



**OPERATING MANUAL**  
for  
**QUARTZDYNE®**  
**Frequency Output Pressure Transducers**

**Quartzdyne, Inc.**

**A DOVER COMPANY**

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# Quartzdyne Frequency Output Pressure Transducer Operating Manual

## Table of Contents

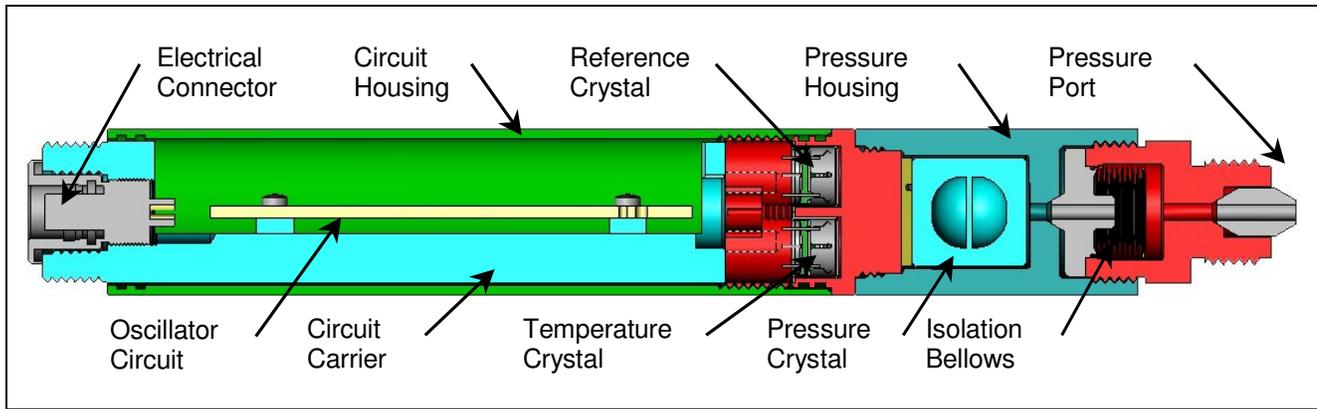
<b>1</b>	<b>GENERAL INFORMATION.....</b>	<b>3</b>
1.1	INTRODUCTION .....	3
1.2	PRESSURE SENSOR DESIGN.....	4
1.3	PRESSURE MEASUREMENT SYSTEM DESIGN THEORY.....	4
1.4	ELECTRICAL CONNECTION TO QUARTZDYNE TRANSDUCERS .....	5
<b>2</b>	<b>PERFORMANCE .....</b>	<b>6</b>
2.1	BELLOWS AND DIAPHRAGMS.....	6
2.2	ASIC KICK-START CIRCUIT .....	6
2.3	FREQUENCY CHANGES WITH PRESSURE AND TEMPERATURE .....	6
<b>3</b>	<b>FREQUENCY COUNTING.....</b>	<b>8</b>
3.1	DIRECT FREQUENCY COUNTING.....	8
3.2	PERIOD COUNTING.....	9
3.3	TEMPERATURE RESOLUTION REQUIREMENTS .....	11
3.4	EFFECT OF SENSOR FREQUENCY JITTER ON RESOLUTION .....	11
3.5	REFERENCE-BASED COUNTING.....	12
<b>4</b>	<b>CALIBRATION.....</b>	<b>13</b>
4.1	TRANSDUCER CALIBRATION DATA .....	13
4.2	TRACEABILITY OF CALIBRATION.....	13
4.3	TYPICAL VALUES OF CORRECTIONS USED IN CALIBRATION .....	13
4.4	PRESSURE CONTROL REQUIRED FOR CALIBRATION .....	14
4.5	TEMPERATURE CONTROL REQUIRED FOR CALIBRATION .....	14
4.6	FREQUENCY MEASUREMENT DURING CALIBRATION.....	15
<b>5</b>	<b>CALIBRATION COEFFICIENT FILES.....</b>	<b>16</b>
5.1	STANDARD AND REFERENCE-BASED CALIBRATION COEFFICIENTS .....	17
5.2	CALCULATIONS USING STANDARD OR REFERENCE-BASED COEFFICIENTS.....	18
5.3	STANDARD COEFFICIENT EXAMPLE CODE .....	19
5.4	HEX COEFFICIENT FORMAT .....	20
5.5	HEX COEFFICIENT CHECKSUM CALCULATION .....	20
5.6	PRESSURE AND TEMPERATURE CALCULATIONS USING HEX FILE COEFFICIENTS .....	21
5.7	HEX COEFFICIENT EXAMPLE CODE .....	22
5.8	INTEL HEX FILE CODING.....	23

# 1 General Information

## 1.1 Introduction

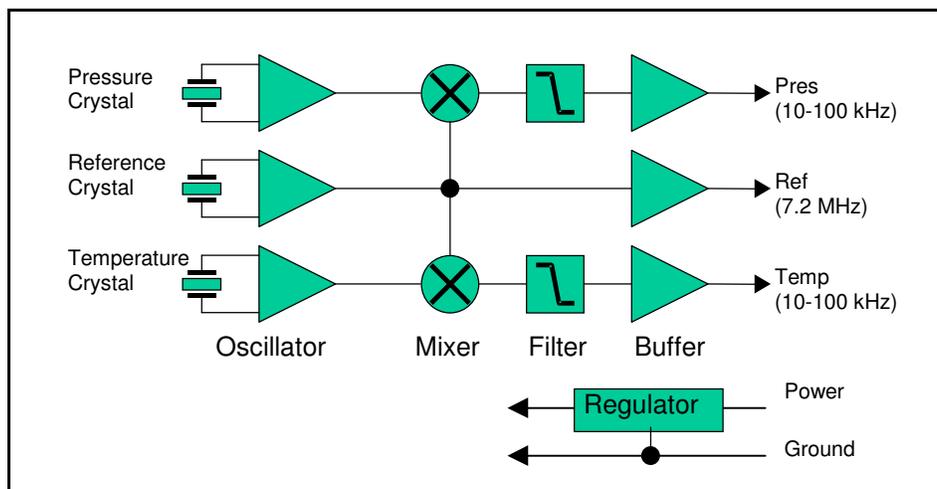
This Manual documents the electrical interface for Quartzdyne Frequency Output Pressure Transducers.

All Quartzdyne Pressure Transducers contain three quartz crystal sensor elements. The first of these is sensitive primarily to exposed pressure, the second responds to temperature, and the third has minimal sensitivity to either pressure or temperature. The crystals are arranged mechanically to provide good thermal coupling. The quartz sensing elements provide high stability and extremely fine resolution for sensing pressure. A bellows is used to protect the pressure crystal from the process fluids. A circuit provides stimulus for the quartz sensing elements, and the corrosion-resistant, high-strength alloy housing provides mechanical support and protection to each of these elements. Various mechanical configurations are available.



**Figure 1. Parts of a Quartzdyne Pressure Transducer (Model QUB shown).**

The circuit consists of three oscillators, two mixers, buffering circuitry and a regulator. The outputs are two low frequency (10-100 kHz) sensor output signals and a high frequency (7.2 MHz) reference signal. The transducer must be connected to a frequency counter and power supply. The high frequency reference signal may be used to count the two low frequency signals using the "reference-based" coefficients. Alternatively, the user may supply another reference signal and use the "standard" coefficients. Pressure is computed using the two low frequency signals, the unique calibration coefficients for the transducer, and the algorithm shown in this manual. Temperature may also be calculated from the frequencies.



**Figure 2. Oscillator Circuit Block Diagram.**

## 1.2 Pressure Sensor Design

The important advantages of the Quartzdyne thickness-shear pressure technology are precision, long-term stability, ruggedness, and rapid transient response.

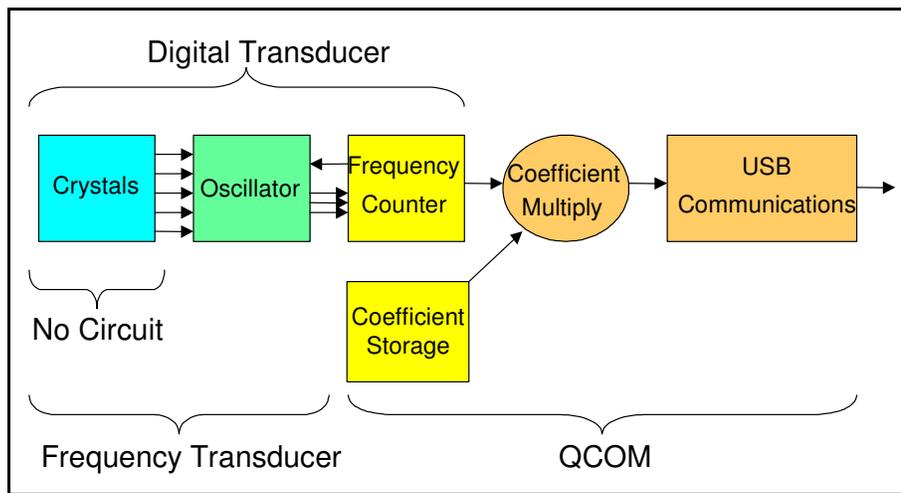
The pressure sensor is a quartz resonator that changes frequency in response to applied pressure. Crystalline quartz is an ideal material for precision sensors because it is perfectly elastic. The design of the Quartzdyne quartz pressure sensor retains the repeatable performance inherent in the single-crystal material.

The quartz pressure sensor is a thick-walled, hollow cylinder with closed ends. A thickness-shear mode resonator divides the central portion of the hollow cylinder. Fluid pressure on the exterior walls hydrostatically compresses the quartz cylinder, producing internal compressive stress in the resonator. The frequency of the resonator changes in response to the internal stress.

