User's Guide
SNIA020–March 2015

Interfacing a Water Flow-meter Sensor to TDC1000-TDC7200EVM

Ultrasonic flow-meters are gaining wide usage in commercial, industrial and medical applications. Major benefits of utilizing this type of flow meter are higher accuracy, low maintenance (no moving parts), non-invasive flow measurement, and the ability to diagnose the meter's health regularly. A major advantage of using TI's ultrasonic sensing is the ultra-low power consumption, which allows metering companies to use the same battery for a very long time.

This article is intended as an introduction to ultrasonic flow sensing and describes a demonstration setup to measure velocity of flow in a pipe using an ultrasonic water flow-meter sensor, the TDC1000 ultrasonic analog-front-end (UAFE), and TDC7200 precision time interval timer.

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1 Background: Transient-time Ultrasonic Flow-meters

In Figure 1, a typical ultrasonic flow sensor is shown. The sensor consist of a pipe with nominal diameter of “D” and two piezoelectric transducers placed at fixed distance “L” from each other. The transducers are mounted in a protective housing. The housing and the transducers are inserted in the holes in the pipe, exposing the inner cover to the fluid in the pipe. Two reflection mirrors in the pipe direct the ultrasonic signals from one transducer to the other one in the opposite location.

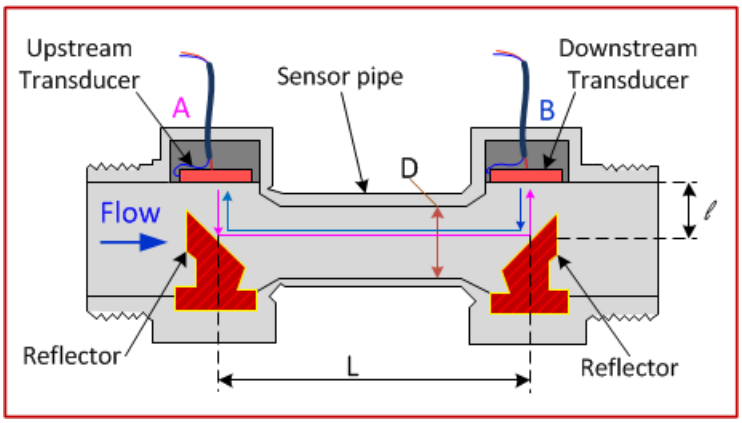


Figure 1. Ultrasonic Water Flow-meter Pipe

The single path sensor of Figure 1 is used for flow applications where the diameter of the pipe is small. For larger diameter pipes, sensors with multiple paths are used. Other types of ultrasonic flow sensors are available with clamped-on transducers. In this article, the discussion will be limited to reflective-type single path sensors such as the one shown in Figure 1.

2 Measurement Sequence

Referring to Figure 2, the measurement sequence starts by exciting one of the transducers, “A”, by applying a burst of given number of pulses (in Figure 2, three TX pulses) to the transducer. The frequency of excitation signal must be equal to the resonance frequency of the transducer. For water flow applications, transducers with resonant frequency of one to three MHz are used.

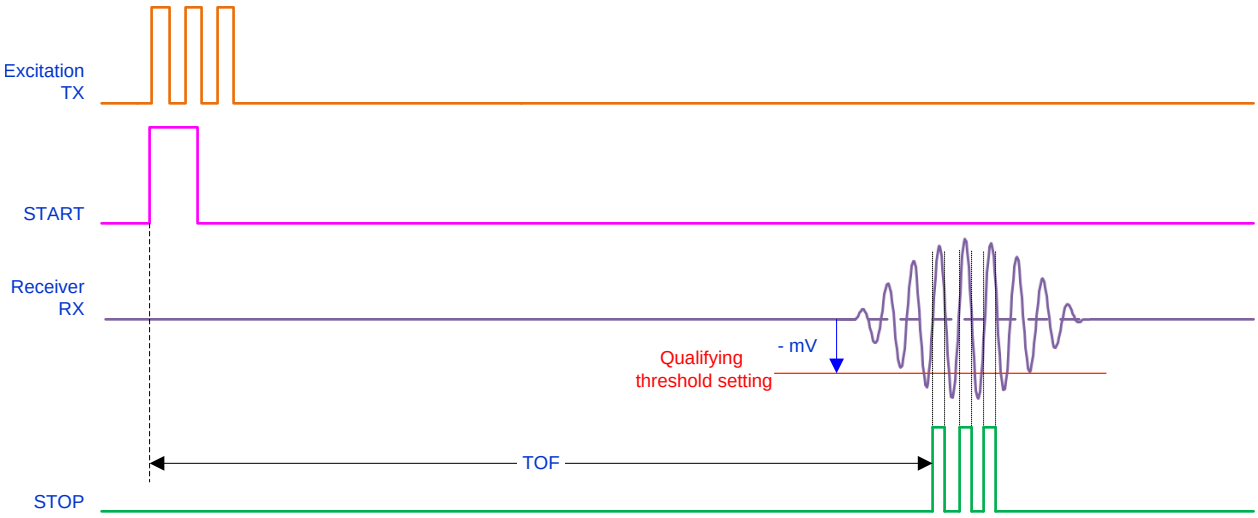


Figure 2. Ultrasonic Signal Measurement Sequence.

The transducer generates ultrasonic pressure pulses that are directed towards the second transducer, in this case B, by means of the reflectors in the pipe. At the same time that the first pulse is being applied to the transducer, a “START” signal is generated to mark the beginning of the “time-of-flight” measurement.

On the receiver side, the electronic circuits in the path condition the received signal and generate a "STOP" pulse to mark the time the ultrasonic pulse is received at the other end. The time taken for the ultrasound wave to travel from one sensor to the other is referred as the "Time-Of-Flight" (TOF). A stop watch is needed to measure the time internal between the "START" and "STOP", in this case $TOF_{AB.}$

The direction of the transmit/receive sequence is switched and next the TOF_{BA} is measured. The difference between TOF_{AB} and TOF_{BA} is proportional to the velocity of the flow of the medium in the pipe.

3 Volumetric Flow Calculations

The expressions for calculating the TOF between two transducers is given as:

$$TOF = \frac{\text{distance between the transducers}}{\text{speed of sound}} \quad (1)$$

Referring to Figure 1 , the expressions for TOF for downstream (TOF_{AB}) and upstream (TOF_{BA}) are:

$$TOF_{AB} = \frac{1}{C}\ell + \frac{L}{C+V} + \frac{1}{C}\ell \quad (2)$$

$$TOF_{BA} = \frac{1}{C}\ell + \frac{L}{C-V} + \frac{1}{C}\ell$$

where

- ℓ = D/2: D is the inner diameter of the pipe
- C = Speed of sound in the medium
- V = Average Velocity of the medium (fluid/gas) in the pipe (3)

Rearranging the terms and solving for V:

$$\Delta TOF = \left(\frac{D}{C} + \frac{L}{C-V}\right) - \left(\frac{D}{C} + \frac{L}{C+V}\right)$$

$$= \frac{L2}{C-V} - \frac{L2}{C+V}$$

$$= \frac{(C+V)L - (C-V)L}{C^2 - V^2} \quad (4)$$

$$\Delta T\ (C^2 - V^2) = 2 * L * V \quad (5)$$

Since C >> V:

$$(C^2 - V^2) \sim C^2 \quad (6)$$

And:

$$\Delta T * C^2 = 2 * L * V \quad (7)$$

$$V = \frac{\Delta T * C^2}{2L} \quad (8)$$

4 Calculation of Volumetric Flow Rate, Q

The relationship for calculate the volumetric flow rate is:

The relationship for calculate the volumetric flow rate is: Q = K * V * A

where

- K = Pipe calibration factor depending on the sensor
- V = Average velocity though of the fluid in the pipe
- A = The cross-sectional area of the meter pipe (9)

TDC 1000 uses a common approach known as "zero-crossing" method to generate the "START" and "STOP". At low flow rates, the difference between TOF_{AB} and TOF_{BA} is very small, for this reason a highly accurate timer such as TDC7200 with picoseconds resolution is required.

