OPERATING MANUAL
for
QUARTZDYNE®

Digital Pressure Transducer

QUARTZDYNE, INC.
A DOVER COMPANY

www.quartzdyne.com

Revision History

FPGA/ASIC ID	BCF ID	Date	Comments
0D020102	N/A	April 14, 2001	Initial Preliminary Release
0D020103	0D010100	August 24, 2001	Fix overflow problem when gate time > 1.3 seconds Add calibration coefficient sections
0D020201	0D010100	January 3, 2002	Initial Production Release Two-byte addressing for 64k EEPROM Change status bit labels from “Valid” to “Detect” Add Write Protect control for EEPROM Coefficient files provided in MSB first format only (0D01)
0D020201	0D010100	March 19, 2001	Clarify dummy read/trigger command
0D020201	0D010100	December 15, 2003	Add Connector Pin Assignments. Clarify EEPROM Protocol. Describe EEPROM Hung Bus bug. Include general transducer information
0D020301 0D050301	0D010100	February 14, 2006	Change start-up sequence to avoid “stuck status bit” condition.
0D020302 0D050302		July 21, 2006 April 10, 2007 July 26, 2007	Improved power on reset in FPGA Add Section 3.4 concerning sticky SDA line (power-on reset warning) Add Sections 3.5 and 3.6 - recommended start-up procedures. Increase maximum current specifications, Clarify Status/FPGA ID addressing
0D050303		September 1, 2007 February, 23 2009	Reduce startup time with ASIC implementation Remove Electrical Specs/add link to Specs
0D090402		April 16, 2009	Updated to cover digital ASIC 4.02 enhancements. Checksum, 4 byte Control Word, 7.2 MHz REF_OUT option, and A1& A2 as outputs.
		Nov 16, 2009	Include 7-pin universal cabling with reference out EEPROM Warning
		January, 2010	Describe redundant coefficient storage.
		August, 2010	Fix defaults and description for 7.2MHz and A1P/A2P pins

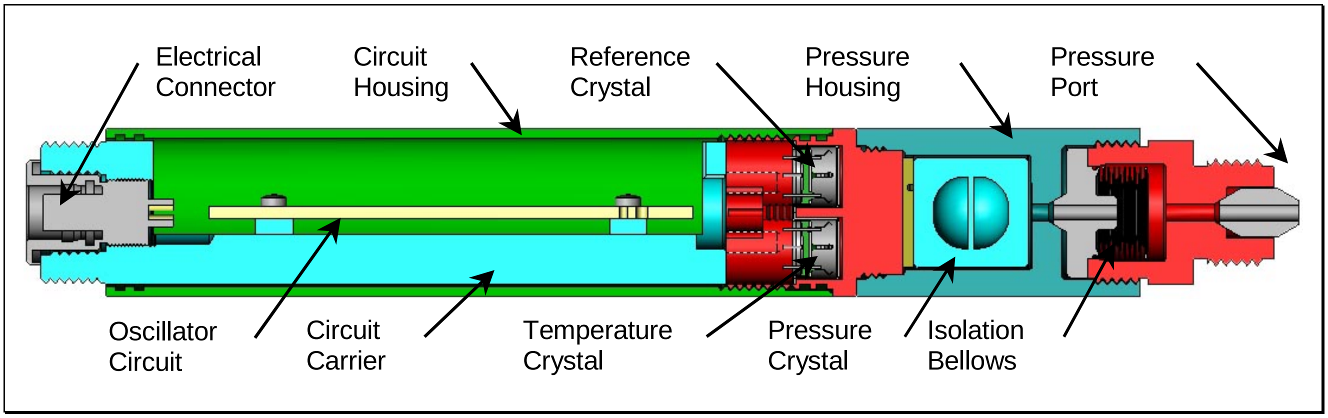
Quartzdyne Digital Pressure Transducer
Operating Manual

Table of Contents

1 Theory of Operation

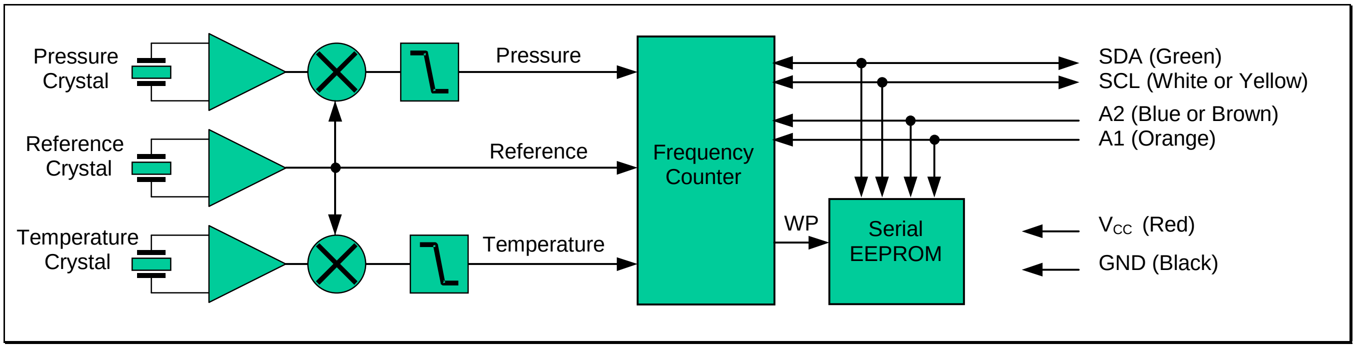
All QUARTZDYNE® Pressure Transducers contain three quartz crystal sensor elements. The first of these is sensitive primarily to exposed pressure, the second responds to temperature, and the third has minimal sensitivity to either pressure or temperature. The crystals are arranged mechanically to provide 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 DMB shown).



