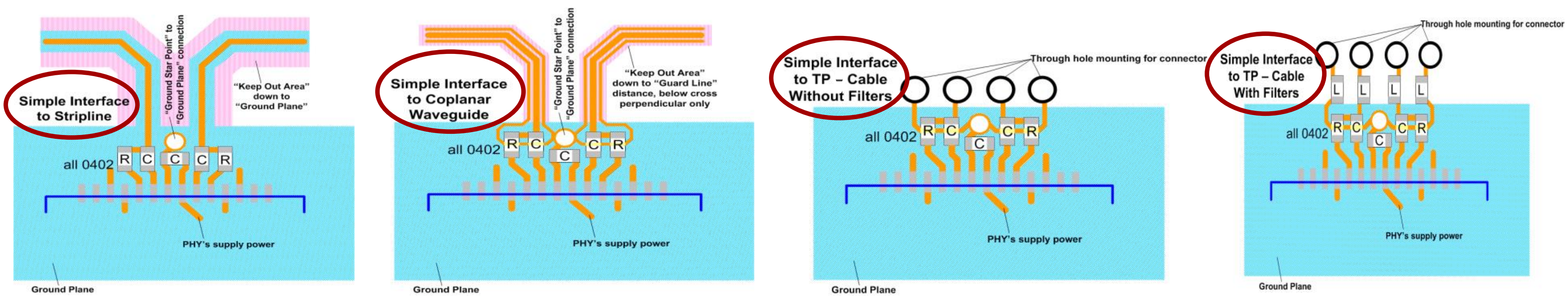
- Control measurement sequence
- Start/Stop PPG & SDHS
- Programmable events