## 1.3 Pressure Measurement System Design Theory

The *transducer* is the assembly required to convert the physical parameters of pressure and temperature into the frequency output signals. Each transducer assembly includes the quartz pressure sensor, a temperature sensor crystal (for digital temperature compensation), and a precision reference crystal. An oscillator circuit provides stimulus to the quartz elements, converting their natural resonant frequencies into electrical signals. The reference crystal's frequency is mixed with the frequencies from the two sensors to make these signals easier to count and transmit. It also provides the transducer with a stable time base that can be used in the user's frequency counter.

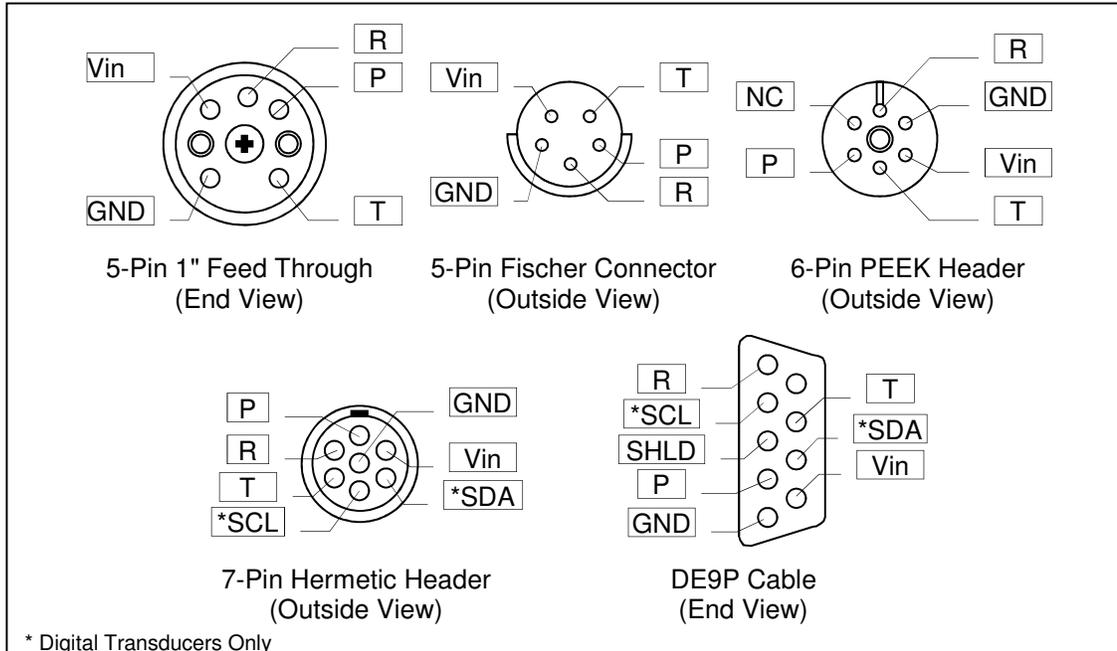
For a complete measurement system, the customer must provide power, a frequency counter, means for calculating pressure from the measured frequencies and provided coefficients, and either storage or a transmission method for the data. Digital transducers are available from Quartzdyne, which include the frequency counter and coefficient storage. The QCOM interface unit is also available for connecting either type of transducer to a PC (Figure 3).



**Figure 3. Function blocks for Quartzdyne quartz pressure measurement systems. Each bracketed block is available from Quartzdyne.**

### 1.4 Electrical Connection to Quartzdyne Transducers

Several electrical connection options are available for Quartzdyne Frequency Output Pressure Transducers. See Figure 4 for pin-out assignments. In applications requiring high reliability, solder connections are preferred to connectors. The 5-Pin 1" Feed Through, the 6-Pin PEEK Header and the 7-Pin Hermetic Header are designed for direct soldering using high melting point solders. In some cases, an installed connector can be removed exposing 2-4" of wires, which can be soldered directly to the customer's circuit. Table 1 shows standard wire colors for units where flying leads are provided.



**Figure 4. Pin assignments for various Quartzdyne Pressure Transducer connector options**

**Table 1. Pin and wire labels and their functions**

Label	Function	Wire Color (Std)	Alternate Colors
Vin	Power Supply (Pos)	Blue (3-5V)	Red (5-12V)
GND	Power Supply (Neg)/Chassis	Black or B/W	Black
SHLD	Shield Termination/Chassis		
R	Reference Frequency Output	White	White
P	Pressure Frequency Output	Purple	Purple
T	Temperature Frequency Output	Yellow	Yellow
*SCL	Not used (Digital Transducers Only)	Slate	N/A
*SDA	Not used (Digital Transducers Only)	Green	N/A

**WARNING!** The oscillator circuit can be damaged if excess current or voltage is applied to the pins. Always use current-limited power supplies to prevent excessive current in the event that the device is incorrectly wired.

**WARNING!** The GND pin is internally connected to chassis. High currents will flow if a grounded power supply is incorrectly connected to this pin. Currents of several Amps are possible while power supply filter capacitors are being discharged.

**WARNING!** Avoid static discharge when handling transducers, and particularly when mating connectors. Fully discharge the cable to the chassis of the transducer before mating the connector. Transducers should be stored and transported in static-safe containers.

## **2 Performance**

### **2.1 Bellows and Diaphragms**

The transducer may be fitted with either a bellows or diaphragm which isolates and protects the pressure crystal from the fluids being measured. The effect of the bellows on the pressure reading is small, but must be compensated for in the calibration. Removal or physical damage to the bellows or diaphragm will change the pressure response and necessitate recalibration of the transducer.

Although the bellows is backfilled under vacuum with oil which has been thoroughly degassed, it is possible that small amounts of gas may be trapped inside the bellows. Normally this gas will be dissolved in the oil and have no measureable effect on pressure performance. At ambient pressures it is possible that some of the gas may be driven out of solution temporarily causing the bellows to expand resulting in a pressure reading as much as 10 psi higher than ambient pressure. The unit will return to normal pressure readings as soon as pressure is applied. Quartzdyne pressure transducers with bellows are specified for accuracy only above 200 psia.

### **2.2 ASIC Kick-start Circuit**

Any contaminant or imperfection on the surface of a quartz resonator can cause its impedance to increase. Usually, the impedance increase will vary depending on the crystal drive level, and is often worse at lower drive levels. This phenomenon is known in the industry as drive level sensitivity (DLS) and can cause a crystal oscillator to fail to start up when power is supplied. While we take every effort to ensure that the crystals included in Quartzdyne pressure transducers are free from such imperfections, it is possible that a contaminant can move in response to shock experienced in the field.

With the introduction of the ASIC oscillator to our hybrid circuits (September 2007), a kick-start feature was added. This feature applies an increased drive level to the crystals during the start-up phase in order to overcome any potential DLS, and then backs off once stable oscillation has been achieved. This significantly reduces the chance that a DLS crystal will cause a field failure. In many cases, the excess drive literally moves the offending contaminant to an area where it no longer affects performance.

A possible, but rare side-effect of this feature is that if a crystal fails for gradually increasing high impedance that is not related to DLS, it may reach a point where the kick-start feature repeatedly engages and disengages. This will be seen as abnormally high jitter in the pressure and/or temperature measurement. If the impedance continues to increase, the jitter will stop as the kick-start feature stays engaged fully, and eventually the oscillator will flat-line. Non-ASIC circuits would have flat-lined long before any of these symptoms were manifested.

### **2.3 Frequency Changes with Pressure and Temperature**

Nominal frequency sensitivities to pressure and temperature for the various sensors are shown on the data sheets of the respective products. Figure 5 through Figure 8 depict the typical change in the frequencies of the two output signals of a QU20K transducer with changes in pressure and temperature. Figure 5 shows the nominal change in frequency of the temperature sensor. All temperature sensors show very similar sensitivities, but the frequency at 25°C will vary from unit to unit. Figure 6 shows the change in frequency of the pressure signal with changes in pressure and temperature. Note that changes in temperature produce changes in both zero and span.

The data from Figure 6 has been re-plotted in Figure 7 for additional examination. In Figure 7, the pressure frequency data is plotted versus temperature at various pressures. The data has also been normalized at the minimum frequency so that the temperature sensitivity can be observed more clearly. Note that the temperature sensitivity is positive at ambient pressure, but negative at full-scale pressure, with a zero sensitivity point that occurs at higher temperatures as the pressure is increased.

The pressure sensor has been designed to minimize transient errors in downhole work. Care has been taken to provide good thermal coupling between the pressure and temperature crystals. Under transient conditions (temperature ramps, or large pressure steps), a small temperature difference is possible. Figure 8 shows the nominal sensitivity of the pressure sensor due to temperature differences that may occur during a transient condition. If the transducer is used in the typical down-hole pressure and temperature ranges where the sensitivity is in the zero to 10 psi/°C range, the transient errors will be small. Conversely, if used at the extremes of high temperature - low pressure, or high pressure - low temperature, the transient errors will be more significant. See our website for a detailed transient report comparing the performance of various pressure transducer configurations.