The Digital Transducer Circuit contains three quartz crystal oscillators (Pressure, Temperature, and Reference), mixers, a frequency counter, and a serial EEPROM (Figure 2). The pressure and temperature signals are mixed with the reference signal to improve resolution in the counter. The frequency counter outputs two numbers: the ratio of the mixed Pressure Frequency to Reference Frequency and the ratio of the mixed Temperature Frequency to Reference Frequency. Pressure and Temperature are calculated by the end user from these ratios using coefficients stored in the EEPROM. Communication is via an I^{2}C compatible 2-wire serial interface. See our website (www.quartzdyne.com) for detailed Electrical Specifications.

Figure 2. Digital Pressure Transducer Block Diagram



For a complete measurement system, the user must provide power and a means for calculating pressure from the measured frequencies and provided coefficients. Storage and/or transmission of the data must also be considered. The QUARTZTDYNE® Q-Link interfaces to a PC in a laboratory environment and calculates pressure and temperature for up to four digital transducers. It also provide basic data logging functions

1.1 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.

1.2 Sensor Output Changes with Pressure and Temperature.

Figure 3 through Figure 6 depict the typical change in the output counts of a DMB20K digital transducer with changes in pressure and temperature. Figure 3 shows the nominal change in Temperature Output versus temperature. All temperature sensors show very similar sensitivities, but the counts at 25°C will vary from unit to unit. Figure 4 shows the change in pressure output counts with changes in pressure and temperature. Note that changes in temperature produce changes in both zero and span.

The data from Figure 4 has been re-plotted in Figure 5 for additional examination. In Figure 5, the pressure output counts are 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 transducer has been designed to minimize transient errors in down hole work. Care has been taken to provide good thermal coupling between the pressure and temperature crystals. In a uniform and static temperature environment, the two crystals will be at the same temperature and the output will be fully compensated. Under transient conditions (temperature ramps, or large pressure steps), a small temperature difference between the two sensors is possible. Figure 6 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 10psi/°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 web site (www.quartzdyne.com) for a detailed transient report comparing the performance of various pressure transducer configurations.

Figure 3. Typical Temperature Sensor Output as a function of Temperature.

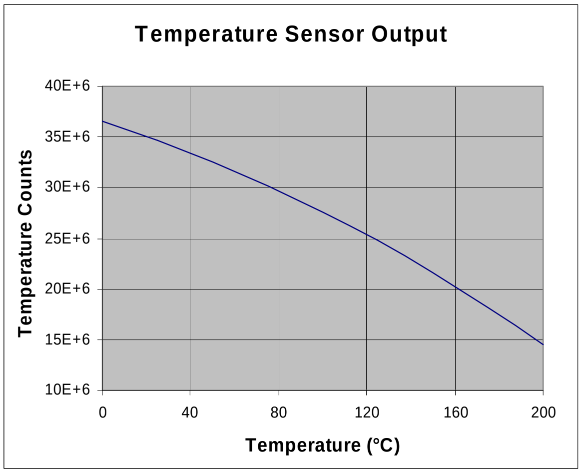


Figure 4. Typical Pressure Sensor Output at various temperatures.

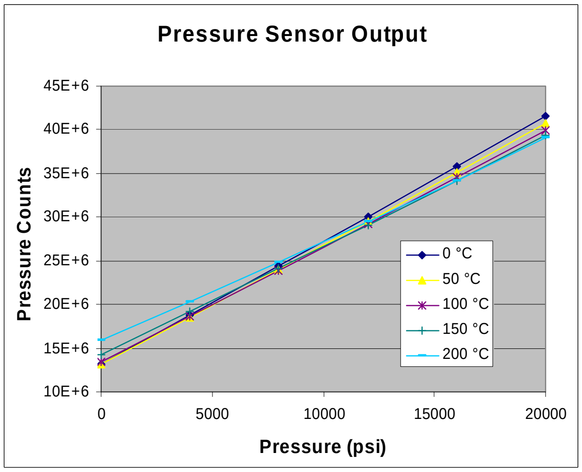


Figure 5. Pressure Sensor Output plotted vs. Temperature and normalized to the minimum (zero - sensitivity) point for each pressure.

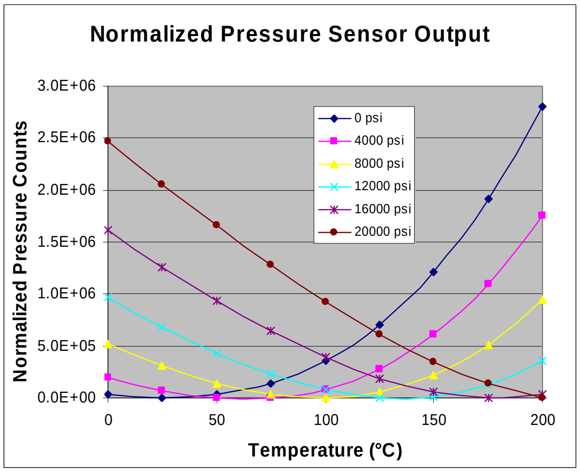
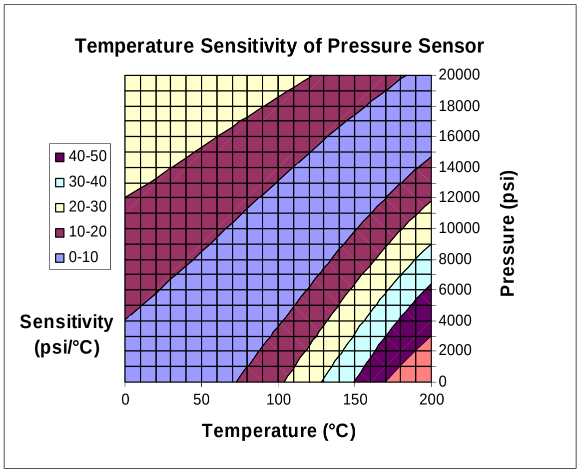


Figure 6. Pressure Sensor Temperature sensitivity gradient plot showing low sensitivity along a typical well gradient. Transient errors will be worse in ranges with high sensitivity.