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

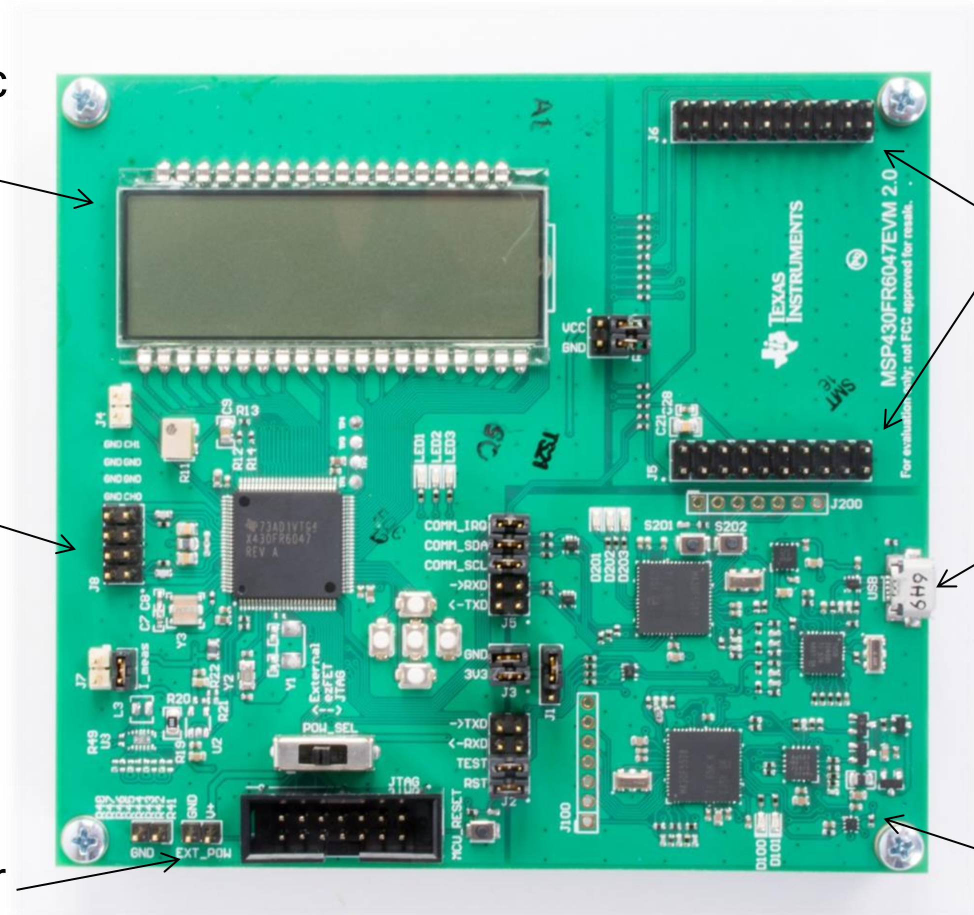
www.ti.com/tool/EVM430-FR6047

EVM430-FR6047 Key Components

Alphanumeric LCD

Transducer Connectors

External Power



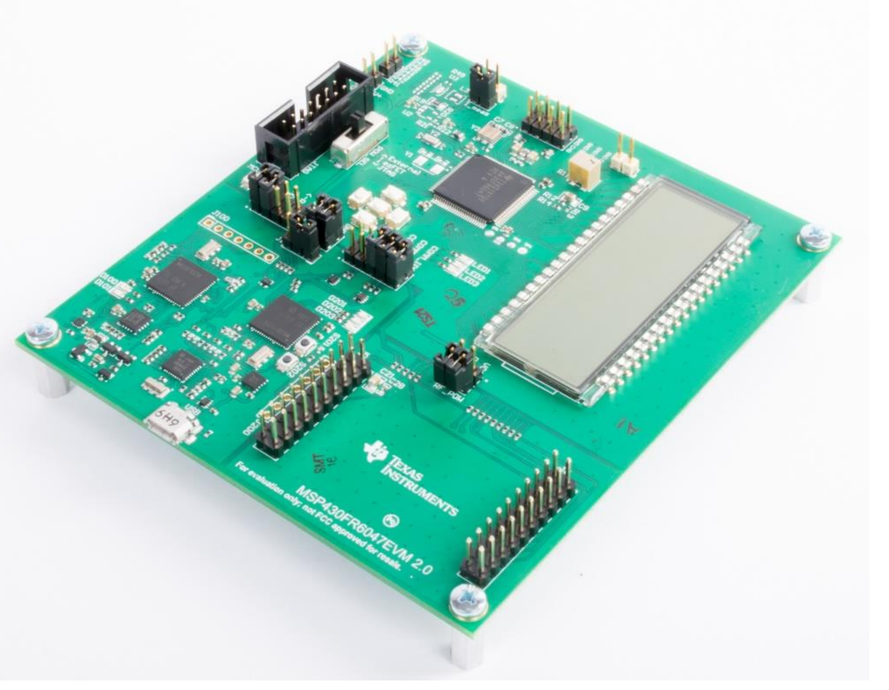
BoosterPack Connectors

USB Interface

eZ-FET emulation circuit

EVM430-FR6047 Features

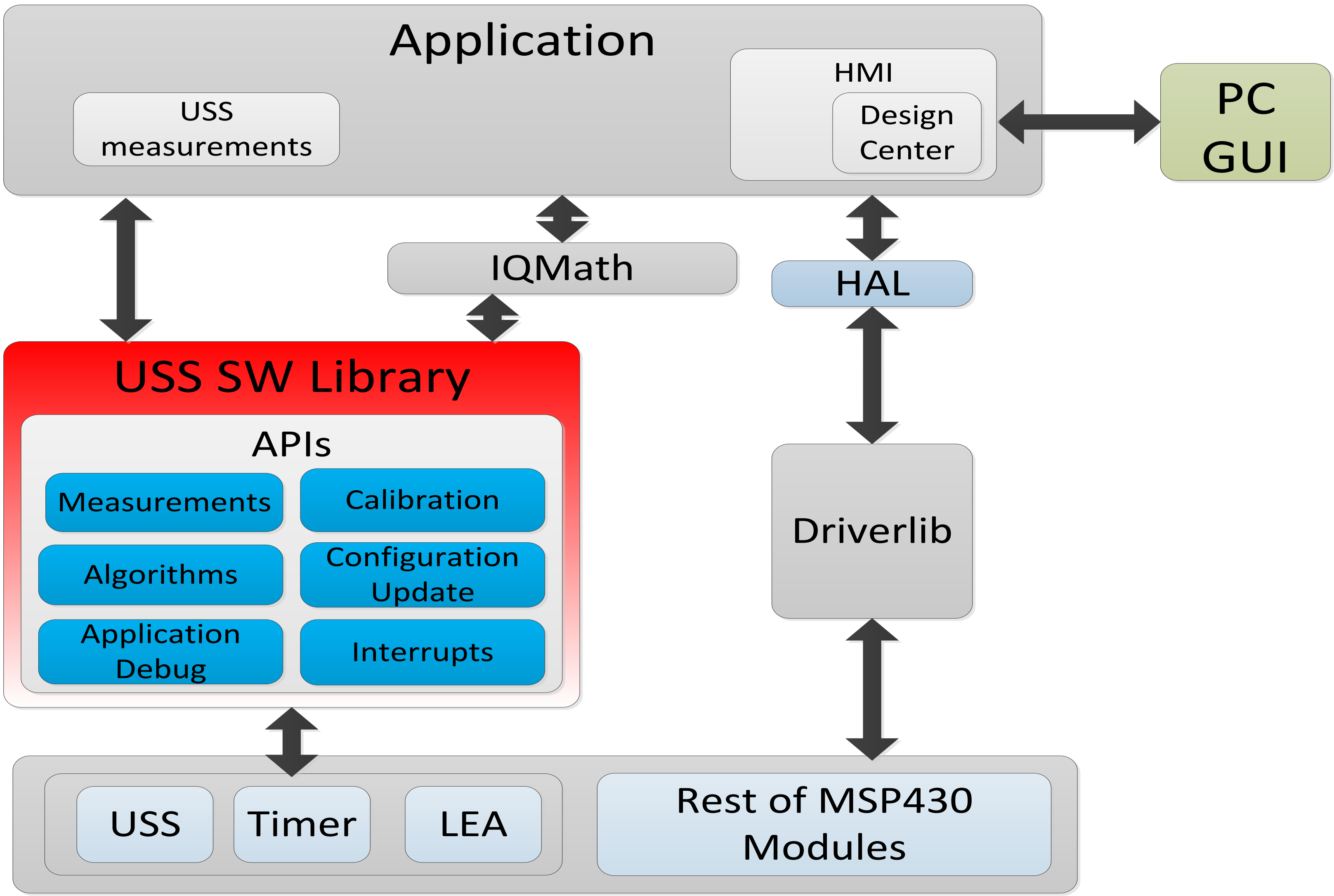
- External/USB Power Options
- On-board eZ-FET for programming/debug
- Header available to measure current consumption
- USB HID interface to PC GUI
- Alphanumeric LCD for stand-alone operation
- Two transducers can be connected
- Booster-Pack Connectors for additional functionality such as RF
- Compatible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