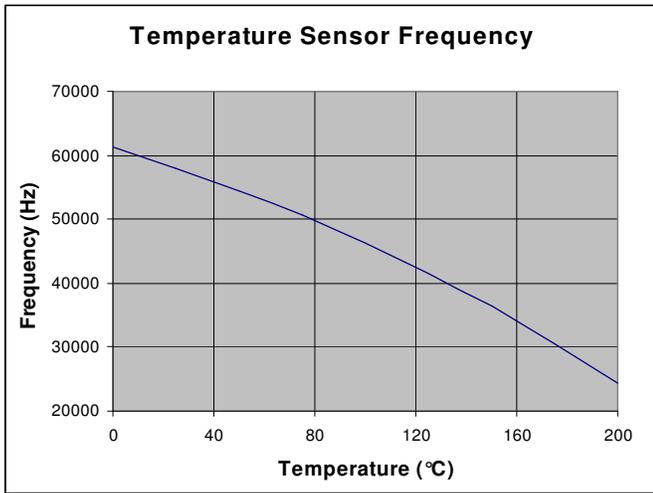


Figure 5. Typical Temperature Sensor frequency as a function of temperature.

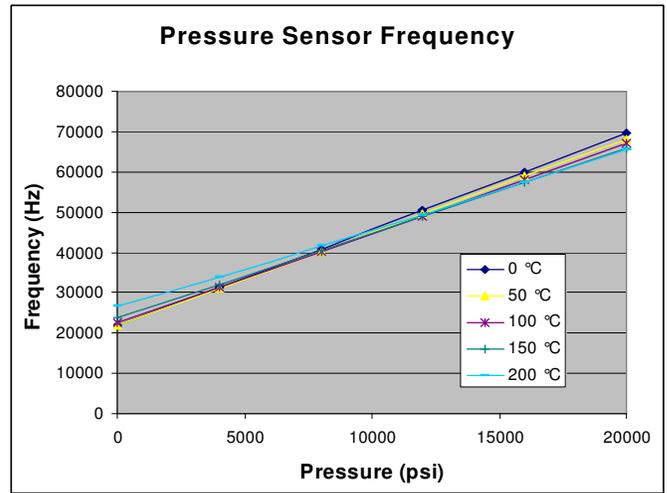


Figure 6. Typical Pressure Sensor frequency at various temperatures.

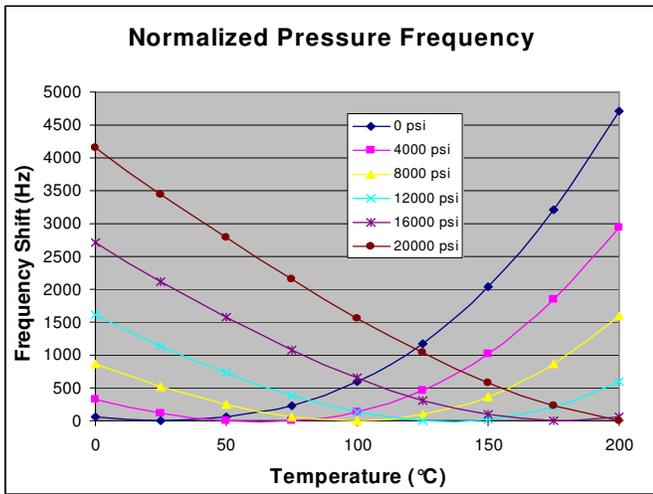


Figure 7. Pressure Sensor frequency plotted vs. temperature and normalized to the minimum (zero-sensitivity) point for each pressure.

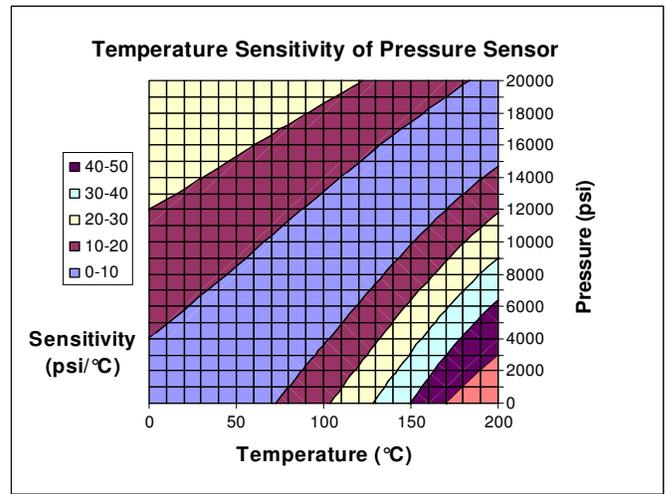


Figure 8. Pressure Sensor Temperature sensitivity gradient plot showing low sensitivity along a typical well gradient. Transient errors will be worse in ranges with high sensitivity.

### 3 Frequency Counting

The pressure resolution that is available from a Downhole Transducer is a function of the user's time base frequency, the gate time during which the frequency is counted, the pressure sensitivity of the pressure sensor, and the method of frequency counting. The two most common methods of counting are direct frequency counting and period (or reciprocal) counting. Both of these will be discussed below. The following definitions will be used:

$T_G$	=	<i>gate time (sec)</i>
$F_R$	=	<i>reference crystal or time base frequency (Hz or MHz)</i>
$F_S$	=	<i>sensor frequency (Hz or MHz)</i>
$N_R$	=	<i>number of counts of reference during <math>T_G</math></i>
$N_S$	=	<i>number of counts of sensor during <math>T_G</math></i>
$S_{PP}$	=	<i>Pressure Sensor Pressure Sensitivity (Hz/psi)</i>
$S_{PT}$	=	<i>Pressure Sensor Temperature Sensitivity (Hz/°C)</i>
$S_{TP}$	=	<i>Temperature Sensor Pressure Sensitivity (Hz/psi)</i>
$S_{TT}$	=	<i>Temperature Sensor Temperature Sensitivity (Hz/°C)</i>
$R$	=	<i>Resolution (psi or Hz)</i>

Some of the equations shown below refer to the nominal sensitivities and frequency ranges of the pressure and temperature sensors. Please refer to the various product specification sheets for actual sensitivities.

#### 3.1 Direct Frequency Counting

Direct frequency counting is simple and can be used with any time base. Its disadvantage is that it has poor resolution with low sensor frequencies. It is only preferred if the sensor frequency is higher than the user's time base frequency. It is generally not appropriate for Quartzdyne transducers, but is included in this discussion for comparison purposes.

Direct Frequency Counters use the time base frequency to determine the gate time during which the sensor frequency is counted (Figure 11). Usually, the implementation provides for the gate time,  $t$ , to be determined by a fixed number of counts of the reference, or time base frequency:

$$T_G(\text{sec}) = \frac{N_R(\text{counts})}{F_R(\text{Hz})}$$

The sensor frequency is calculated from the number of counts of the sensor signal during the gate time:

$$F_S(\text{Hz}) = \frac{N_S(\text{counts})}{t(\text{sec})}$$

In direct frequency counting, the frequency resolution is a function of the gate time. For example, a one second gate time provides 1 Hz resolution; longer gate times provide higher resolution:

$$\text{Frequency Resolution (Hz)} = \frac{1}{T_G(\text{sec})}$$

The pressure or temperature resolution in direct frequency counting is a function of the gate time and the sensitivity of the sensor:

$$R(\text{psi}) = \frac{1}{T_G(\text{sec})} \frac{1}{S_{PP}(\text{Hz/psi})}$$

$$R(^{\circ}\text{C}) = \frac{1}{T_G(\text{sec})} \frac{1}{S_{TT}(\text{Hz/}^{\circ}\text{C})}$$

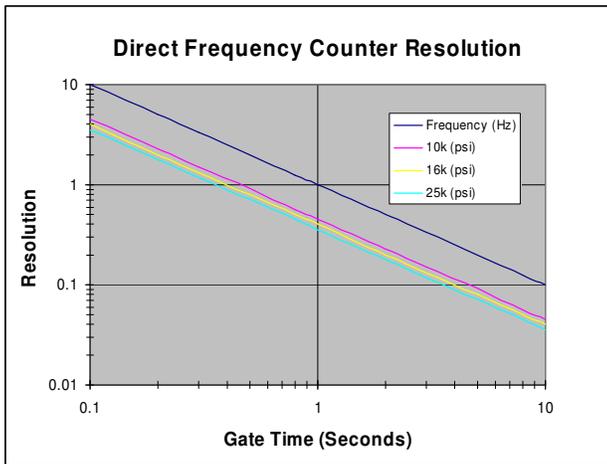


Figure 9. Resolution provided by a direct frequency counter as a function of gate time in Hz, and in psi for various sensor types.

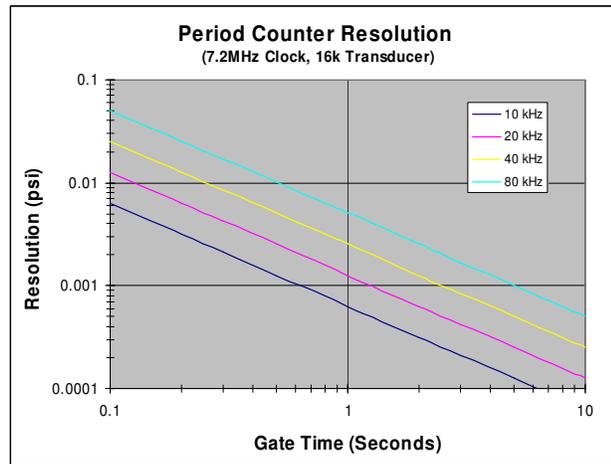


Figure 10. Resolution of a Period Counter for a typical 16k transducer. Note that for a Period Counter, resolution is a function of gate time and sensor frequency.