5 Zero Flow Measurement Setup

In this document, we describe interfacing of TDC1000 and TDC7200 integrated circuits. The block diagram of the setup is shown in Figure 3. MSP430 microcontroller is used for programming of TDC1000 and TDC7200 and for communication with a host PC over USB interface. A Graphic User Interface (GUI) is used for programming the registers of TDC1000 and TDC7200 and for displaying ΔTOF at zero flow condition.

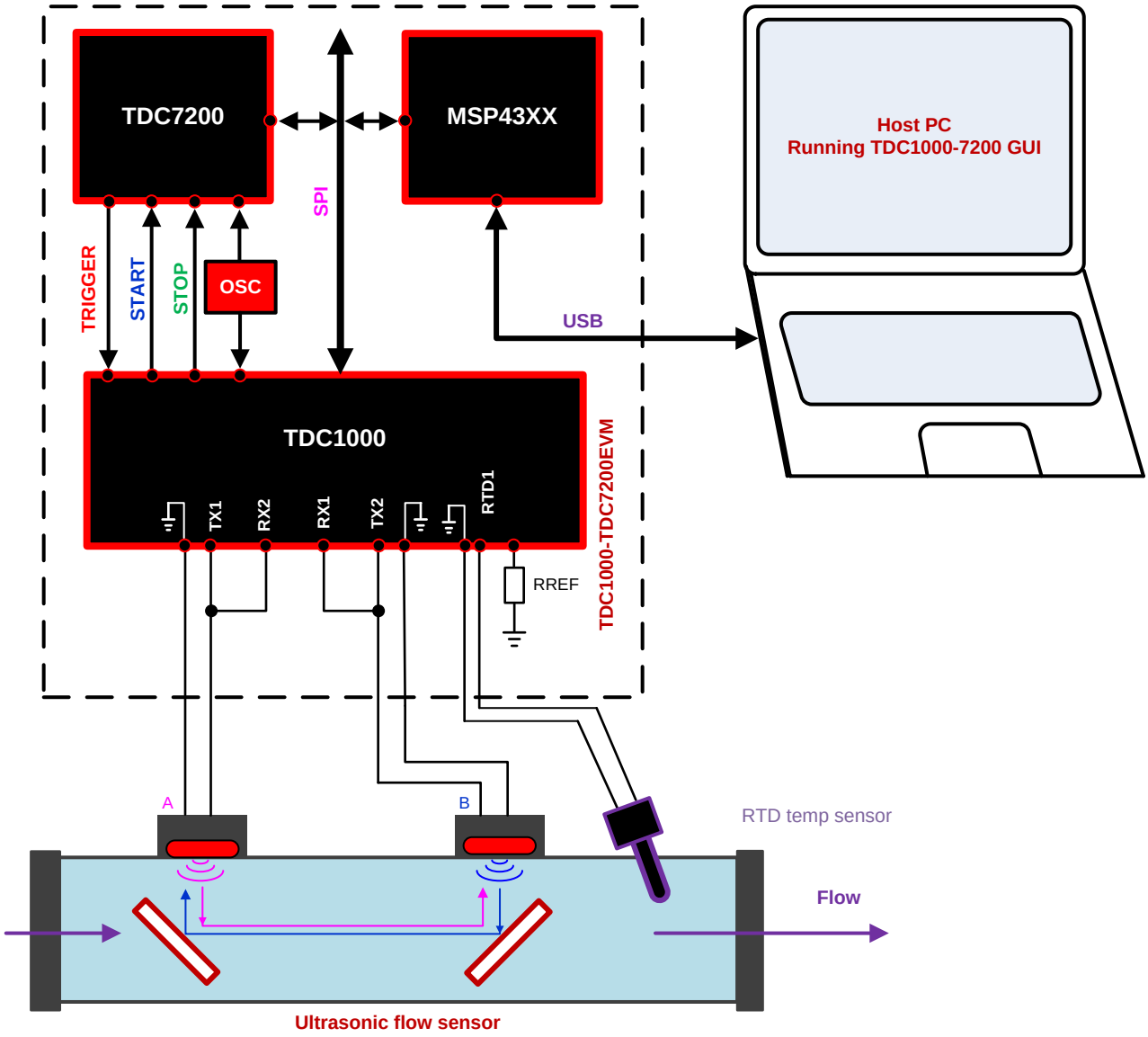


Figure 3. Zero Flow Measurement Setup

6 The Choice of the Ultrasonic Flow-meter Sensor

The zero-flow demonstration setup is shown in Figure 4.

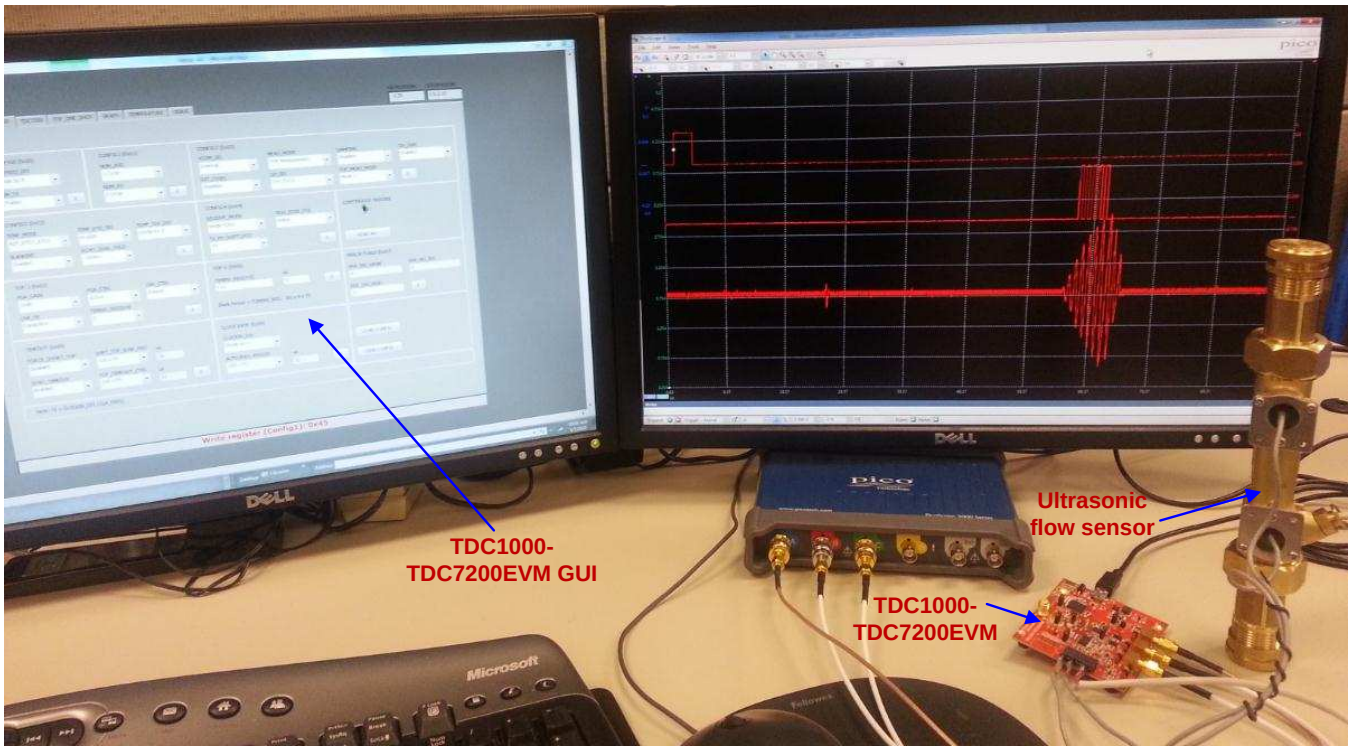


Figure 4. Zero Flow Demonstration Setup

System requirements, standards, and cost dictate the choice of flow-meter sensors. Water is a good medium for propagating ultrasonic pressure pulse and the most common sensors in this application have resonance frequency in the range of MHz, 1 MHz in this case.