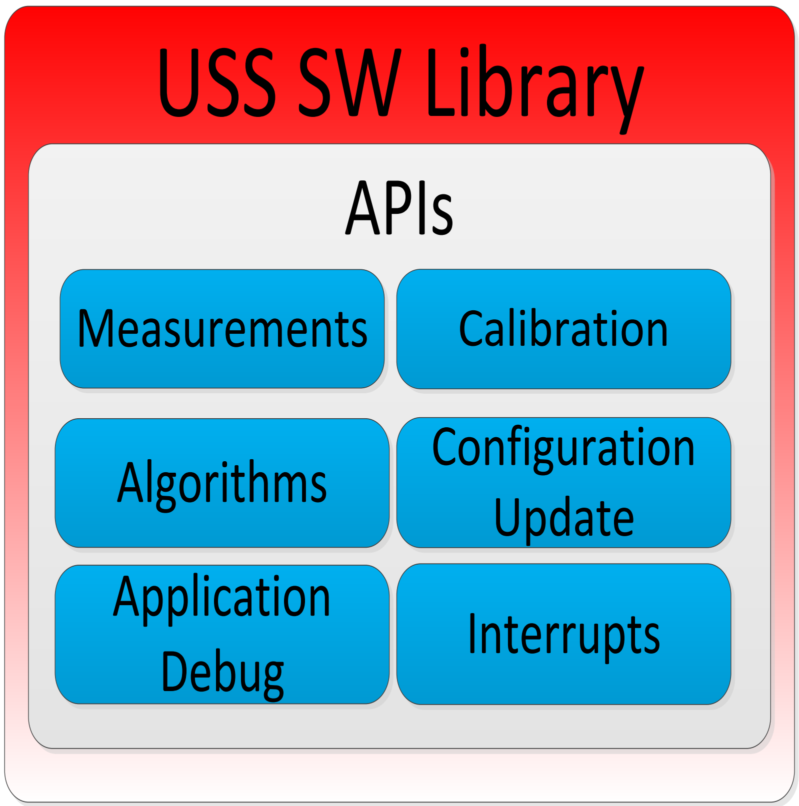
Application Software and USS SW Library

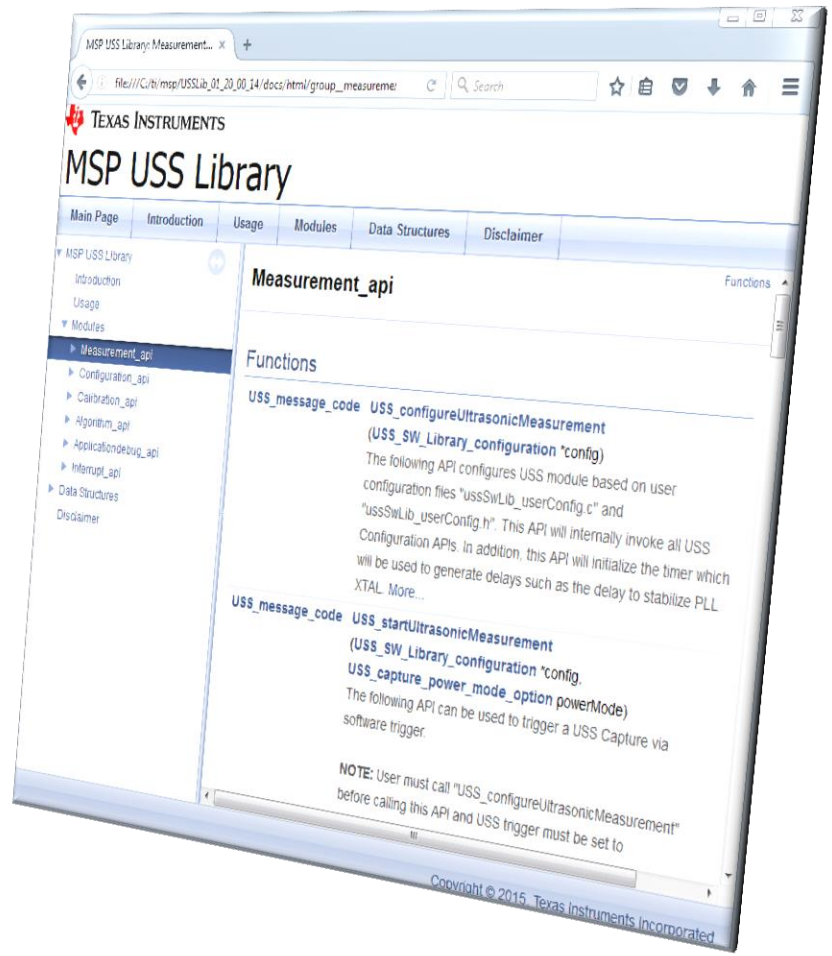
www.ti.com/tool/MSP-USSSWLIB

Software Architecture – Ultrasonic Application



Ultrasonic Software Library





Ultrasonic Software Library - Implementation

USS_userConfig.c

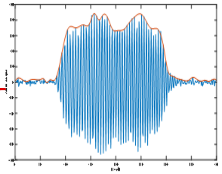
```
USS_SW_Library_configuration
    .systemConfig
    .meterConfig
    .measurementConfig
    .pllConfiguration
    .captureConfig
    .triggerConfig
    .algorithmsConfig
    .interruptConfig
```