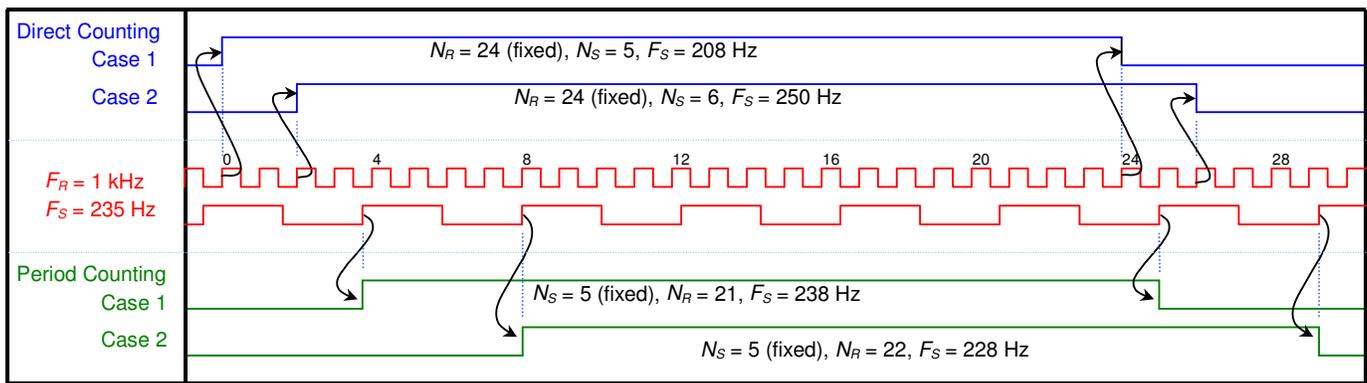


Figure 11. With Direct Frequency Counting the gate opens for a fixed number of counts of the Reference Frequency while Sensor Frequency Counts are accumulated. With Period Counting the gate opens for a fixed number of counts of the Sensor Frequency while Reference Counts are accumulated. Resolution is improved when the variable counts are higher. In this example, the Direct Counter has 42 Hz resolution while the period counter is able to resolve 10 Hz.

### 3.2 Period Counting

Period counting, also called reciprocal counting, uses the sensor frequency to determine the gate time during which the reference frequency is counted. This method can provide much higher resolution than direct frequency counting using a high frequency time base. The sensor frequency is calculated from the reference frequency and the number of counts of the sensor and reference frequencies during the gate time:

$$F_S(\text{Hz}) = \frac{F_R(\text{Hz})N_S}{N_R}$$

In period counting, the frequency resolution is a function of the frequency being measured and the total number of counts of the time base frequency:

$$R(\text{Hz}) = \frac{F_S(\text{Hz})}{N_r} = \frac{F_S(\text{Hz})}{F_R(\text{Hz})T_G(\text{sec})}$$

To determine the resolution both the frequency and sensitivity of the sensor must be known:

$$R(\text{psi}) = \frac{F_s(\text{Hz})}{F_R(\text{Hz})t(\text{sec})S_{PP}(\text{Hz/psi})}$$

$$R(^{\circ}\text{C}) = \frac{F_s(\text{Hz})}{F_R(\text{Hz})t(\text{sec})S_{TT}(\text{Hz/psi})}$$

Figure 10 shows the gate time required for the desired pressure resolution of a typical 16k Downhole Transducer. Note that the resolution is a function of the sensor frequency, and will therefore vary significantly over the pressure range. The resolution is better at lower frequencies.

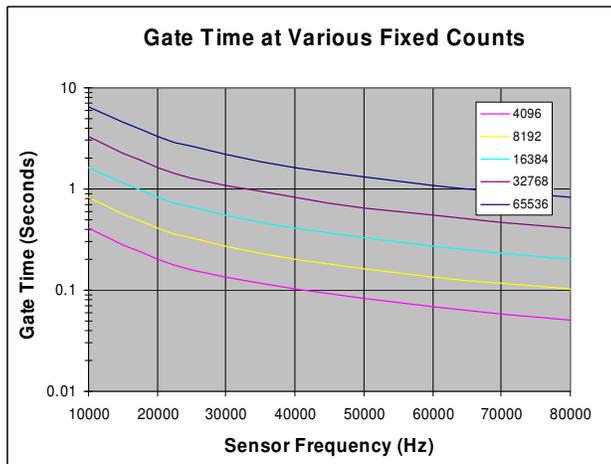
In period counting, the gate time is equal to the number of counts of the sensor frequency divided by the actual frequency:

$$T_G(\text{sec}) = \frac{N_s}{F_s(\text{Hz})}$$

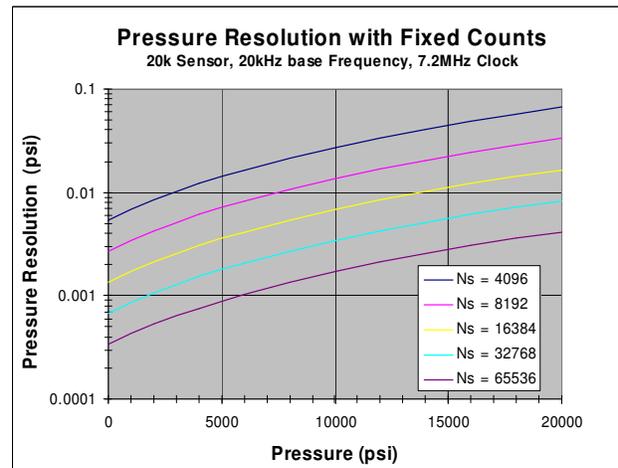
Precise gate times are difficult to achieve since the sensor frequency must be known to determine the actual gate time. A simple option for determining the gate time is to set  $N_s$  to a constant. This results in gate times that can vary significantly over the frequency range of  $F_s$ . Figure 12 shows gate time as a function of sensor frequency for a number of values of  $N_s$ . The sensor resolution using this method can be determined by substituting for  $t(\text{sec})$  in the above sensitivity equation:

$$R(\text{psi}) = \frac{F_s^2(\text{Hz}^2)}{F_R(\text{Hz})N_s(\text{counts})S_{PP}(\text{Hz/psi})}$$

Note that the equation shows resolution improving with larger  $N_s$  (longer gate times) and higher time base frequencies. The equation also shows that the resolution improves at lower sensor frequencies. This results in a resolution which approaches % of reading rather than the fixed resolution (% FS) of direct frequency counters (See Figure 13).

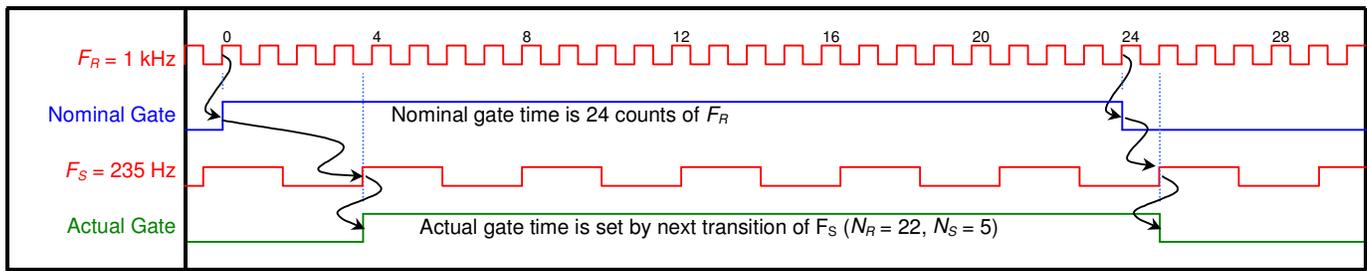


**Figure 12.** In a period counter where  $N_s$  is constant, the gate time will vary significantly over the sensor frequency range.



**Figure 13.** The pressure resolution is better at lower pressures with a fixed-count period counter.

If variable gate times are a problem,  $N_s$  may be chosen dynamically based on the previous frequency measurement, or a separate timer may be used to arm the counter to terminate on the next transition of  $F_s$  (Figure 14). The down side to this approach is a more complex counter, and the need to store both  $N_s$  and  $N_R$ , or to compute the ratio of the two prior to storage. Quartzdyne's Digital transducer uses the latter approach, reporting the divided ratio of  $N_s$  and  $N_R$ . The gate time is set by the end user based on the query rate.



**Figure 14. A fixed gate time can be achieved with a period counter by setting a nominal gate as in a Direct Frequency Counter, but controlling the actual gate as in a Period Counter. Both  $N_R$  and  $N_S$  are variable with this counting method.**

### 3.3 Temperature Resolution Requirements

The temperature sensor included in Quartzdyne Pressure Transducers has sensitivity  $S_{TT}$  between 100 Hz/°C and 300 Hz/°C over the various operating temperature ranges. Adequate temperature resolution may be achieved by using the same counting method and gate time for both temperature and pressure frequencies. A counting method which provides pressure resolution of 0.1 psi will provide temperature resolution of 0.002°C. The primary purpose of the temperature sensor is to provide temperature compensation for the pressure sensor. At the extremes of low pressure-high temperature and high pressure-low temperature, the pressure sensor may have a sensitivity to temperature  $S_{PT}$  as high as 100 Hz/°C. In this case the pressure resolution will be dominated by the temperature frequency counter.

Note that the temperature frequency decreases with increasing temperature, while the pressure frequency increases with pressure. In a fixed count system the shortest combined gate time will be at high pressure and low temperature, while the longest combined gate time will be at low pressure and high temperature.

### 3.4 Effect of Sensor Frequency Jitter on Resolution

Thus far, the discussions of resolution have ignored the effect of sensor frequency jitter. Jitter is the small variation in the period,  $1/f$ , of the sensor signal. The jitter (typically  $\pm 100$  nanosecond) is due to the cross talk between the pressure and temperature signals. While the effect of jitter is minimized by counting multiple periods of the signal, sensor jitter may still limit useful pressure resolution, particularly when a very high frequency time base is used. Note that the counter-induced jitter using the 7.2M Hz reference signal is  $\pm 140$  nanoseconds. The following equation includes the effects of both the counter and the sensor jitter:

$$R(\text{psi}) = \frac{F_s}{S_{PP}} \left( 1 - \frac{T_G}{T_G + T_J + \frac{1}{F_R}} \right),$$

where

- $R$  = Resolution (psi)
- $F_s$  = Sensor Frequency (Hz)
- $S_{PP}$  = Sensitivity (Hz/psi) (see specifications on transducer datasheets)
- $T_G$  = Gate time (sec)
- $T_J$  = Sensor pressure jitter (sec)
- $F_R$  = Time base frequency.