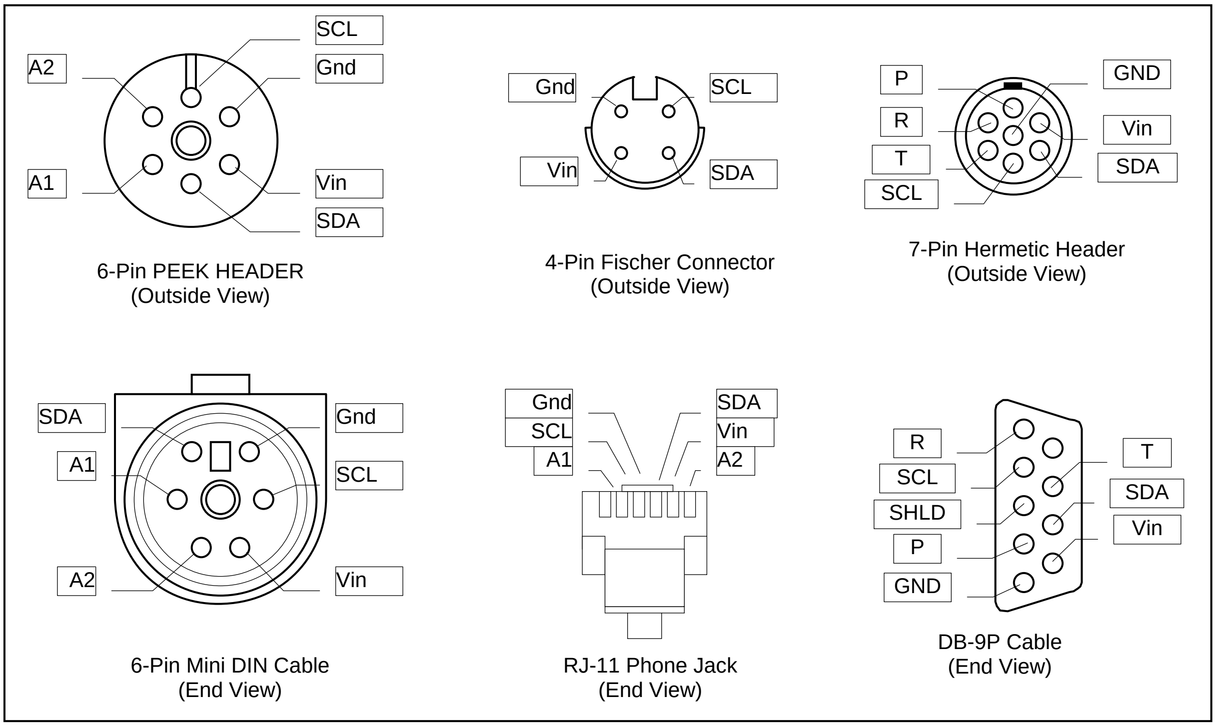


2 Interface Requirements

2.1 Electrical Connections

Each device requires power (2.7 to 5.5 V_{DC}) and two signaling lines SDA and SCL. A1, A2 and R may also be available, but should be connected only if used. The signaling lines are open collector, and should be tied to V_{IN} on the master board using a suitable pull-up resistor. Lower values of R_P are required for longer cables, and higher clock speeds. A1 and A2 have weak pull-ups and are susceptible to noise when not connected. R contains a 7.2MHz high-frequency signal, and should be isolated from the other lines to prevent cross-talk. The length of these lines should be minimized (<12" recommended) to avoid noise problems and to minimize power supply current through R_P. A 2-twisted pair cable is recommended, with SDA and V_{IN} twisted together, and SCL and GND twisted together. A 7-conductor cable with an overall shield is recommended when the optional lines are to be used. V_{IN} and GND should be bypassed with a 0.1μF capacitor at the master end of the cable. GND is connected internally to the chassis. Shielding may be required in electrically noisy environments to prevent interference on the communication lines. See Figure 7 for connector pin assignments. Table 1 shows wire colors for units provided with flying leads.

Figure 7. Pin Assignments for Various Digital Transducer Connector Options.



6-Pin PEEK HEADER
(Outside View)

4-Pin Fischer Connector
(Outside View)

7-Pin Hermetic Header
(Outside View)

6-Pin Mini DIN Cable
(End View)

RJ-11 Phone Jack
(End View)

DB-9P Cable
(End View)

Table 1. Pin and wire labels and their functions

Label	Function	Wire Color (Digital ASIC)	Alternate Colors (FPGA)
Vin	Power Supply (Pos)	Blue	Red
GND	Power Supply (Neg)/Chassis	Black	Black
SHLD	Shield Termination/Chassis	-	-
R	Reference Frequency Output	White	-
A2/P	Address 2 / Pressure Frequency Output	Purple	Blue
A1/T	Address 1 / Temperature Frequency Output	Yellow	Orange
SCL	SCL (Serial Clock)	Slate	White
SDA	SDA (Serial Data)	Green	Green

2.2 Addressing

Up to four transducers may be wired together in a single system. The individual transducers are distinguished using the A2 and A1 inputs. If connected to GND, these are interpreted as ‘0’; if left floating, A2 and A1 are interpreted as ‘1’. Warning! Do not connect these inputs to V_{CC}, as this may cause internal device damage. For multiple transducer systems, A1 and A2 must be connected appropriately (“00”, "01","10","11") to provide a unique address for each device. The device addresses are shown in Table 2. For transducers with four pin connectors, the address lines A2 and A1 are accessible inside the transducer. These are normally open when shipped (address "11").