For demonstration purposes, we use an Audiowell ultrasonic water flow-meter pipe shown in Figure 5. This sensor can be obtained from the source included in the reference section.

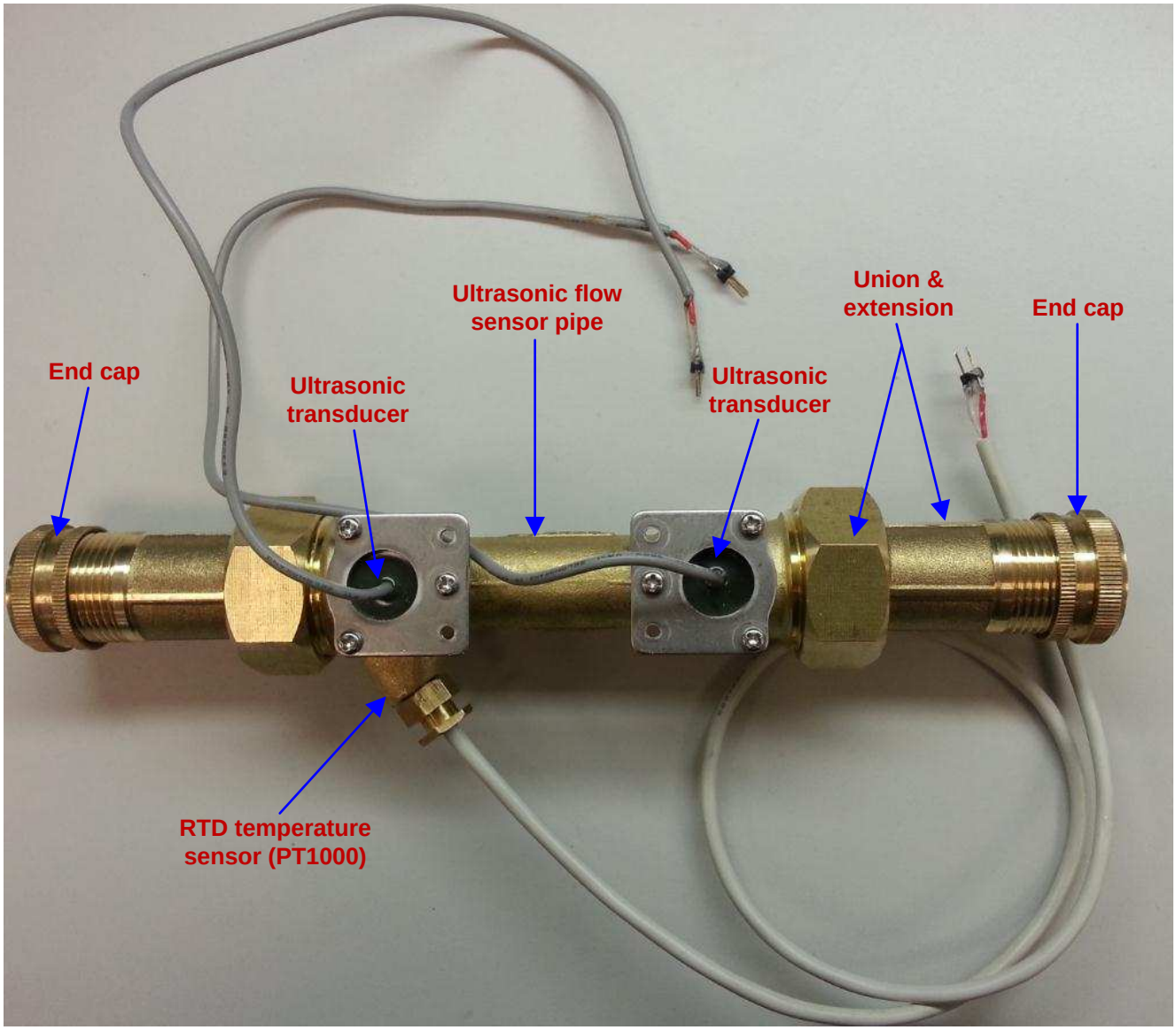


Figure 5. Ultrasonic Flow-meter Sensor Pipe

7 Steps to Configure the Setup

1. Obtain a TDC1000-TDC7200EVM
2. Obtain the ultrasonic water flow sensor shown in Figure 5 from the source in the reference section of this document (Audiowell). The union and the pipe extension are not necessary for zero flow test but you would need the end caps to confine water in the pipe for the test. The RTD temperature senor is not included in the sensor and can be obtained from a different manufacturer. The RTD used in this setup is a JUMO PT1000. If you need to use a PT500 temperature senor, you would need to change the temp sensor reference resistor (RREF) on the TDC1000-TDC7200EVM to 500 Ω (the EVM board comes with a 1000-Ω resistor reference resistor).
3. Place a cap at one end of the sensor and fill the pipe with clean water. Make sure there are no bubbles trapped in the sensor. Place the second cap and the open end of the pipe to confine water inside the pipe.
4. Connect the sensor to the EVM connector as shown in Figure 6. Place the pipe on a flat surface in a standup position as shown in Figure 4. This would move up any bubbles trapped between the two transducers to the top of the pipe and away from the signal path. Bubbles trapped in the signal path cause severe attenuation of signal.
5. You may want to view the signal waveforms (Start, Stop, and Ultrasound received waveform at the input of TDC1000 internal comparators) on a scope to make sure proper operation of the sensor. You can either connect the scope probes to the provided terminals (test points) on the EVM or solder SMA connector on the EVM board and use the cables shown in Figure 4.

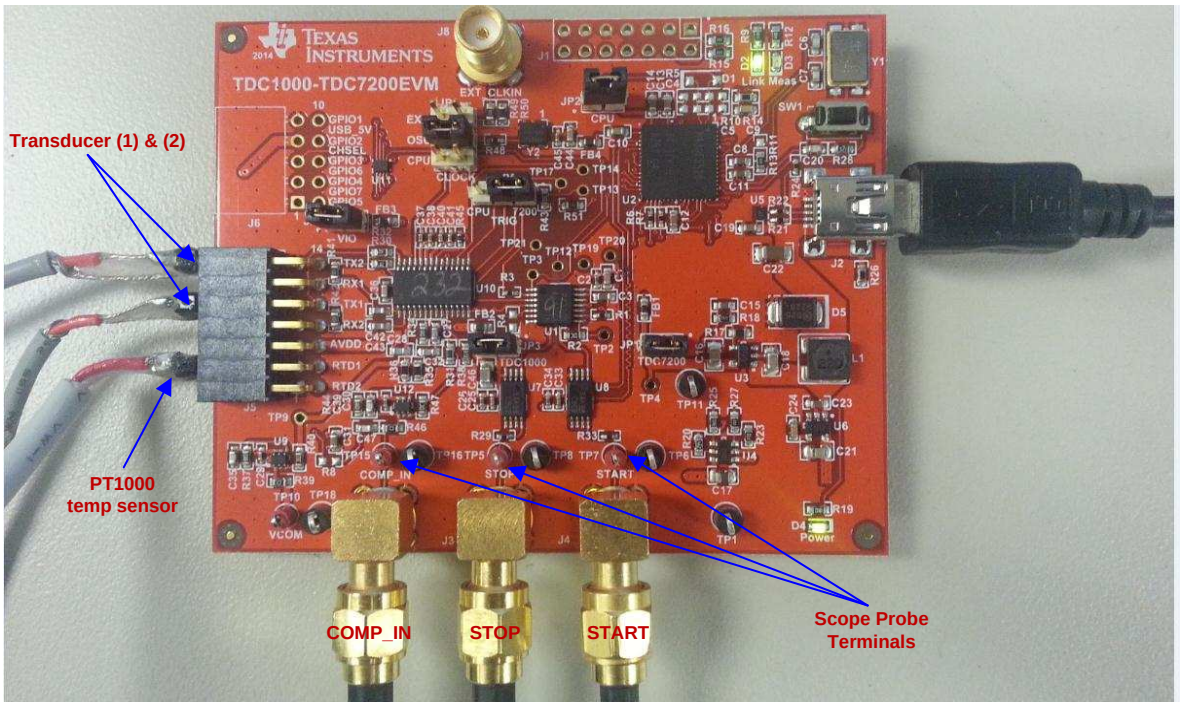


Figure 6. EVM Connections to the Sensor

6. Install the TDC1000-TDC7200EVM software per the instruction in the user's manual
7. Connect the EVM to the Host PC using the provided USB cable

8 GUI Configuration

1. Run the GUI; if prompted, upgrade the version of the EVM firmware per the instructions in the TDC1000-TDC7200EVM User's Manual.
2. Set the registers in the TDC1000 menu to the values shown in Figure 7, Figure 8, and Figure 9. Flip the "CONTINOUS TRIGGER" switch to the top position (switch will turn to green from red indicating that the system is running).