Including the effect of sensor jitter results in the effective resolution shown in Figure 15. The results of the previous discussions can be duplicated by setting  $T_J = 0$ . Note that at 7.2 MHz, the time base and sensor have nearly equal jitter. At lower time base frequencies (1-4 MHz) the time base jitter is the limiting factor; at higher time base frequencies (such as 16 MHz), the sensor jitter will dominate.

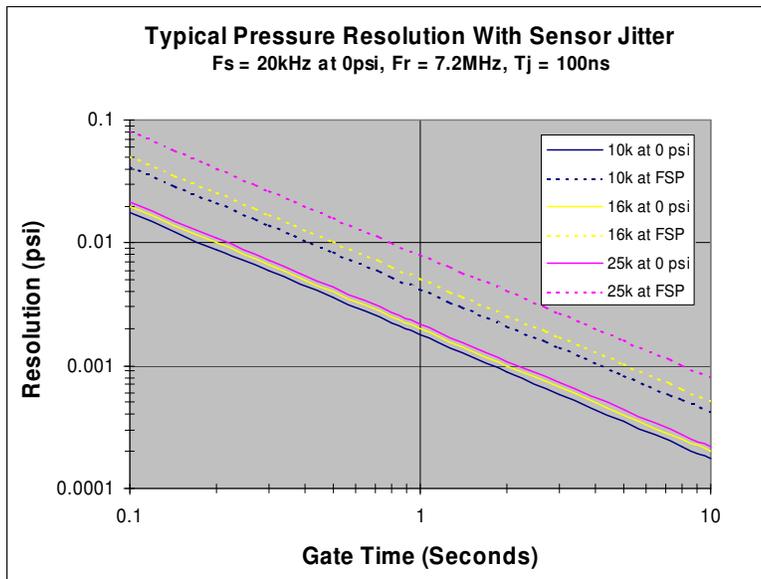


Figure 15 . Effect of Sensor Jitter on Pressure Resolution.

### 3.5 Reference-based Counting

Downhole Transducers have a reference frequency output. This output is approximately 7.2 MHz and has good thermal coupling to the temperature and pressure crystals. Using the internal reference frequency as the time base for the frequency counters provides digital temperature compensation of the time base. To achieve the same effect using an external time base, the entire tool would need to be calibrated as a unit. Even then, the thermal coupling between the temperature sensor and the time base crystal will not be as good. In addition, if the time base is changed, the tool must be calibrated again. A 40 ppm error in the user's time base frequency will result in approximately 1 psi error in the transducer. By using the transducer reference as the time base for the counter, the pressure transducer becomes a fully contained transfer standard.

Two sets of coefficient files are provided with Quartzdyne transducers that have a reference frequency output. These are referred to as standard and reference-based coefficients. The standard coefficients assume that a frequency counter with its own calibrated time base is used to count frequency. Frequency errors in the time base will directly effect the transducer frequency readings and consequently the calibrated transducer output.

The reference-based coefficients assume that the frequency counter uses the reference frequency of the transducer as its time base. At each pressure/temperature point there is a unique combination of the ratio of  $F_p / F_r$  and  $F_t / F_r$ . This ratio (scaled by 7.2E6) is used as the input to the curve fit. The curve fit provides digital temperature compensation for changes in  $F_r$ . To make the ratios look more like frequencies, we arbitrarily multiply them by a constant 7.2 MHz. This gives an output frequency that does not yet reflect the digital compensation. It will differ from the true frequency as shown:

$$F_{true} = F_{apparent} \times \frac{F_r}{7.2 \text{ MHz}} .$$

$F_r$  may vary from 7.2 MHz by as much as  $\pm 7.0$  kHz depending on the transducer and operating temperature. In our calibration system, we measure all three frequencies with a true frequency counter and calculate the apparent frequency as follows:

$$F_{apparent} = F_{true} \times \frac{7.2 \text{ MHz}}{F_r} .$$

$F_{apparent}$  should be used when computing reference-based coefficients during recalibration. If a reference-based counter is used to recalibrate, this is automatic.

## 4 Calibration

### 4.1 Transducer Calibration Data

The performance demonstrated during calibration of each transducer is shown in the Transducer Calibration Chart supplied with each transducer. The chart shows the deviation of each point from the calibration equation using the coefficients calculated for the transducer. Figure 16 shows the performance typical of Quartzdyne Pressure Transducers. The residual error at all temperatures is less than 0.01% of full scale (FS). This includes any errors in the linearity correction, repeatability, hysteresis, and temperature errors. Note that the residual error compares the transducer to the calibration standard; the error of the standard must be added to the residual error shown. Quartzdyne's calibration standard is a deadweight tester that is accurate to  $\pm 0.01\%$  of reading.

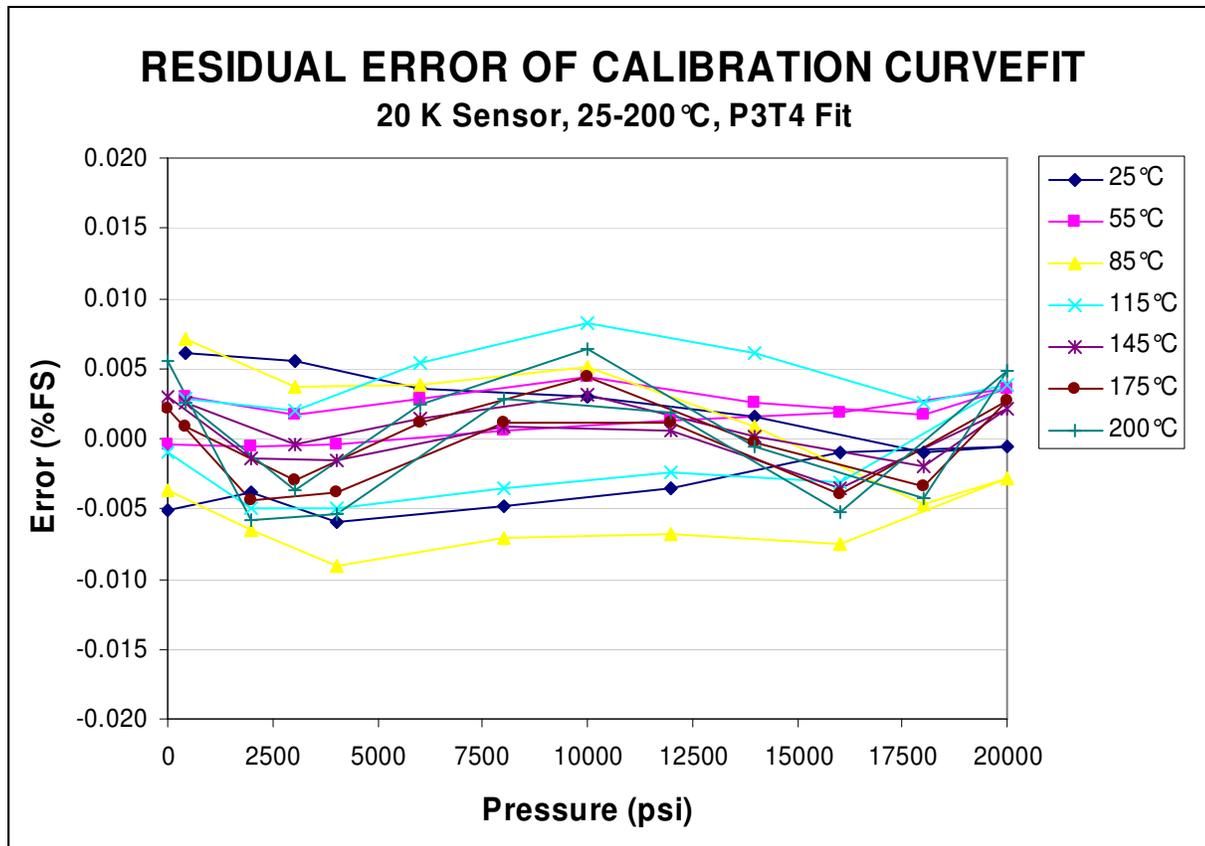


Figure 16 . Calibration curve typical of Quartzdyne Pressure Transducers.

### 4.2 Traceability of Calibration

Calibration of Quartzdyne Pressure Transducers is traceable to the U.S. National Pressure Standards maintained by the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards (NBS).

### 4.3 Typical Values of Corrections Used in Calibration

Achieving the 0.01% of reading accuracy specification of our pressure calibration standards requires that all potential sources of calibration error are identified. In the Quartzdyne calibration laboratory the atmospheric pressure reference is either a Mensor 2104 or DH Instruments PG-7302-M Digital Pressure Gauge. The height of the head is measured to within 0.25 inches [6.35 mm], providing a head pressure correction to 0.008 psia [0.570 mbar]. The pressure generated by our DH Instruments Model 50300-01 and Model 50000 Class S fundamental (deadweight) pressure standards includes corrections for local gravity, air buoyancy, and pressure and temperature effects on the cross-sectional area of the pistons. With these corrections, the pressure generated by the pressure standards is accurate to 0.01% of reading. The typical values used in calibration at our facility are "non-standard" values due to our 4251 ft [1296 m] elevation.