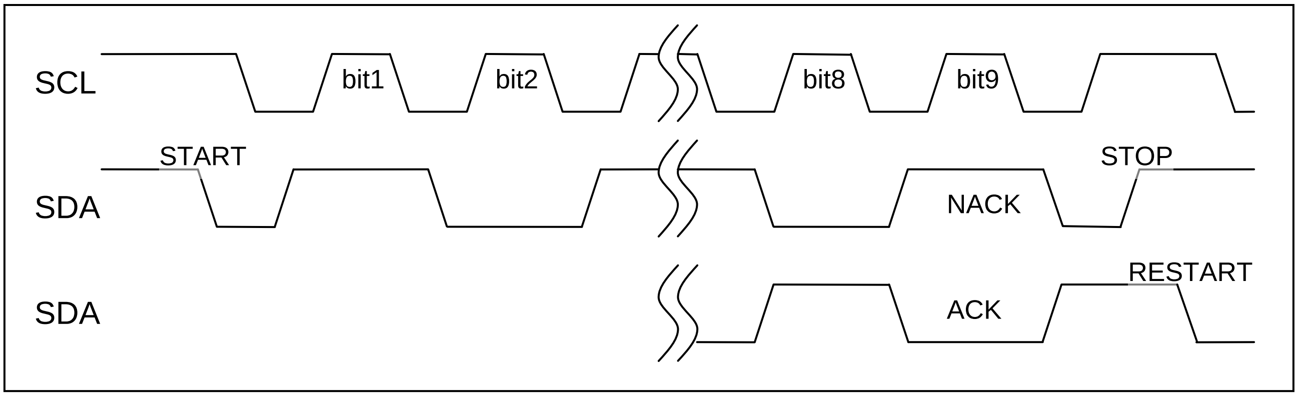
Table 2. Device Addresses

	MSB							LSB
Frequency Counter	1	0	0	1	A2	A1	T/P	R/W
Status and Control Registers	1	0	0	1	A2	A1	Status/ID	R/W
EEPROM	1	0	1	0	A2	A1	0	R/W

2.3 Signaling

The transducer has been designed for compatibility with the NXP I^2C interface. The SDA and SCL lines are normally pulled high by a resistor on the master device. Data transitions of SDA are allowed only while SCL is low. A START condition is signaled by the master asserting SDA low while SCL is high, and a STOP condition is signaled by a low to high transition of SDA while SCL is high. Data is transferred eight bits at a time, followed by an ACK (SDA low) or NACK (SDA high) which is generated by the receiving device. A message consists of a START condition followed by an Address Byte (MSB first) generated by the master, followed by an ACK generated by the slave. If the LSB of the Address Byte is low (WRITE), the master continues to send data, the slave generating ACK as appropriate, until the end of message is indicated by a STOP condition generated by the master. If the LSB bit of the Address Byte is high (READ), the bus changes direction, and further data is supplied by the slave, with ACK generated by the master. The master indicates receipt of the last byte with an NACK followed by a STOP condition.

Figure 8. I2C bus timing



2.4 Power-on Reset Warnings

Some FPGA and EEPROM devices contained in transducers do not come out of power-on reset gracefully. Two separate problems have been observed.

Transducers with FPGA ID’s lower than 3.02 will occasionally hold SDA low during a Write Control, or Read FPGA ID command (3.4) immediately following a power-up condition. This condition has been remedied in versions 3.02 and higher. When this occurs the slave holds the SDA line low, preventing further communication. The master can clear this condition by issuing 9 clock pulses while allowing the SDA line to float, followed by a STOP bit. This clears all devices on the I^2C bus, and is applicable any time the master observes a stuck SDA line.

A similar problem exists in the EEPROM. A Read-Specific Address command (4.2) issued after a power-on reset will cause some devices to latch the SDA line low at certain temperatures, preventing further communication. Unfortunately, this condition is not cleared by issuing 9 clock pulses. The only remedy is to cycle the power. This problem can be avoided by issuing a Read-Current Address command (4.1) prior to sending any other commands to the EEPROM.

EEPROM coefficient storage is limited to 180°C. Above this temperature, the data is likely to become corrupt. In systems where Pressure and Temperature will be calculated locally, it is important that the checksum in the coefficient file be verified before using the data. As of January 2010, four redundant copies of the coefficients are provided in successive memory locations. The system may use this redundancy to re-create the true coefficients in case of corruption.

2.5 Power-on Sequencing

To assure reliable data at power-on, the following minimum wait-time sequence is recommended:

1. Apply power to devices.
2. Wait at least 0.1 seconds for internal power supply to stabilize.
3. Issue an EEPROM Read-Current Address command if the EEPROM is to be read anytime during this power cycle (1 byte is sufficient).
4. Upload coefficients if needed. WARNING: Verify the coefficient checksum before using coefficients to calculate P/T.
5. Query Pressure and Temperature counters successively until both respond with ACK. (To avoid possible start-up anomalies you may choose to wait an additional 0.1 seconds after both counters respond and then re-trigger.)
6. Wait desired gate time.
7. Read Pressure and Temperature counters and repeat 6-7 as desired.

For systems where simplicity is preferred over minimum start-up time:

1. Apply power to devices.
2. Wait 1.0 seconds for the internal power supply to stabilize, for the frequencies to come up, and in addition allow for a reasonable gate time.
3. Issue an EEPROM Random Read Command if the EEPROM is to be read anytime during this power cycle (1 byte is sufficient).
4. Upload coefficients if needed. WARNING: Verify the coefficient checksum before using coefficients to calculate P/T.
5. Query Pressure and Temperature counters – both should be ready with good data. (First gate time will vary depending on startup time.)
6. Wait desired gate time and repeat step 5-6 as desired.