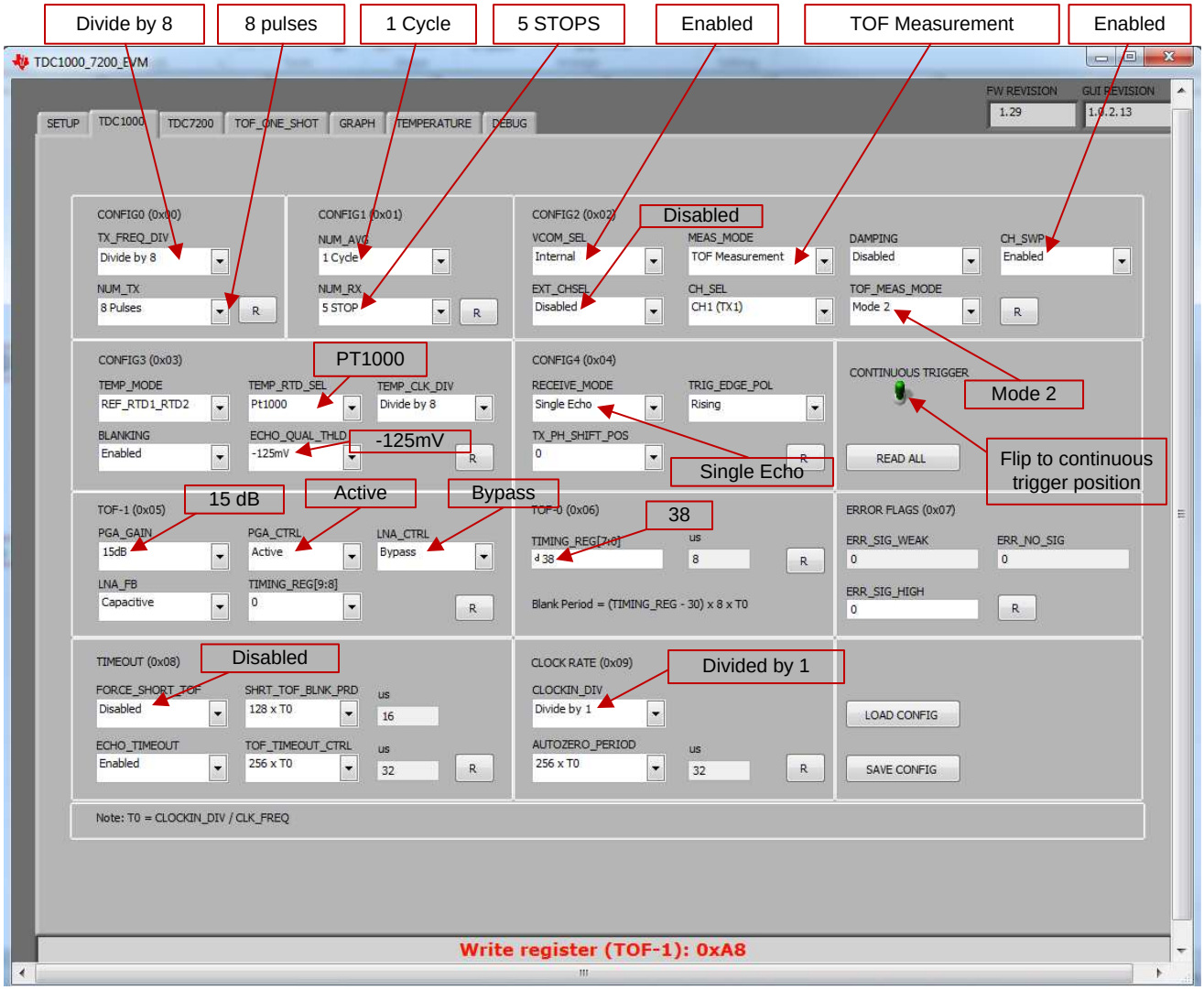


Figure 7. TDC1000 Setup Menu in the GUI

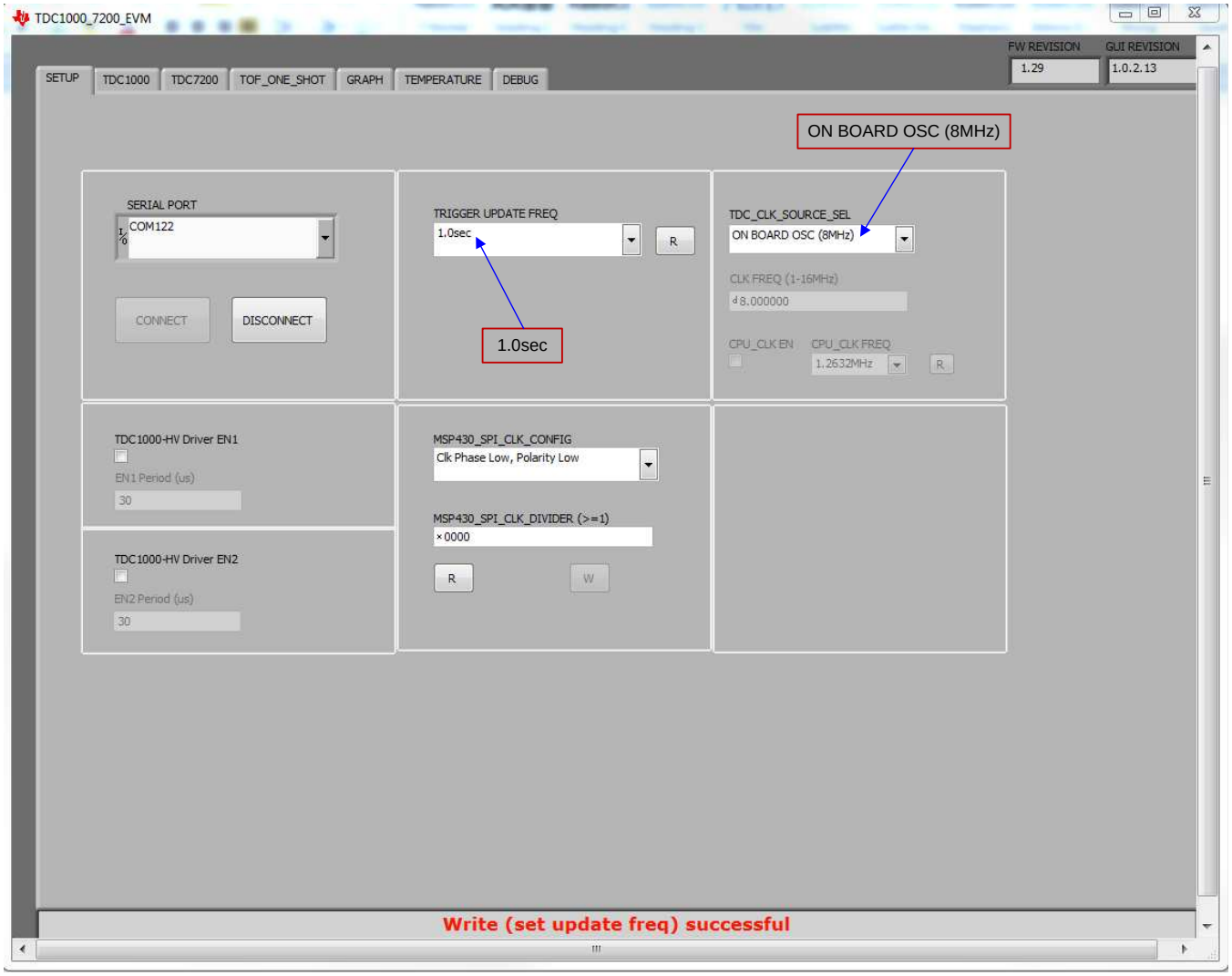


Figure 8. Sampling Interval Setup

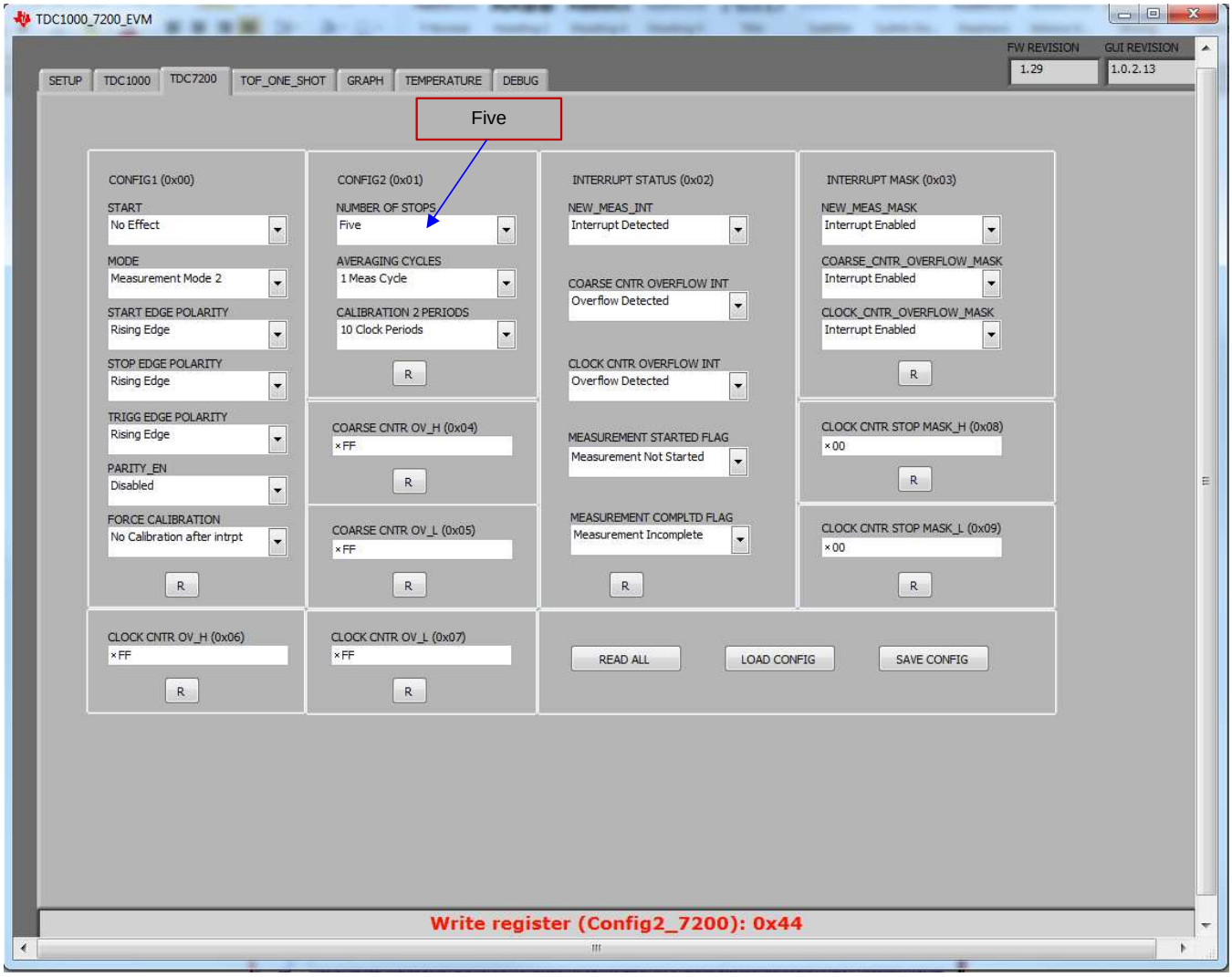


Figure 9. TDC7200 Registers Setup

9 Observing the Waveform Using an Oscilloscope

Table 1. Waveform Observations Using an Oscilloscope

CH A	START, 5 V/DIV
CHAB	STOP, 5 V/DIV
CH C	COMP_IN, 5V/DIV
Trigger	Normal, on Ch A , positive edge
Time base	20 uV/DIV

You should be able to get similar display on you scope screen as shown in Figure 10. The time of flight can be measured reference to STOP pulse one to five. When calculating the delta