$P_{\text{atm}}$	=	12.6 psi [869 mbar] (measured continuously during calibration)
$P_{\text{head}}$	=	0.033 psi/in [0.897 mbar/cm]
Local gravity	=	9.797930 m/s <sup>2</sup> (interpolated from National Geodetic Survey data <a href="http://www.ngs.noaa.gov/">http://www.ngs.noaa.gov/</a> )
air density	=	1.015 gm/cm <sup>3</sup> (buoyancy correction is 23 ppm less than standard)
Piston pressure effect	=	60 ppm at 10,000 psi [689 bar]
Piston temperature effect	<	50 ppm typical

## 4.4 Pressure Control Required for Calibration

Quartzdyne Pressure Transducers measure absolute pressure. The pressure that the transducer senses during our calibration is the sum of the atmospheric pressure, head pressure, and the pressure generated by the (gauge) pressure source.

The calibration equation is a polynomial in temperature and pressure. The order of the equation determines the number of different pressures and temperatures required in the calibration. As a minimum, at least one more data point is required than the order of the fit for each variable. Some redundancy in the pressure and temperature measurement is recommended. For example, in our calibrations we typically apply a sequence of pressures at each of five or six temperatures. Four temperatures are required for a third order fit, five for a fourth order. At each temperature, measurements are made at ambient atmospheric pressure, at 400 psia [27.6 bar], and at least every 20% of range up to full scale. The pressures are typically applied in the sequence:

ambient, 20%, 60%, 80%, 100%, 90%, 70%, 40%, 400 psia.

It is not necessary to follow this exact procedure, but this sequence has several advantages:

- (1) It provides a large enough sample of different pressures (four are required for a third order curve fit; nine unique pressures are used) without excessive repetition.
- (2) Two low pressure points show the zero return. (The lowest pressure at which our automated fundamental pressure standard provides 0.01% of reading accuracy is 400 psia [27.6 bar]; at lower pressures the error is a constant 0.02 psia [0.00138 bar].)
- (3) It provides the same number of increasing and decreasing pressure data points; the curve fit will be forced through the center of any apparent hysteresis loop.

## 4.5 Temperature Control Required for Calibration

The pressurization process described above must be performed at several temperatures as dictated by the fit order. The temperature need not be measured (unless a calibrated temperature output is desired), but it must be stable. A temperature chamber with stability of at least 0.25°C is recommended. Monitoring the temperature sensor crystal will provide an indication of the thermal stability of the transducer; when the temperature sensor has stabilized, a pressure calibration cycle may begin. Note that the temperature sensitivity varies from approximately 115 Hz/°C at -40°C to 260 Hz/°C at 200°C.

It is desirable that the temperature of the three crystals in the transducer be as uniform as possible. Beware of thermal gradients that can develop along the length of the transducer as these may cause significant errors in the calibration. Figure 17 shows possible sources of temperature gradients that may occur in a calibration oven or bath. The error will be most pronounced in the areas of high thermal sensitivity as shown in Figure 8.

At least four temperatures are dictated by a third-order temperature dependence. At least five temperatures are required for a fourth order dependence. The six- to seven-temperature calibration done by Quartzdyne provides adequate redundancy. It is recommended that the entire temperature range of use be covered in the calibration. Specifications of the transducer outside the factory calibrated temperature range are not guaranteed.

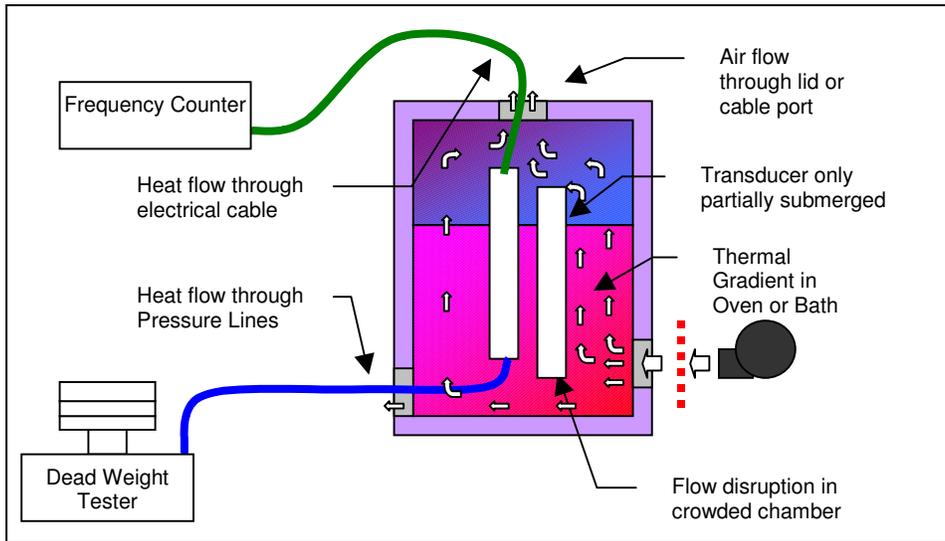


Figure 17. Possible sources of temperature gradients in a calibration oven or bath.

### 4.6 Frequency Measurement during Calibration

In addition to proper pressure and temperature control, calibration requires measurement of the transducer's output frequencies. Normally this is done with the frequency counter that is to be used in the field. The Quartzdyne QCOM may be used to measure the transducer frequencies if the customer's tool will be using the transducer reference frequency as the time base. At Quartzdyne, Agilent 53131A frequency counters are used to measure the absolute frequency of all three signals (Figure 18). The counters are linked to an Agilent 58501A GPS receiver that provides frequency accuracy to better than  $1 \times 10^{-12}$ . Reference-based coefficients are generated by mathematically computing the reference-based frequencies per the equation:

$$F_s(\text{reference-based}) = 7.2E6 \times \frac{F_s(\text{true})}{F_r(\text{true})}$$

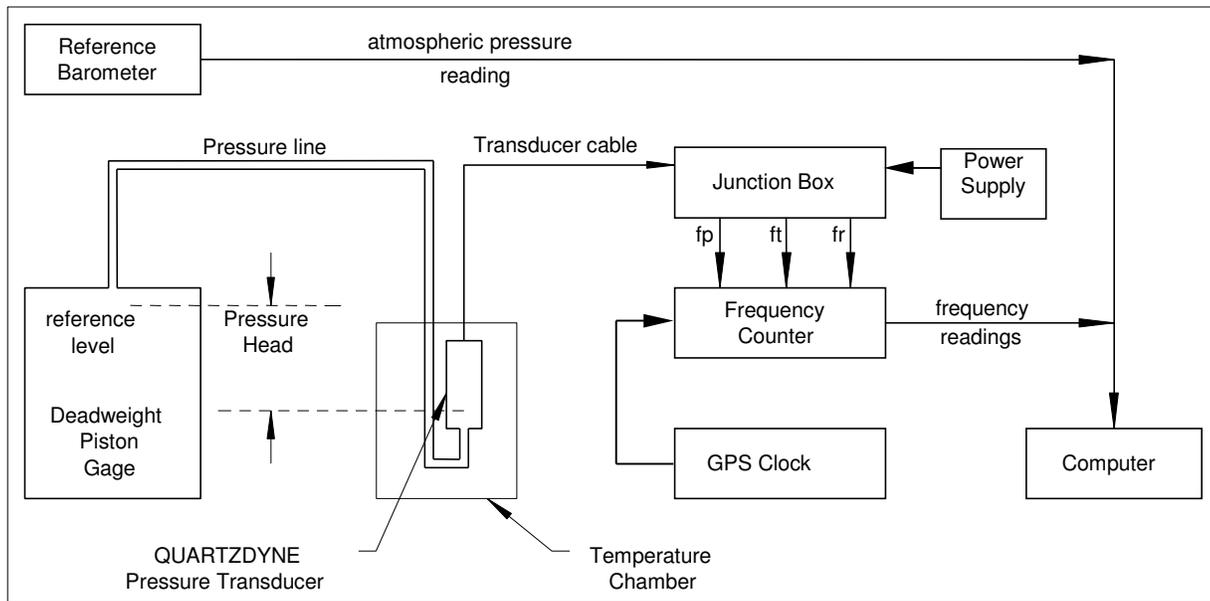


Figure 18. Transducer Calibration

## 5 Calibration Coefficient Files

Each transducer is supplied with multiple sets of coefficients as listed below. These are used to calculate pressure and temperature from the measured frequencies. Each type of coefficients is applicable to a specific frequency counter type. It is important that the correct coefficients be used.

The coefficient file name is the 6-digit serial number of the transducer followed by one of five file extensions indicating the type of coefficients. For laboratory transducers the serial number may be appended an "L" indicating a reduced temperature-range calibration (0 to 40 °C as compared to -40 to +85 °C). The "L" coefficients should give slightly better results than the normal coefficients within the reduced temperature range.

123456.CFF	Standard Pressure Coefficients
123456.CFT	Standard Temperature Coefficients
123456.CRF	Reference-based Pressure Coefficients
123456.CRT	Reference-based Temperature Coefficients
123456.HEX	Intel-Hex digital coefficients for use with QCOM

**Standard coefficients** (CFF/CFT) should be used only if the frequency is counted using a frequency counter with its own time base. The accuracy of the pressure and temperature calculation will be dependent on the accuracy of the time base in the counter. The file format for Standard Coefficients is described in Section 5.1.

**Reference-based coefficients** (CRF/CRT) should be used if the transducer's internal 7.2 MHz reference frequency is used as the time base in frequency counting as described in Section 3.5. Using Reference-based Coefficients eliminates the need to provide a calibrated time-base, resulting in improved accuracy. The file format for Reference-based Coefficients is the same as for Standard Coefficients as described in Section 5.1. It was the file format of choice for use with the Series I (no longer available).