2.6 Suggestions for Robust I^2C Communications:

1. Assure that SDA and SCL lines are both high before beginning communications
2. Wait at least 2.5uS (one quarter of 100Khz SCL clock) between each transition of either SDA or SCL - Do not change SDA and SCL simultaneously!
3. Verify that the desired data actually takes before moving on (set a reasonable timeout period).
4. If conflicts are detected (timeout exceeded), issue 9 clock pulses followed by a STOP before proceeding.
5. If a transducer fails to respond, Issue a Trigger (Dummy Read) Command and try again after 1 gate time.
6. Couple SDA and SCL lines to V_{IN} and GND respectively, and shield from any possible electrical noise sources.
7. Slow the host clock speed to allow time for voltages to stabilize with high-capacitive loads (long cables and/or multiple devices on the same bus).
8. Do not use edge-transitions to run internal state machines. SCL and SDA should be sampled with a local system clock to avoid inadvertent double-clocking on noisy edges.

3 Frequency Counter

The Frequency Counter is an ASIC (Chip) that provides an interface to the crystal oscillators in a Quartzdyne transducer. It provides serial communications compatible with the NXP I^2C bus. Temperature and Pressure frequencies may be queried as well as Chip ID and Status. Control bits may be written to select certain features of the transducer. The Chip controls the Write Enable bit for the memory.

3.1 Read Counter Command

The Counter Chip includes two completely independent frequency counters providing simultaneous counting of both frequencies with no dead time. The Read request triggers the Chip to transfer count data to a serial divide circuit and the counter starts counting again while the divide is taking place.

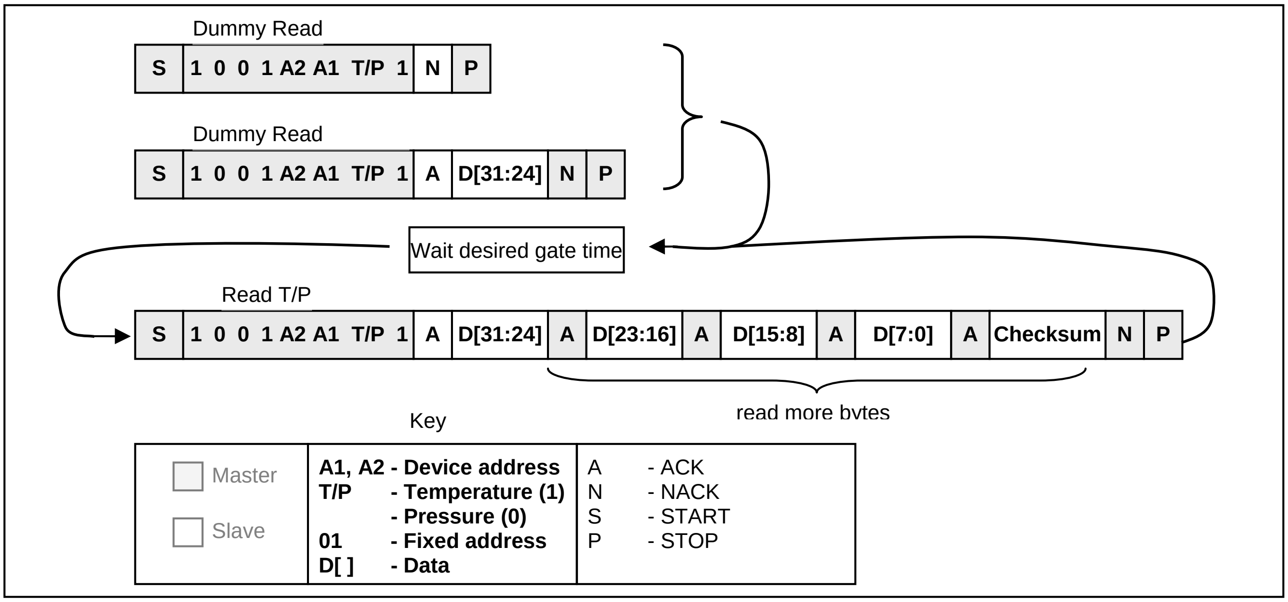
The counters can be queried by issuing a Dummy Read (see Figure 9) to each counter successively. If the counter is ready it will acknowledge (ACK) the request; otherwise it will not acknowledge (NACK). If the counter acknowledges, the master must read at least one byte followed by NACK and STOP to clear the bus cycle. If it is not ready, the master should issue a STOP. In either case, the counter that has just been addressed will be re-triggered. Reading one counter does not affect the other counter.

An alternative to the above method is to use the Read Status command and examine the TDetect and PDetect bits. This method returns the status of both counters at the same time while they continue to count. Additionally, the two counters can be simultaneously triggered by writing to the Control Register (see section 3.3 and 3.4 for more details.)

Once it is determined that a counter is working it can be queried continuously using the desired gate time interval. If a counter is not queried within 2.3 seconds, it will overflow and go into a reduced power mode until re-triggered.

Normally, the master will read four bytes of data. For Chip versions 4.02 and greater, an optional fifth-byte checksum may be read (See Section 3.2).

Figure 9. Read Counter Command



Frequency is reported as the ratio of Pressure (X_P) or Temperature (X_T) counts divided by Reference Counts. It is expressed as an unsigned fixed-point number with the MSB representing 2^{-1}. Frequencies in the range of 10kHz to 100kHz can be read to any precision up to 32 bits in byte increments with the most significant byte first. The first five bits will always be zero.

The gate time (T_G) is determined by how often the master queries each counter and can range from .001 to 2.3 seconds. The effective limit of resolution of the result is determined by the number of counts of the reference frequency $N_R = T_G * F_R$ (approximately 1 part per 7.2 million per second). Increased gate time will give better precision.