TOF, if the same STOP pulse is used to measure the TOF for upstream and downstream, the net effect is canceled out and the delta TOF is the same no matter what STOP pulse is used to measure The TOF.

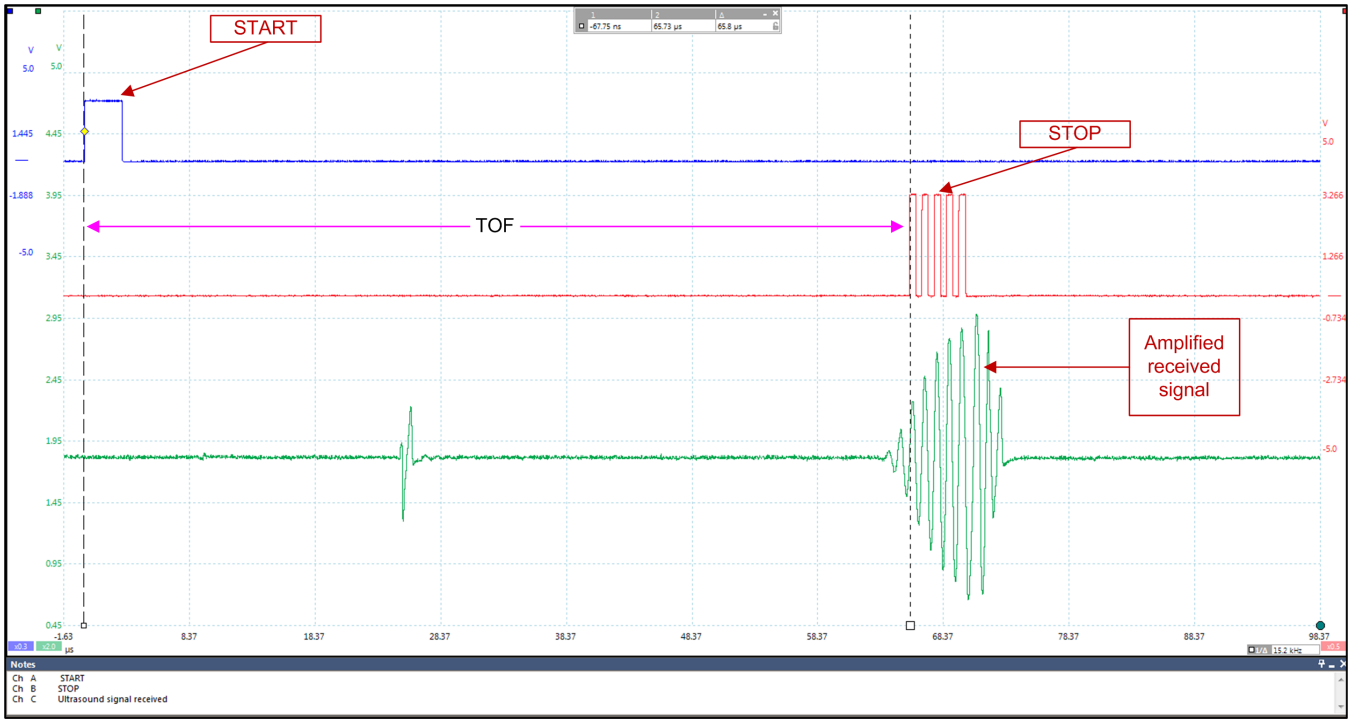


Figure 10. Scope Trace TOF Measurement Sequence

Now change the time base of the scope to 200 uV/DIV, you should see the TX/RX sequence for both directions as shown in Figure 11. In mode 2 of TDC1000 operation if CH_SWP is enabled, the state machine upon receiving a trigger pulse will TX/RX in one direction, then switch the direction. Upon receiving a second trigger, it will TX/RX in the other direction.