**Hex digital coefficients** are required when using a Quartzdyne QCOM interface with either a frequency or digital transducer. Coefficients for both Pressure and Temperature are included in a single file using the Intel-Hex file format as described in Sections 5.4 through 5.8. The coefficients are stored in EEPROM on digital transducers. They provide the same benefit as Reference-based coefficients. It is recommended that the Hex coefficients be used for new designs wherever possible.

## 5.1 Standard and Reference-based Calibration Coefficients

Standard and Reference-based Coefficient files are plain text. Each line in the coefficient file represents a single field as described below. No blank lines or comments are allowed. The file extension indicates the coefficient type as described above.

**Table 2. Coefficient File Format**

Line	Symbol	Description	Typical Value (.CRF)	Typical Value (.CRT)
1	S/N	Pressure Sensor ID**	157879R	157879R
2	CT	Calibration Type	Pressure	Temperature
3	CU	Calibration Units	psia	°C
4	NT	Polynomial Order in Temperature*	3	3
5	PT	Temperature Prescale Algorithm	1	1
6	MT	Temperature Scaling Factor*	0.01	0.01
7	FT0	Temperature Offset Frequency*	58020	58020
8	NP	Polynomial Order in Pressure*	3	0
9	PP	Pressure Prescale Algorithm	1	1
10	MP	Pressure Scaling Factor	0.01	0.01
11	FP0	Pressure Offset Frequency	21982	21982
12	A0	First Fit Coefficient	1.10390186144E+01	2.51641904936E+01
13	A1	Fit Coefficient	-1.28452244351E-01	-7.27120283063E-01
.	.		.	.
.	.	Number of coefficients is variable ( $\leq 25$ );	.	.
.	.	$N = (NT+1) * (NP+1)$ .	.	.
.	.		.	.
N+11	D3/A3	Last Fit Coefficient (Symbol varies with NT, NP)	-2.91212554073E-14	-6.78716126821E-07
N+12	SPAN	May be used for units conversion*	1.000000000000	1.000000000000
N+13	ZERO	May be used for units conversion*	0	0
N+14	TMIN	Minimum temperature of calibration (°C)	25	25
N+15	TMAX	Maximum temperature of calibration (°C)	175	175
N+16	PMIN	Minimum pressure of calibration (psia)	12	12
N+17	PMAX	Maximum pressure of calibration (psia)	20000	20000
N+18	DATE	Date of calibration	08 Sep 2003	08 Sep 2003
N+19	Model	Transducer model	SPB002-20-177	SPB002-20-177

**\* Warning! Typical values are not fixed, and should not be assumed. These are subject to change without notice. Do not assume values for Nt, Np, Mt, Mp, Span or Zero!**

**\*\* For Frequency output transducers an “R” in the Sensor ID field indicates referenced-based coefficients (see Section 3.5)**

The values of NP and NT will vary depending on sensor technology, and the temperature and pressure ranges of the calibration. The user is cautioned not to hard-code fit order or for pressure or temperature. Historic and future transducer designs may include temperature frequency outputs with some pressure sensitivity. In Quartzdyne calibrations, the product of  $(NT + 1) * (NP + 1)$  will not exceed 25 for either coefficient type.

The calibration type and units are provided in the coefficient file to allow for calibrations in different units and of different parameters. The output can be calculated from the two frequencies as follows:

## 5.2 Calculations using Standard or Reference-based Coefficients

Scale the frequencies according to the prescale algorithm specified in the coefficient file. All Standard and Reference-based coefficients currently use Prescale type 1 for both PP and TP which has the following form:

$$\begin{aligned}XP &= MP(FP - FP0) \\XT &= MT(FT - FT0),\end{aligned}$$

where FP and FT are the measured pressure and temperature frequencies, respectively.

The output is calculated from the coefficients and the two pre-scaled values, XP and XT, using the following equation:

$$Output = A + XP(B + XP(C + XP(D + XP(E))))),$$

where the coefficients A, B, C, D, and E are computed as:

$$\begin{aligned}A &= A0 + XT(A1 + XT(A2 + XT(A3 + XT(A4)))) \\B &= B0 + XT(B1 + XT(B2 + XT(B3 + XT(B4)))) \\C &= C0 + XT(C1 + XT(C2 + XT(C3 + XT(C4)))) \\D &= D0 + XT(D1 + XT(D2 + XT(D3 + XT(D4)))) \\E &= E0 + XT(E1 + XT(E2 + XT(E3 + XT(E4))))\end{aligned}$$

The expansion above assumes a value of 4 is for both NP and NT. In a typical case of NP = 3 and NT = 3, the terms A4, B4, C4, D4, E and E0 through E4 would not be applicable and would be assumed to be zero. An alternate form of the same equation using indexed notation for the coefficients is shown below.

$$Output = \sum_{i=0}^{Np} \sum_{j=0}^{Nt} C_{ij} (MP(FP - FP0))^i (MP(FT - FT0))^j$$

Pressure transducers calibrated by Quartzdyne are normally calibrated to pressure in psi absolute and temperature in °C. Units-conversion can be accomplished by using the appropriate SPAN and ZERO values. When making modifications to SPAN and ZERO, be sure to edit Line 3 ("Calibration Units") appropriately. The equation allows the zero to be entered in the desired units:

$$Output \text{ (desired units)} = SPAN \times Output \text{ (base units)} + ZERO \text{ (desired units)}$$

$$\begin{aligned}Pressure \text{ (bar)} &= 0.0689476 \times Pressure \text{ (psia)} + 0 \\Temperature \text{ (}^\circ\text{F)} &= 1.8 \times Temperature \text{ (}^\circ\text{C)} + 32 \text{ }^\circ\text{F}\end{aligned}$$

Example code is provided in the next section and on our website ([www.quartzdyne.com](http://www.quartzdyne.com))

### 5.3 Standard Coefficient Example Code

The following VBA code snippet is taken from Calcfunctions.xls which may be downloaded from our website [www.quartzdyne.com](http://www.quartzdyne.com). It demonstrates calculation of Pressure or Temperature from Quartzdyne Standard coefficient files. Before calling this function, the coefficient file is pasted into the spreadsheet at any convenient location. The measured frequencies Ft and Fp and a reference to the coefficients are passed to this function.

```
Public Function qdCfCalc(Fp As Double, Ft As Double, cfFile As Range) As Double
    ' Calculates pressure or temperature from counter readings
    ' using a standard Quartzdyne coefficient file.
    ' The file contents should be pasted into the spreadsheet at any convenient location.
    ' cfFile should be set to entire range of cells that contain the coefficient file.
    '
    Dim xp As Double, xt As Double
    Dim i As Integer, j As Integer, n As Integer
    Dim Temp As Double

    ' Apply Prescaling to Fp and Ft
    xt = cfFile.Item(6) * (Ft - cfFile.Item(7))      ' xt = mt * (ft - ft0)
    xp = cfFile.Item(10) * (Fp - cfFile.Item(11))    ' xp = mp * (fp - fp0)

    ' n points to last coefficient, nCoefs = (nt+1)*(np+1)
    n = (cfFile.Item(4).Value + 1) * (cfFile.Item(8).Value + 1) + 11
    For i = 0 To cfFile.Item(8).Value ' outer loop for np, xp polynomial
        qdCfCalc = qdCfCalc * xp      ' multiply by xp (0 first time through loop)
        Temp = 0
        For j = 0 To cfFile.Item(4).Value ' inner loop for nt, xt polynomial
            Temp = xt * Temp + cfFile.Item(n) ' process coefficients from last to first
            n = n - 1
        Next j
        qdCfCalc = qdCfCalc + Temp ' add temperature compensated pressure coefficient
    Next i

    ' Calculate output in user units using SPAN and ZERO
    n = i * j ' find last coefficient again
    qdCfCalc = cfFile.Item(n + 12) * qdCfCalc + cfFile.Item(n + 13) ' output = calc *
    SPAN + ZERO
End Function
```

## 5.4 Hex Coefficient Format

Coefficients for both Digital and Frequency Transducers may be supplied in an Intel-Hex format file (see section 5.8). The file is a hex (text) representation of binary data stored in the EEPROM of Quartzdyne Digital Pressure Transducers. Hex coefficients should be used for all digital transducers or when using a QCOM to communicate with a Frequency-output transducer. The 256-byte data includes both Pressure and Temperature coefficients.