X_P and X_T are used directly to calculate pressure and temperature, and are related to counts (N_P, N_T, N_R) and frequency (F_P, F_T, F_R) as follows:

$$X_P\ [n\ \text{bits}] = N_P * 2^n / N_R = F_P * 2^n / F_R$$
$$X_T\ [n\ \text{bits}] = N_T * 2^n / N_R = F_T * 2^n / F_R$$

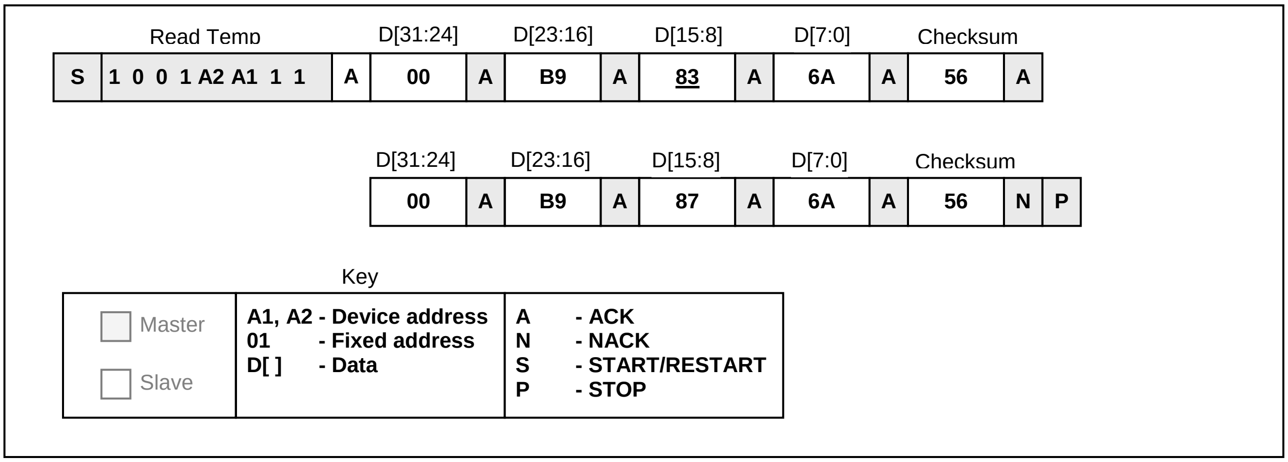
3.2 Checksum

A checksum feature was added to Counter Chip version 4.02. When reading any data including Frequency, Status or Chip ID, a checksum is output as the fifth byte (see example calculation below). If a checksum error is detected the master may re-read the data by continuing to acknowledge (ACK) bytes. As long as the master acknowledges, the Chip re-sends the original data including the checksum. A NACK followed by STOP terminates reading of data. Once the command is terminated the original data cannot be retrieved.

Compatibility Note: Reading the first four bytes is backward compatible to previous versions. Additional bytes in prior versions can be read, but should be considered noise.

Warning: The first time data is read it is new data. Continued reading without terminating the read command simply re-transmits old data. Thus, continued reading of the counters or status without issuing a STOP will not reflect new data.

Figure 10. Read data with checksum showing transmission error in 3rd byte.



Example checksum calculation:

(A)		(B)	
0000 0000		0000 0000	
1011 1001		1011 1001	
1000 0011	bad bit [2]	1000 0111	correct data
0110 1010		0110 1010	
0101 0110	checksum	0101 0110	checksum
-------------------		-------------------	
01 1111 1100	non zero	10 0000 0000	discard two carry-out bits, the rest is zero

Note: The checksum feature does not apply to writing to the Control Register or accessing external Memory (EEPROM).

3.3 Write Control/Status Bits

The control word allows for enabling or disabling various features in the frequency counter ASIC. Reading and writing the first byte of the control word is backward compatible with FPGA versions 3.03 or earlier. Additional control bits have been added for a total of 32 bits described in Figure 11 and Table 3. The “Control” register and “Status” register refer to the same digital bits. “Control” is used in the context of writing to the bits and controlling features. “Status” is used in the context of reading and querying. For example the TDetect and PDetect bits can only be read as “Status” bits. However, dummy values are needed to preserve bit position when writing to the “Control” register.

Figure 11. Control/Status Register bits

byte-1

TD	PD	WP	--	TP	PP	TE	PE
R	R	1	1	1	1	1	1

byte-2

A1	A2	TO	PO	HF	--	--	--
T	P	0	0	0	0	0	0

byte-3

--	--	--	--	--	--	--	--
0	0	0	0	0	0	0	0

byte-4

--	--	--	--	--	--	--	--
0	0	0	0	0	0	0	0

Initial values shown

Key

TD	**- TDetect**
PD	**- PDetect**
WP	**- WriteProtect**
“- -“	**- reserved**
TP	**- TPolarity**
PP	**- PPolarity**
TE	**- TEnable**
PE	**- PEnable**
A1,A2	**- Address**
TO	**- Temp out**
PO	**- Press out**
HF	**- HighFreqEn**
01	**- initial value**
R	**- Read Only**

Table 3. Control/Status bit descriptions

BIT	SIGNAL	INIT	RW	DESCRIPTION
31	TDetect	na	RO	Valid temperature data available. This bit is ignored during write.
30	PDetect	na	RO	Valid pressure data available. This bit is ignored during write.
29	Write Protect	1	RW	Write protect memories.
28	-reserved-	1	RW	
27	TPolarity	1	RW	Specify polarity of temperature input signal 1-pos 0-neg
26	PPoloarity	1	RW	Specify polarity of pressure input signal 1-pos 0-neg
25	TEnable	1	RW	Enable temperature counters.
24	PEnable	1	RW	Enable pressure counters.
23	A1 Address	A1T	RO	Address on pin A1T during power-on reset is stored in this bit.
22	A2 Address	A2P	RO	Address on pin A2P during power-on reset is stored in this bit.
21	Temp out	0	RW	Enable pin A1T as a high drive mixed temperature out If address A1T is 0 this cannot be set.
20	Pres out	0	RW	Enable pin A2Pas a high drive mixed pressure out If address A2P is 0 this cannot be set.
19	HighFreqEn	1	RW	Sets pin RO to be 7.2 MHz(1) or 1Khz (0)
18	-reserved-	0	RW	
17	-reserved-	0	RW	
16	-reserved-	0	RW	
15-8	-reserved-	0	RW	
7-0	-reserved-	0	RW	

General: Writing to byte-1 resets both counters simultaneously. To select any of the features in byte-2 of the control word, byte-1 must also be written and care must be taken when doing this to rewrite the intended values.