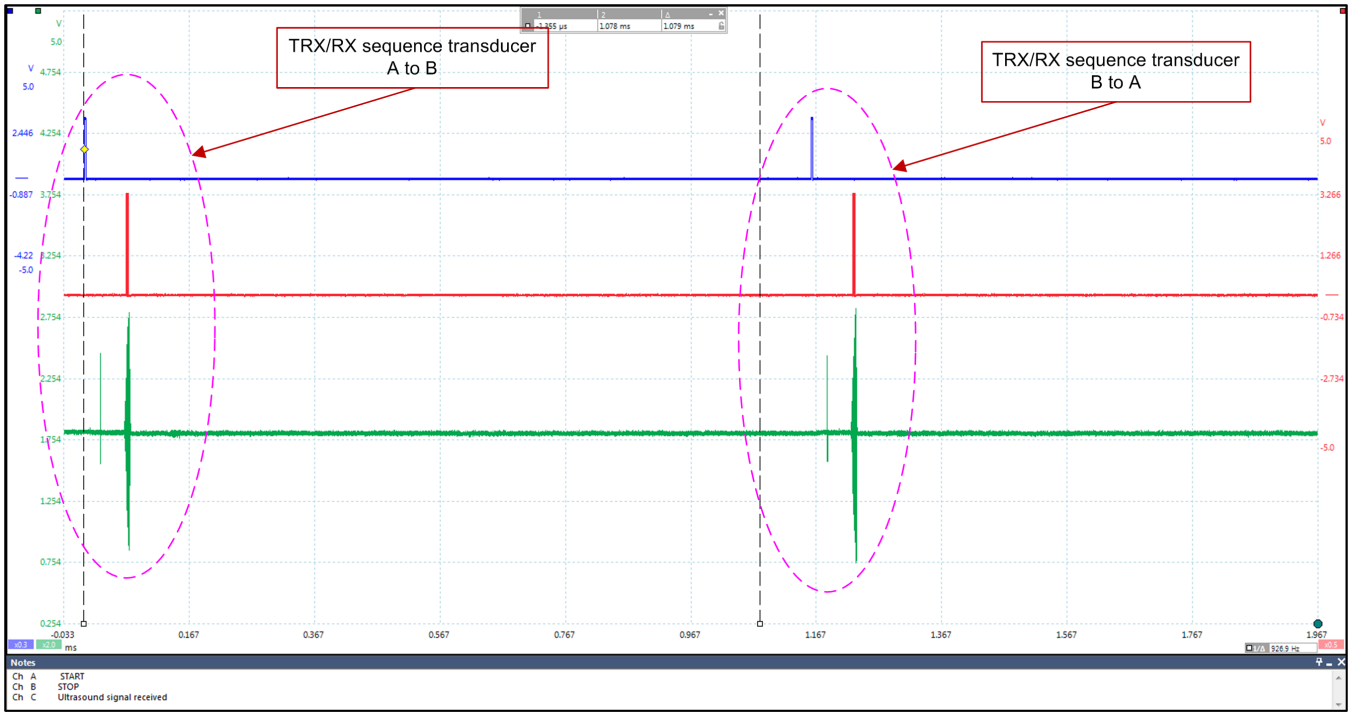


Figure 11. ΔTOF Measurement Sequence

10 Displaying the Delta TOF in GUI's GRAPH Menu

Click on the "GRAPH" tab to display the "GRAPH" menu. In the box below "Flow MODE" on the right bottom corner of the display, check the flow mode option. In this mode, the GUI generates a downstream and upstream sequence, calculates the "Delta TOF", and displays it at the top right of the screen under "FLOW DELTA AVG (ns)". Under "TDC_SELECT", chose the STOP pulse (STOP1, STOP2, etc.) that provides the best accuracy in calculating the TOF. Try different selection and observe the changes in delta TOF and STADEV. As mentioned in the previous section, as the TOF in the upstream and the downstream directions are measured in reference to the same STOP pulse, the net effect is independent of the choice of the STOP pulse.

To start the graph, click on "START Graph" tab, you should see the yellow moving trace of the delta TOF versus time as shown in Figure 12. If the numbers in delta TOF and the STDEV boxes are changing but the graph is not being displayed (black screen) then the graph is out of scale. To force the graph to be displayed in the window, place the cursor on the black background and right-click your mouse. A drop window display will show up giving you the option to select auto scale in the X and Y axis. Once you check mark the auto scale box, the GUI will scale the graph to fit in the display window.