Application

```
USS_configureUltrasonicMeasurement
USS_initAlgorithms
```

Application

```
USS_startUltrasonicMeasurement
```



Application

```
USS_runAlgorithms
```

AbsTOF
dTOF
Flow Rate

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

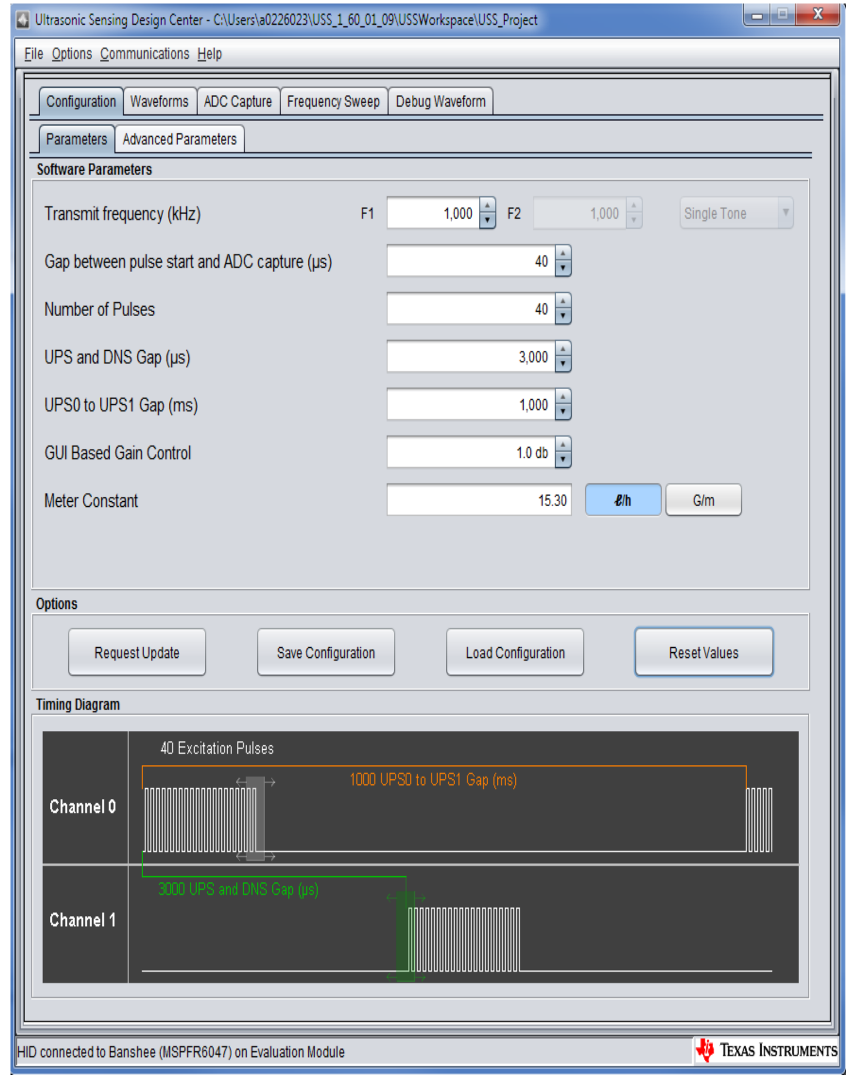
Ultrasonic Design Center GUI

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:

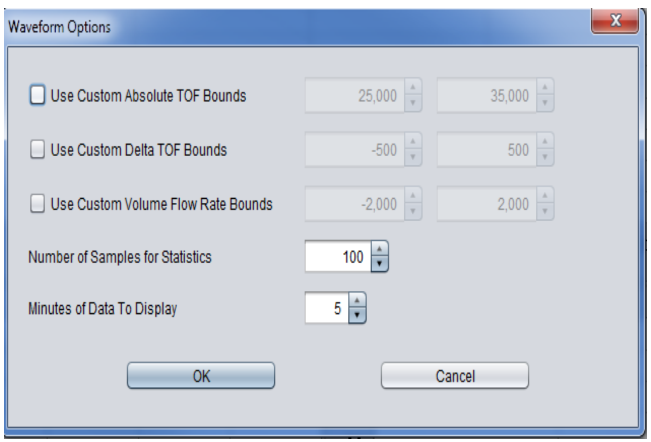
- The excitation frequency of the ultrasonic pulse (F1)
- Number of excitation pulses
- Gap between pulses (UPS0 – UPS1 Gap)
- ADC Sampling Frequency
- USS crystal settling time
- … Much more

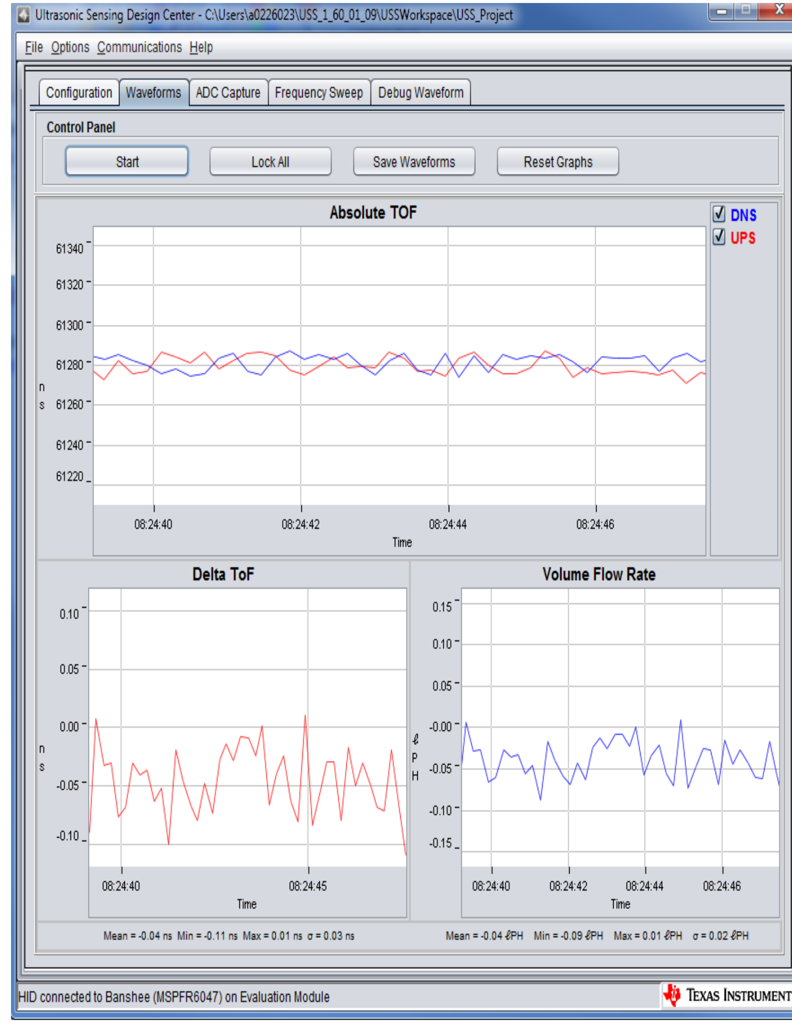


Ultrasonic Design Center GUI

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 though a ‘Waveforms Options’ pop-up window.