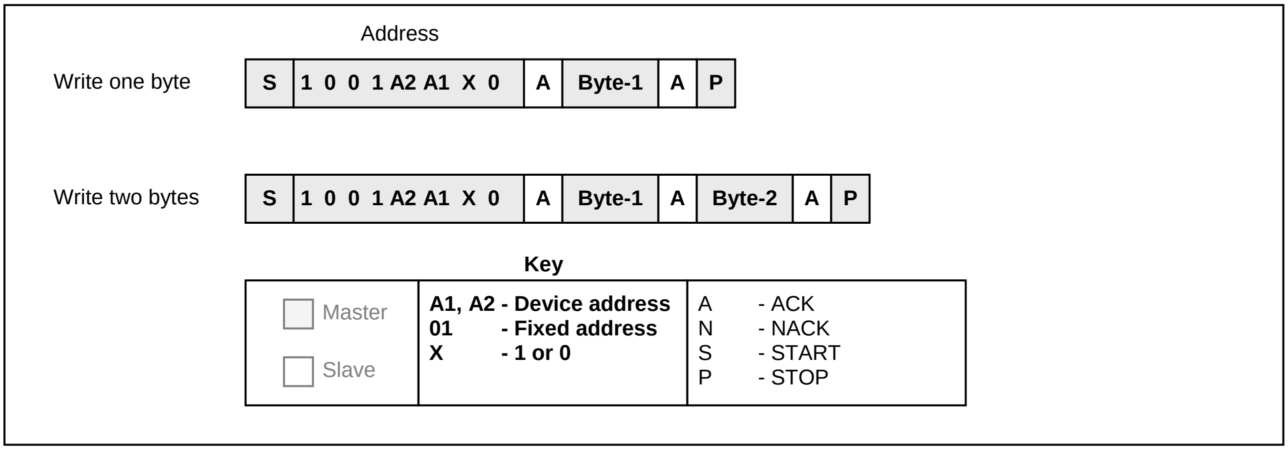
Bits 30-31: Prior to version 3.01 (0D020301, 0D050301) it was possible that Temperature or Pressure Detect remained inactive even though a signal was present. This occurs during the startup sequence, when the Pressure or Temperature signal starts sporadically after the reference frequency is stable. The counter detects a sporadic signal as an under-frequency condition (overflow) and shuts down the counter. When this occurs, the counter can be restarted by executing a Dummy Read to trigger the counter. In order to avoid this situation in versions prior to 3.01, it is recommended that the Query Counter command be used to detect startup, rather than the Query Status command. For Chip or FPGA versions 3.01 and greater, this problem has been resolved; the counter will ignore sporadic startup conditions, and continually retry until a valid frequency is detected. In order to guaranty accurate readings, the host system should wait at least 0.1 seconds after signal detection before triggering the counter for the first read after power is applied.

Bits 20-23: The A1T and A2P pins have tristate drivers with internal pullups. During power-on reset, the logical values on these pins are written into control bits 23 and 22 and become part of the device address. Writing different values after power-on reset are ignored but their current value is reported when querying the status register. If nothing is pulling them down during startup then they will be “1” because of the internal pullup. After startup they may be programmed as Temperature and Pressure outputs through the I2C interface only if the startup value is “1”. This is accomplished by writing a “1” to TO (bit 21) for Temperature or PO (bit 20) for Pressure. They may be turned off by writing a “0”. These pins are independent and may be controlled separately. If either pin is tied to Ground at startup this feature is disabled. Driving the pins with an external digital device is not recommended since the chip and the external device could end up driving the pin at the same time and cause permanent damage. As long as these pins are either floating (externally) or tied to ground during power-on reset there is no problem.

Writing: The control register is written to as follows (see Figure 12). A START transition begins the command. The correct address is sent with R/W=1 and the Chip responds with an ACK. The master then writes control Byte-1. After receiving the first control byte, the Chip responds with an ACK and the master can terminate the command with a STOP transition. The master may continue to write bytes and the Chip will ACK after each byte. After four bytes are written, subsequent bytes are ignored, but the Chip will still ACK until the master sends a STOP transition. The STOP must immediately follow a Chip ACK.

After writing any number of bytes and following a Chip ACK the master may send a RESTART instead of a STOP followed by a second address byte and read either the Status or Chip ID. This is described in further detail in “Query Status or Chip ID Command” section 3.4.