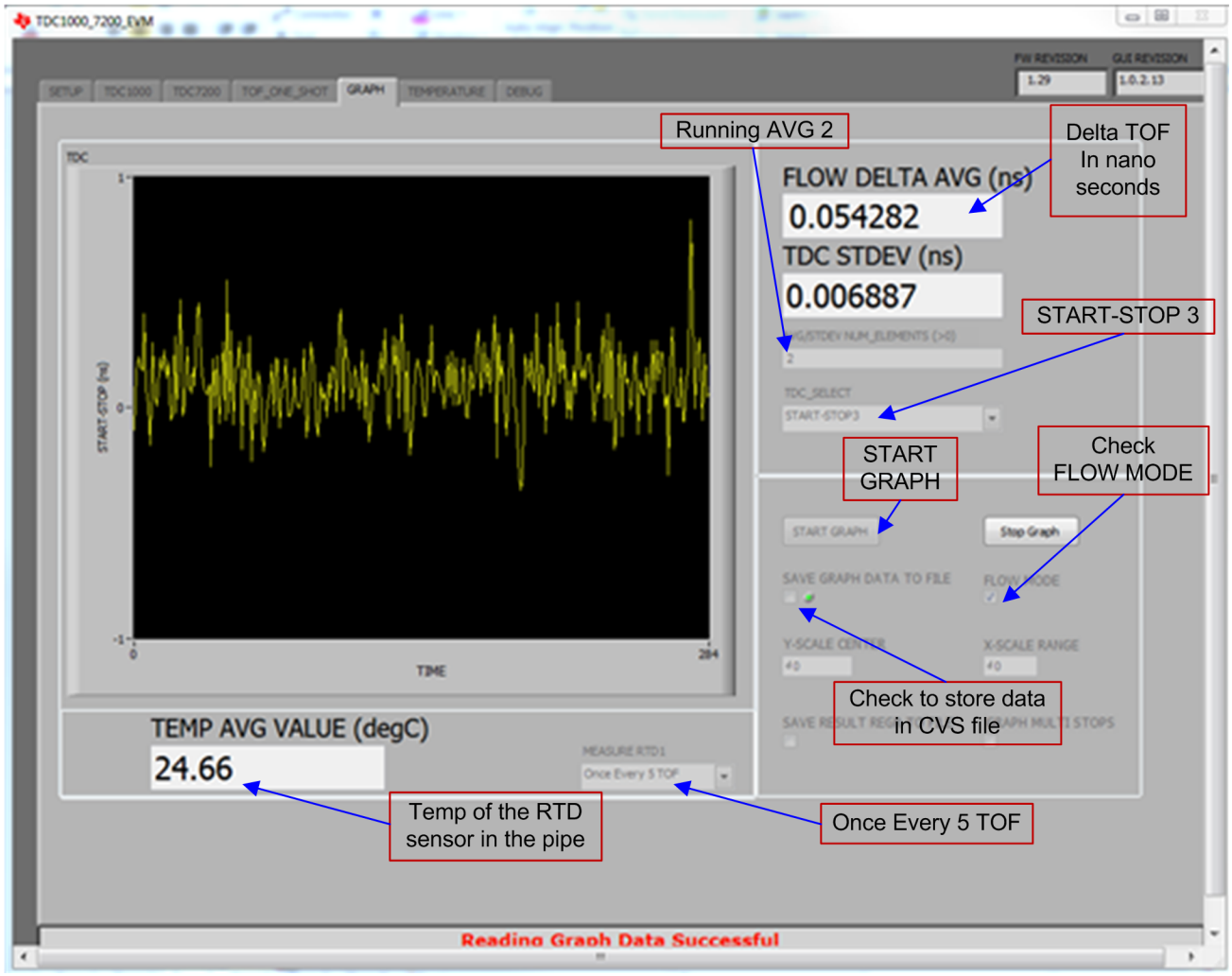
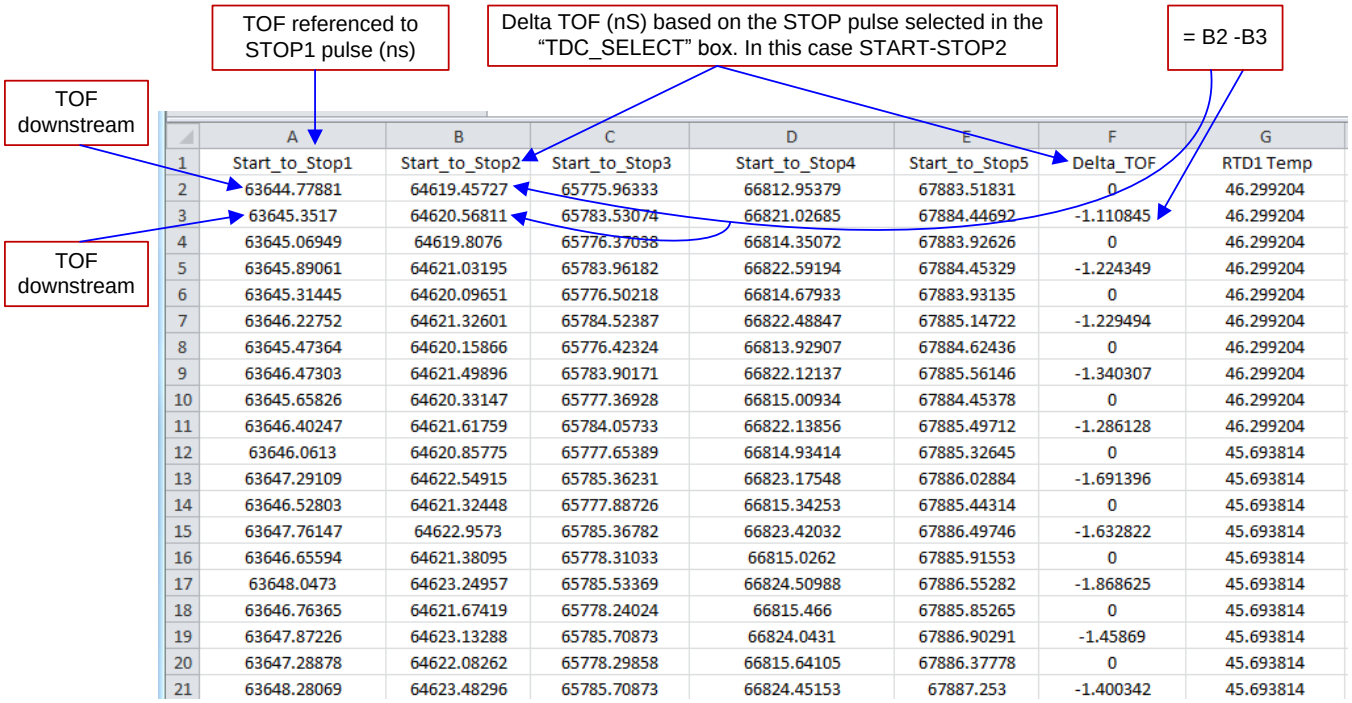


Figure 12. ΔTOF Graph Display

11 Saving Data in a File

To save data in a file for post processing purpose, check the box “SAVE GRAPH DATA TO FILE” before running the graph by clicking on “START GRAPH” button. You will be asked to name the file and identify a location in your computer to store the file. When you type in the information click the ok tab, you will be prompted to type the number of samples to be saved. If type ok without typing in the number of samples in the displayed box (0 samples by default), the GUI will continuously save unlimited number of data in the file until the “STOP GRAPH” tab is pressed to stop displaying the graph. The content of the file includes information as shown in Figure 13.



	A	B	C	D	E	F	G
1	Start_to_Stop1	Start_to_Stop2	Start_to_Stop3	Start_to_Stop4	Start_to_Stop5	Delta_TOF	RTD1 Temp
2	63644.77881	64619.45727	65775.96333	66812.95379	67883.51831	0	46.299204
3	63645.3517	64620.56811	65783.53074	66821.02685	67884.44692	-1.110845	46.299204
4	63645.06949	64619.8076	65776.37038	66814.35072	67883.92626	0	46.299204
5	63645.89061	64621.03195	65783.96182	66822.59194	67884.45329	-1.224349	46.299204
6	63645.31445	64620.09651	65776.50218	66814.67933	67883.93135	0	46.299204
7	63646.22752	64621.32601	65784.52387	66822.48847	67885.14722	-1.229494	46.299204
8	63645.47364	64620.15866	65776.42324	66813.92907	67884.62436	0	46.299204
9	63646.47303	64621.49896	65783.90171	66822.12137	67885.56146	-1.340307	46.299204
10	63645.65826	64620.33147	65777.36928	66815.00934	67884.45378	0	46.299204
11	63646.40247	64621.61759	65784.05733	66822.13856	67885.49712	-1.286128	46.299204
12	63646.0613	64620.85775	65777.65389	66814.93414	67885.32645	0	45.693814
13	63647.29109	64622.54915	65785.36231	66823.17548	67886.02884	-1.691396	45.693814
14	63646.52803	64621.32448	65777.88726	66815.34253	67885.44314	0	45.693814
15	63647.76147	64622.9573	65785.36782	66823.42032	67886.49746	-1.632822	45.693814
16	63646.65594	64621.38095	65778.31033	66815.0262	67885.91553	0	45.693814
17	63648.0473	64623.24957	65785.53369	66824.50988	67886.55282	-1.868625	45.693814
18	63646.76365	64621.67419	65778.24024	66815.466	67885.85265	0	45.693814
19	63647.87226	64623.13288	65785.70873	66824.0431	67886.90291	-1.45869	45.693814
20	63647.28878	64622.08262	65778.29858	66815.64105	67886.37778	0	45.693814
21	63648.28069	64623.48296	65785.70873	66824.45153	67887.253	-1.400342	45.693814

Figure 13. Sample Data Stored in a File

12 Appendix 1: Sensor Manufacturer

Table 2. Sensor Manufacturer

APPLICATION	MANUFACTURER	P/N	FR (kHz)
Heat/water	AudioWell: http://www.audiowell.com/en/product-detail.aspx?id=80	Brass Pipe For Heat meter DN25. Ultrasonic flow sensor AW5Y0980K04L193Z	1000
Heat/water	AudioWell: http://www.audiowell.com/en/product-detail.aspx?id=80	Brass Pipe For Heat meter DN20. Ultrasonic flow sensor AW5Y0980K08L151Z	1000

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      3.1.1 *Notice applicable to EVMs not FCC-Approved:*

      This kit is designed to allow product developers to evaluate electronic components, circuitry, or software associated with the kit to determine whether to incorporate such items in a finished product and software developers to write software applications for use with the end product. This kit is not a finished product and when assembled may not be resold or otherwise marketed unless all required FCC equipment authorizations are first obtained. Operation is subject to the condition that this product not cause harmful interference to licensed radio stations and that this product accept harmful interference. Unless the assembled kit is designed to operate under part 15, part 18 or part 95 of this chapter, the operator of the kit must operate under the authority of an FCC license holder or must secure an experimental authorization under part 5 of this chapter.