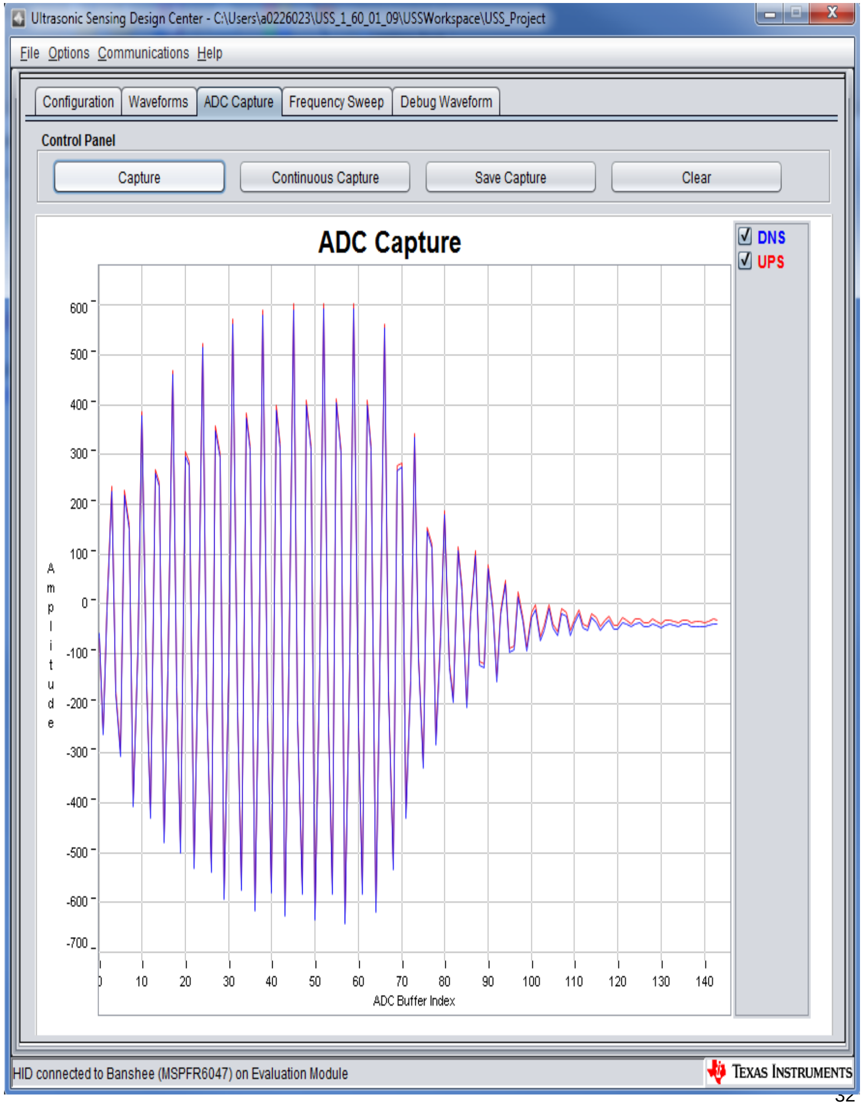


http://www.ti.com/tool/msp-ultrasonic-design-center

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.