**Table 3. Binary Coefficient File Format**

Address	Bytes	Coding	Symbol	Description	Typical Value	Interpretation
000 - 001	2	BCD	Type	File Type	0x0D01	QD BCF
002 - 003	2	BCD	Version	File Version	0x0123	1.23
004 - 007	4	BCD	SerNo	Transducer Serial Number	0x0D062351	SN 062351
008 - 00F	8	ASCII	PartNo	Root Part Number (Left Justified)	QSB001	QSB001
010 - 013	4	BCD Date	CalDate	Calibration Date (yyyymmdd)	0x20011231	December 31, 2001
014 - 014	1	signed[8]	Pmin	Min Pressure (kpsi)	0x00	0
015 - 015	1	signed[8]	Pmax	Max Pressure (kpsi)	0x10	16000
016 - 016	1	signed[8]	Tmin	Min Temperature (x 5 °C)	0xF8	-40
017 - 017	1	signed[8]	Tmax	Max Temperature (x 5 °C)	0x10	80
018 - 018	1	code[8]	Cal1.Type	Output #1 Calibration Type - see coding	0x01	Pressure psi, bar
019 - 019	1	code[8]	Cal1.Prescale	Output #1 Prescale Type - see coding	0x00	0
01A - 01A	1	signed[8]	Cal1.N1	Output #1 Fit Order in X1 (Pressure)	0x03	3
01B - 01B	1	signed[8]	Cal1.N2	Output #1 Fit Order in X2 (Temperature)	0x03	3
01C - 01F	4	float[32]	Cal1.S1	Output #1 Scale Factor Standard Units	0x39800000	1 psi / 4096
020 - 023	4	float[32]	Cal1.S2	Output #1 Scale Factor Alternate Units	0x378D3466	0.0689476 bar / 4096
024 - 027	4	signed[32]	Cal1.OFS2	Output #1 Offset for Alternate Units	0x00000000	0 psi / 4096
028 - 08B	100	signed[32]	Cal1.C(i,j)	Output #1 Coefficients (Max 25)		C00,C01..Cij
08C - 08C	1	code[8]	Cal2.Type	Output #2 Calibration Type - see coding	0x02	Temperature °C, °F
08D - 08D	1	code[8]	Cal2.Prescale	Output #2 Prescale Type - see coding	0x03	0
08E - 08E	1	signed[8]	Cal2.N1	Output #2 Fit Order in X1 (Pressure)	0x00	0
08F - 08F	1	signed[8]	Cal2.N2	Output #2 Fit Order in X2 (Temperature)	0x03	3
090 - 093	4	float[32]	Cal2.S1	Output #2 Scale Factor Standard Units	0x39800000	1 °C / 4096
094 - 097	4	float[32]	Cal2.S2	Output #2 Scale Factor Alternate Units	0x39E66666	1.8 °F / 4096
098 - 09B	4	signed[32]	Cal2.OFS2	Output #2 Offset for Alternate Units	0x00011C72	( 32 / 1.8 ) °C * 4096
09C - 0FB	96	signed[32]	Cal2.C(i,j)	Output #2 Coefficients (Max 24)		C00,C01..Cij
0FC - 0FE	3	Unsigned[8]	EOF	End of File	0xFF0000	
0FF - 0FF	1	Unsigned[8]		Checksum		0x00-SUM(000..0FE)

**Table 4. Calibration Type Coding**

Value	Meaning
0	None
1	Pressure in psi or bar
2	Temperature in °C or °F
255	End of File

**Table 5. Prescale Type Coding**

Value	Meaning
3	$Z = \sum C_{ij} \cdot (X_P/2^{24})^i \cdot (X_T/2^{24})^j$

## 5.5 Hex Coefficient Checksum Calculation

The sum of all bytes in the coefficient file should add to 0x00 using 8-bit addition. The checksum may be calculated as the two's compliment of the sum of all previous bytes.

### 5.6 Pressure and Temperature Calculations using Hex File coefficients

Pressure and Temperature (Z) are calculated using a polynomial expansion of counts Xp and Xt as read from a digital transducer or a QCOM interface according to the following equations:

$$Z_{out}(Standard Units) = S1 \sum_{i=0}^{Np} \sum_{j=0}^{Nt} C_{ij} \left(\frac{Xp}{2^{24}}\right)^i \left(\frac{Xt}{2^{24}}\right)^j$$

$$Z_{out}(Alternate Units) = S2 \left\{ OFS2 + \sum_{i=0}^{Np} \sum_{j=0}^{Nt} C_{ij} \left(\frac{Xp}{2^{24}}\right)^i \left(\frac{Xt}{2^{24}}\right)^j \right\}$$

Standard units are pressure in psi and temperature in °C. Alternate units are bar and °F respectively.

In systems with limited processing power, the polynomial may be computed efficiently using 32-bit signed integer math if it is factored as shown below (example is a 3x4 fit – actual fit order may vary):

$$Z = Temp_0 + \frac{Xp}{2^{24}} \times \left( Temp_1 + \frac{Xp}{2^{24}} \times \left( Temp_2 + \frac{Xp}{2^{24}} \times (Temp_3) \right) \right)$$

where

$$Temp_0 = C_{00} + \frac{Xt}{2^{24}} \times \left( C_{01} + \frac{Xt}{2^{24}} \times \left( C_{02} + \frac{Xt}{2^{24}} \times \left( C_{03} + \frac{Xt}{2^{24}} \times (C_{04}) \right) \right) \right)$$

$$Temp_1 = C_{10} + \frac{Xt}{2^{24}} \times \left( C_{11} + \frac{Xt}{2^{24}} \times \left( C_{12} + \frac{Xt}{2^{24}} \times \left( C_{13} + \frac{Xt}{2^{24}} \times (C_{14}) \right) \right) \right)$$

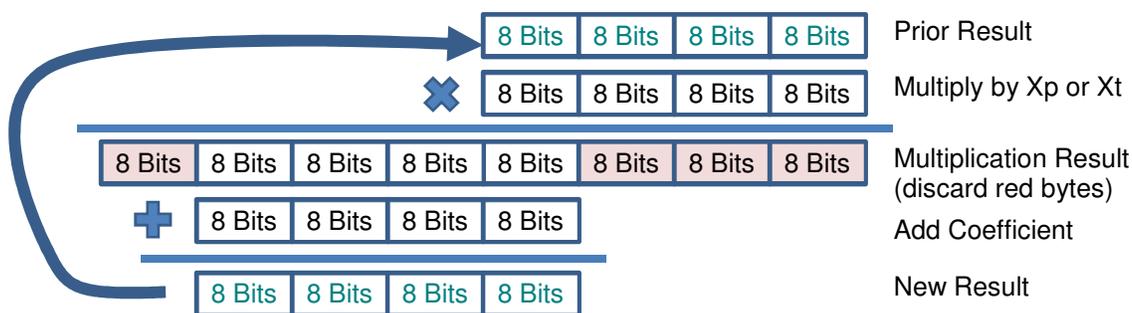
$$Temp_2 = C_{20} + \frac{Xt}{2^{24}} \times \left( C_{21} + \frac{Xt}{2^{24}} \times \left( C_{22} + \frac{Xt}{2^{24}} \times \left( C_{23} + \frac{Xt}{2^{24}} \times (C_{24}) \right) \right) \right)$$

$$Temp_3 = C_{30} + \frac{Xt}{2^{24}} \times \left( C_{31} + \frac{Xt}{2^{24}} \times \left( C_{32} + \frac{Xt}{2^{24}} \times \left( C_{33} + \frac{Xt}{2^{24}} \times (C_{34}) \right) \right) \right)$$

The innermost loop is the last coefficient (C<sub>34</sub> in the example). Calculation proceeds by repeatedly adding each coefficient to the prior result, multiplying by either Xp or Xt and then dividing by 2<sup>24</sup>. The inner loop multiplies by Xt creating a temperature-compensated coefficient for the outer loop which multiplies the temporary result by Xp. See the example code in section 5.7.

In systems without floating point processors, the multiplication and 2<sup>24</sup> scaling may be accomplished by computing the 64 bit result of Xp or Xt times the previously accumulated value, and then selecting bytes 7 thru 4 as the result as shown in Figure 19. If the eighth byte is non-zero, an overflow has occurred.

Figure 19. Polynomial computation using integer math.



## 5.7 Hex Coefficient Example Code

The following VBA code snippet is taken from CalcFunctions.xls which may be downloaded from our website ([www.quartzdyne.com](http://www.quartzdyne.com)). It demonstrates calculation of Pressure or Temperature from a Quartzdyne Hex coefficient file. Before calling this function, the Hex file is first parsed into a single Hex string using the function qdHexFileData(). The resultant string is then passed to this function along with the counts as read from a Quartzdyne Pressure Transducer. Within the function, Hex data is further parsed using calls to qdHexGetInt(), qdHexGetLong and qdHexGetFloat, also defined in CalcFunctions.xls.

```
Public Function qdHexCalc(xp As Double, xt As Double, hexData As String, Optional calcT
As Boolean = False, Optional altUnits As Boolean = False) As Double
    ' Calculates pressure from I2C Digital Transducer Readings
    ' using a Quartzdyne Hex coefficient file.
    ' The file contents should be pasted into the spreadsheet at any convenient location.
    ' The data portion must then be extracted using the qdHexFileData function.
    ' Pressure is calculated from the extracted data in the hexData string parameter.
    ,
    Dim xpp As Double, xtp As Double
    Dim Z As Double, Temp As Double
    Dim i As Integer, j As Integer, n As Integer
    Dim np As Integer, nt As Integer
    ,
    ' n points to last coefficient
    ,
    xpp = xp * 2 ^ -24    ' Only prescale type 3 supported for digital coefficients
    xtp = xt * 2 ^ -24
    If calcT Then base = 140 Else base = 24

    n1 = qdHexGetInt(hexData, base + 2) ' Fit order in Xp
    n2 = qdHexGetInt(hexData, base + 3) ' Fit order in Xt
    n = 4 * (n1 + 1) * (n2 + 1) + base + 12 ' point to last coefficient
    Z = 0
    For i = 0 To n1        ' outer loop for np, xp polynomial
        Z = Z * xpp        ' multiply by xp (0 first time through loop)
        Temp = 0
        For j = 0 To n2    ' inner loop for nt, xt polynomial
            Temp = xtp * Temp ' process factored using coefficients from last to first
            Temp = Temp + qdHexGetLong(hexData, n)
            n = n - 4
        Next j
        Z = Z + Temp ' add temperature compensated pressure coefficient
    Next i

    If (altUnits) Then
        Z = Z + qdHexGetLong(hexData, base + 12) ' OFS2 placed just before
coefficients
        qdHexCalc = Z * qdHexGetFloat(hexData, base + 8) ' alternate scale factor S2
    Else
        qdHexCalc = Z * qdHexGetFloat(hexData, base + 4) ' primary units scale factor S1
    End If
End Function
```