      3.1.2 *For EVMs annotated as FCC – FEDERAL COMMUNICATIONS COMMISSION Part 15 Compliant:*

      CAUTION

      This device complies with part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

      Changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate the equipment.

      FCC Interference Statement for Class A EVM devices

      NOTE: This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at his own expense.

FCC Interference Statement for Class B EVM devices

NOTE: This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures:

- *Reorient or relocate the receiving antenna.*
- *Increase the separation between the equipment and receiver.*
- *Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.*
- *Consult the dealer or an experienced radio/TV technician for help.*

3.2 *Canada*

3.2.1 *For EVMs issued with an Industry Canada Certificate of Conformance to RSS-210*

Concerning EVMs Including Radio Transmitters:

This device complies with Industry Canada license-exempt RSS standard(s). Operation is subject to the following two conditions: (1) this device may not cause interference, and (2) this device must accept any interference, including interference that may cause undesired operation of the device.

Concernant les EVMs avec appareils radio:

Le présent appareil est conforme aux CNR d'Industrie Canada applicables aux appareils radio exempts de licence. L'exploitation est autorisée aux deux conditions suivantes: (1) l'appareil ne doit pas produire de brouillage, et (2) l'utilisateur de l'appareil doit accepter tout brouillage radioélectrique subi, même si le brouillage est susceptible d'en compromettre le fonctionnement.

Concerning EVMs Including Detachable Antennas:

Under Industry Canada regulations, this radio transmitter may only operate using an antenna of a type and maximum (or lesser) gain approved for the transmitter by Industry Canada. To reduce potential radio interference to other users, the antenna type and its gain should be so chosen that the equivalent isotropically radiated power (e.i.r.p.) is not more than that necessary for successful communication. This radio transmitter has been approved by Industry Canada to operate with the antenna types listed in the user guide with the maximum permissible gain and required antenna impedance for each antenna type indicated. Antenna types not included in this list, having a gain greater than the maximum gain indicated for that type, are strictly prohibited for use with this device.

Concernant les EVMs avec antennes détachables

Conformément à la réglementation d'Industrie Canada, le présent émetteur radio peut fonctionner avec une antenne d'un type et d'un gain maximal (ou inférieur) approuvé pour l'émetteur par Industrie Canada. Dans le but de réduire les risques de brouillage radioélectrique à l'intention des autres utilisateurs, il faut choisir le type d'antenne et son gain de sorte que la puissance isotrope rayonnée équivalente (p.i.r.e.) ne dépasse pas l'intensité nécessaire à l'établissement d'une communication satisfaisante. Le présent émetteur radio a été approuvé par Industrie Canada pour fonctionner avec les types d'antenne énumérés dans le manuel d'usage et ayant un gain admissible maximal et l'impédance requise pour chaque type d'antenne. Les types d'antenne non inclus dans cette liste, ou dont le gain est supérieur au gain maximal indiqué, sont strictement interdits pour l'exploitation de l'émetteur

3.3 *Japan*

3.3.1 *Notice for EVMs delivered in Japan:* Please see http://www.tij.co.jp/lsds/ti_ja/general/eStore/notice_01.page 日本国内に輸入される評価用キット、ボードについては、次のところをご覧ください。
http://www.tij.co.jp/lsds/ti_ja/general/eStore/notice_01.page

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If User uses EVMs in Japan, not certified to Technical Regulations of Radio Law of Japan, User is required by Radio Law of Japan to follow the instructions below with respect to EVMs:

1. Use EVMs in a shielded room or any other test facility as defined in the notification #173 issued by Ministry of Internal Affairs and Communications on March 28, 2006, based on Sub-section 1.1 of Article 6 of the Ministry's Rule for Enforcement of Radio Law of Japan,
2. Use EVMs only after User obtains the license of Test Radio Station as provided in Radio Law of Japan with respect to EVMs, or
3. Use of EVMs only after User obtains the Technical Regulations Conformity Certification as provided in Radio Law of Japan with respect to EVMs. Also, do not transfer EVMs, unless User gives the same notice above to the transferee. Please note that if User does not follow the instructions above, User will be subject to penalties of Radio Law of Japan.

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3.3.3 *Notice for EVMs for Power Line Communication:* Please see http://www.tij.co.jp/lsds/ti_ja/general/eStore/notice_02.page

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4 *EVM Use Restrictions and Warnings:*

4.1 EVMS ARE NOT FOR USE IN FUNCTIONAL SAFETY AND/OR SAFETY CRITICAL EVALUATIONS, INCLUDING BUT NOT LIMITED TO EVALUATIONS OF LIFE SUPPORT APPLICATIONS.

4.2 User must read and apply the user guide and other available documentation provided by TI regarding the EVM prior to handling or using the EVM, including without limitation any warning or restriction notices. The notices contain important safety information related to, for example, temperatures and voltages.

4.3 *Safety-Related Warnings and Restrictions:*

4.3.1 User shall operate the EVM within TI's recommended specifications and environmental considerations stated in the user guide, other available documentation provided by TI, and any other applicable requirements and employ reasonable and customary safeguards. Exceeding the specified performance ratings and specifications (including but not limited to input and output voltage, current, power, and environmental ranges) for the EVM may cause personal injury or death, or property damage. If there are questions concerning performance ratings and specifications, User should contact a TI field representative prior to connecting interface electronics including input power and intended loads. Any loads applied outside of the specified output range may also result in unintended and/or inaccurate operation and/or possible permanent damage to the EVM and/or interface electronics. Please consult the EVM user guide prior to connecting any load to the EVM output. If there is uncertainty as to the load specification, please contact a TI field representative. During normal operation, even with the inputs and outputs kept within the specified allowable ranges, some circuit components may have elevated case temperatures. These components include but are not limited to linear regulators, switching transistors, pass transistors, current sense resistors, and heat sinks, which can be identified using the information in the associated documentation. When working with the EVM, please be aware that the EVM may become very warm.

4.3.2 EVMs are intended solely for use by technically qualified, professional electronics experts who are familiar with the dangers and application risks associated with handling electrical mechanical components, systems, and subsystems. User assumes all responsibility and liability for proper and safe handling and use of the EVM by User or its employees, affiliates, contractors or designees. User assumes all responsibility and liability to ensure that any interfaces (electronic and/or mechanical) between the EVM and any human body are designed with suitable isolation and means to safely limit accessible leakage currents to minimize the risk of electrical shock hazard. User assumes all responsibility and liability for any improper or unsafe handling or use of the EVM by User or its employees, affiliates, contractors or designees.

4.4 User assumes all responsibility and liability to determine whether the EVM is subject to any applicable international, federal, state, or local laws and regulations related to User's handling and use of the EVM and, if applicable, User assumes all responsibility and liability for compliance in all respects with such laws and regulations. User assumes all responsibility and liability for proper disposal and recycling of the EVM consistent with all applicable international, federal, state, and local requirements.

5. *Accuracy of Information:* To the extent TI provides information on the availability and function of EVMs, TI attempts to be as accurate as possible. However, TI does not warrant the accuracy of EVM descriptions, EVM availability or other information on its websites as accurate, complete, reliable, current, or error-free.

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