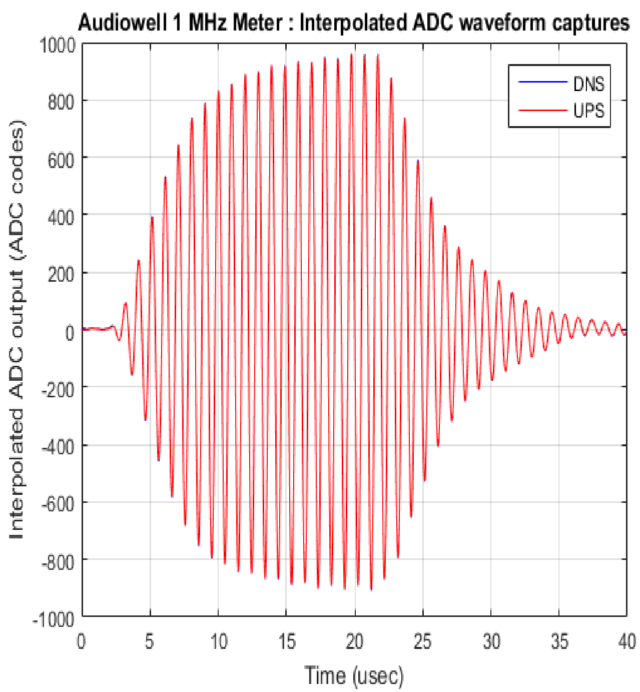
EVM430-FR6047 Test Results

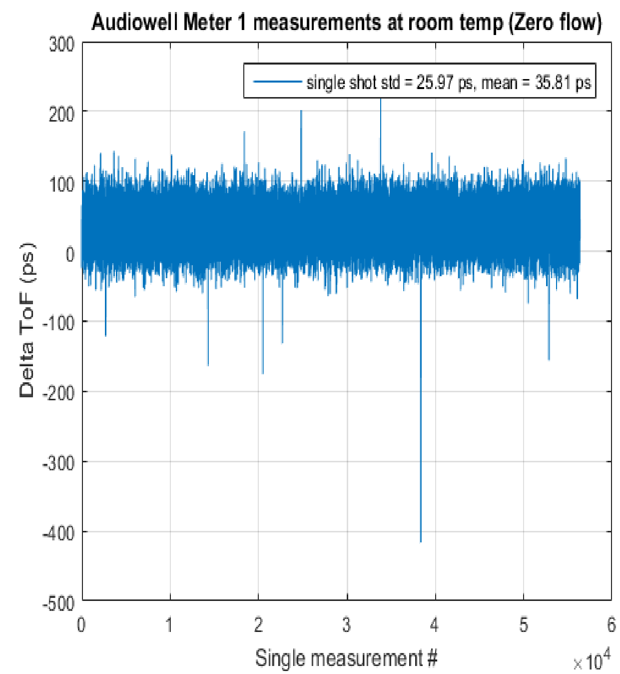
www.ti.com/tool/EVM430-FR6047

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

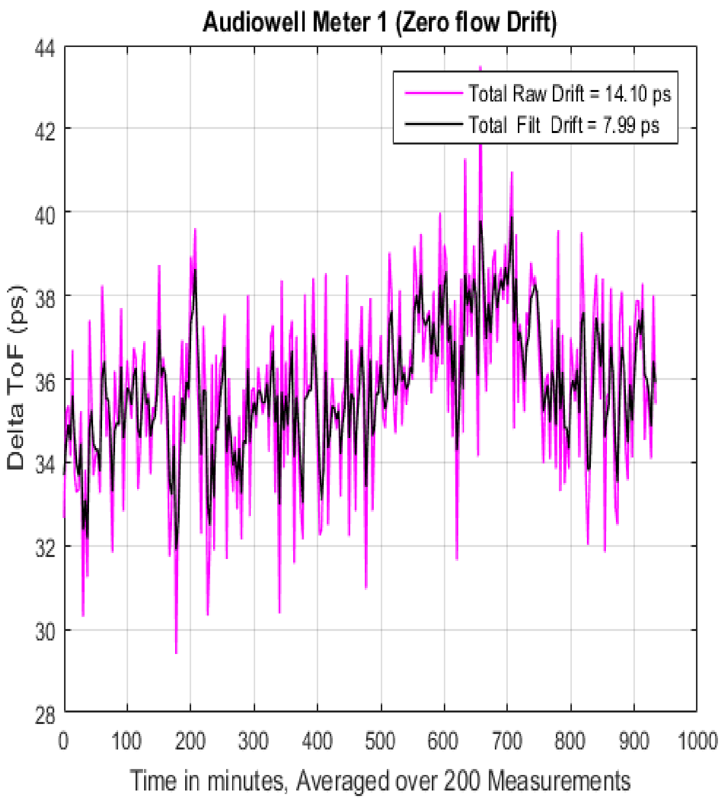


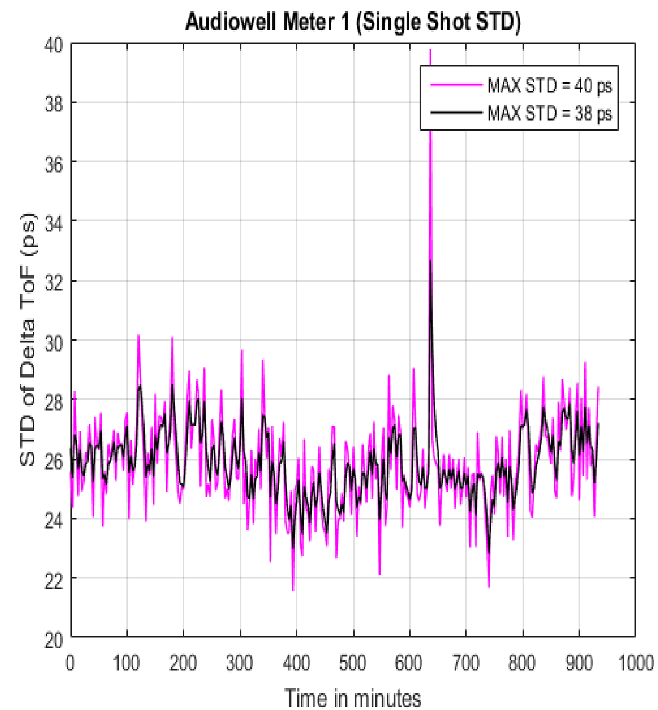


Zero Flow Drift: Room Temp (Overnight)

- Overnight Room Temp ZFD Test
  - Measurement Rate: 1 Hz

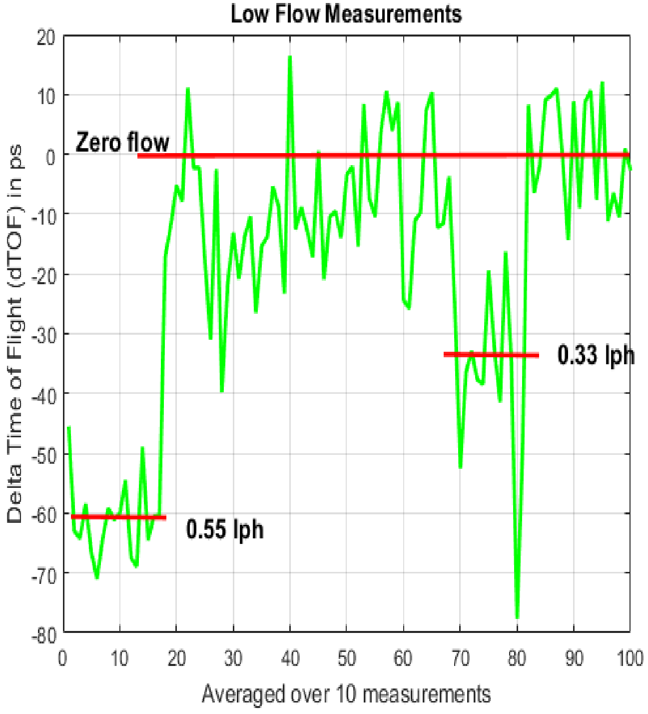
- Zero Flow Drift (ZFD): **8 ps** (15 ½ hours run) (32ps : 40ps)
- Single shot standard deviation (STD): 26 ps

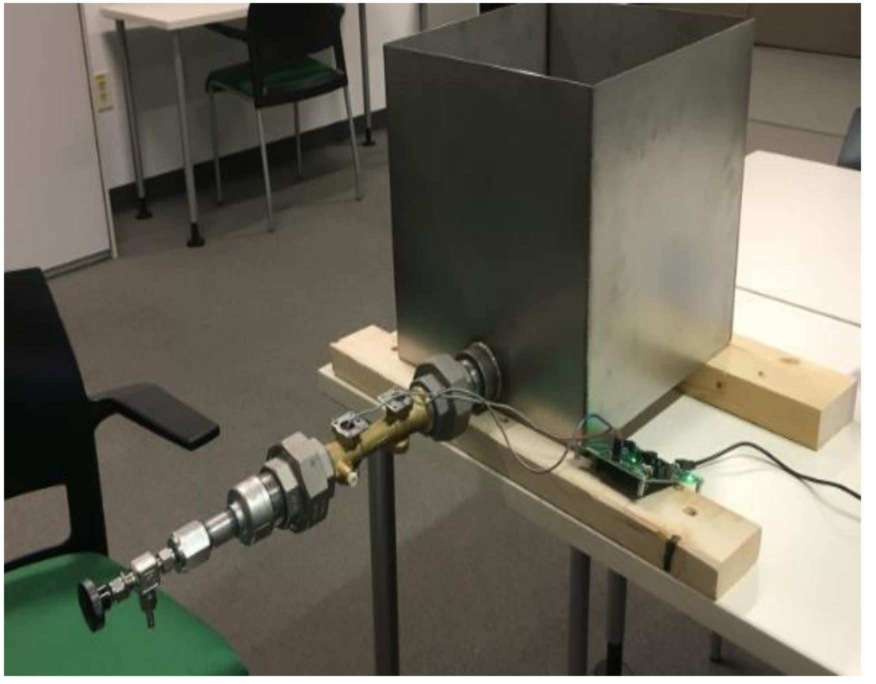




Low Flow Detection

- Setup allows for testing very low flow rates:
  - < 1 drop / sec
  - Equivalent to < 0.2 lph
- Test results for <1L/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[1]
Min. Timing Resolution	5 ps
Average current consumption @ 1Hz	4.29 µA[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 S/W & GUI

Software

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

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

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