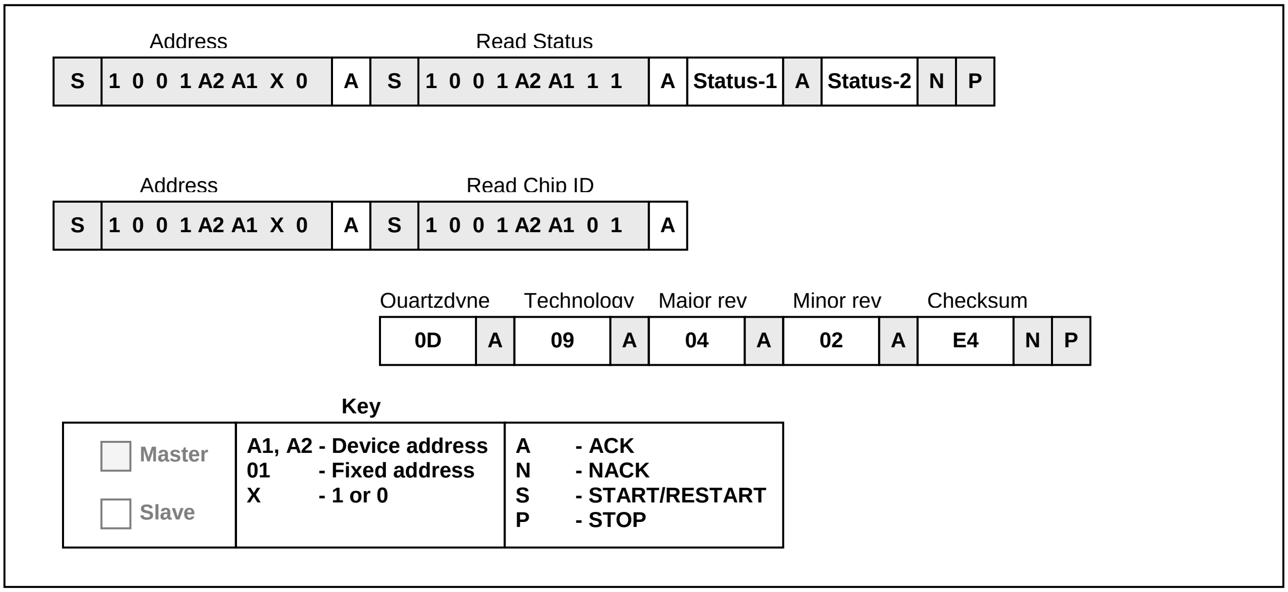
Figure 12. Write Control



3.4 Query Status or Chip ID

Information about the internal Chip is accessed by querying the Status or Chip ID registers (see Figure 11 and Table 3). Start by issuing a Write Control Command (R/W=0) with or without a data to be written. Immediately following a Chip ACK send a repeated START transition (no STOP after ACK). The address is again repeated, this time with R/W=1 and S/V=1 for Status or S/V=0 for Chip ID. The master may then read as many bytes as desired. When reading Status the first byte is compatible with earlier versions. Additional bytes are returned as defined in Figure 11. The fifth byte is a checksum and the data is repeated if the master continues to query (ACK bytes). To terminate the Query command the master responds with no-acknowledge (NACK) followed by a STOP.

Figure 13. Query Status or Chip ID



The Chip ID code is defined as follows:

Q Q C C V V V V

Table 4. Counter Chip ID bits

Bits	Value (Hex)	Description
QQ	0D	Quartzdyne
CC	02	SMT FPGA
	05	Hybrid FPGA
	09	ASIC
V V V V	0103	FPGA version 1.03
	0402	ASIC version 4.02

Example version codes are:
0x0D020103
0x0D090402

4 Serial EEPROM

The EEPROM contains 8192 bytes of non-volatile EEPROM (RAMTRON FM24C64). Data is addressed using two Data Address bytes following the Device Address. Only 13 bits are significant. The remaining bits should be programmed as ‘0’ for compatibility with future devices. On power on, the device is write protected, and can only be programmed if the Write Protect bit is cleared using the Write Control Byte command described earlier. The Serial EEPROM should only be written to store new coefficients. Unused sections of the EEPROM are reserved for use by Quartzdyne only. The presence of the extended EEPROM is not guaranteed in future versions. Note that Transducers with Chip versions prior to 0D010201 used a smaller EEPROM that used a one byte addressing scheme, and had no write protect feature (ATMEL AT24C04). Where the possibility of both versions exists, the Chip ID should be used to determine which ROM is installed. Refer to the ATMEL data sheet for details on programming this device.

On power on, the device is write-protected. Before programming, the Write Protect bit must be cleared using the Write Control Byte command described earlier. To overwrite data in the EEPROM, the device is addressed with the R/W bit set low (WRITE). The EEPROM acknowledges, and the Two Data Address Bytes are then sent from the master. This is also acknowledged by the slave. The next byte transmitted will be written to the memory location defined by the Address Bytes. Subsequent data will be written into consecutive memory locations. If the highest numbered memory location is written, the internal address wraps to the beginning of the device (0x1FFF -> 0x0000), with the potential for data to be overwritten. After all data has been transmitted, the master terminates the write sequence with STOP. The write cycle is nearly instantaneous, so no acknowledge polling is necessary.

Warning: this command may fail if it is the first command issued after a power-on reset. See Section 2.4.

Figure 14. EEPROM Write Command

	Write EEPROM		Mem [12:8]		Mem [7:0]		D [7:0]		
S	**1 0 1 0 A2 A1 0 0**	**A**	**000 BBBBB**	**A**	**BBBB BBBB**	**A**	**DDDD DDDD**	**A**	**P**

Key

☐ Master	**A2, A1 - Device address**	**A - ACK**
	0, 1 - Fixed address	**N - NACK**
☐ Slave	**B - Data address**	**S - START/RESTART**
	D[ ] - Data	**P - STOP**

4.1 EEPROM Read - Current Address

The internal Data Address counter maintains the last address accessed during the last read or write operation, incremented by one. This address stays valid between operations as long as power is maintained. The address rollover during read is from the last byte of the device to the first byte (0x1FFF to 0x0000). To read data beginning with the current address, the device is addressed with the R/W bit set high (READ). The EEPROM acknowledges, and will transmit sequential data as long as the master acknowledges each byte. After the last byte is read, the master terminates the read with NACK followed by STOP. The checksum is not available when reading from external memory.

Figure 15. EEPROM Current Address Read

	Read EEPROM								
S	**1 0 1 0 A2 A1 0 1**	**A**	**Data-1**	**A**	**Data-2**	**A**	**Data-3**	**N**	**P**

Key

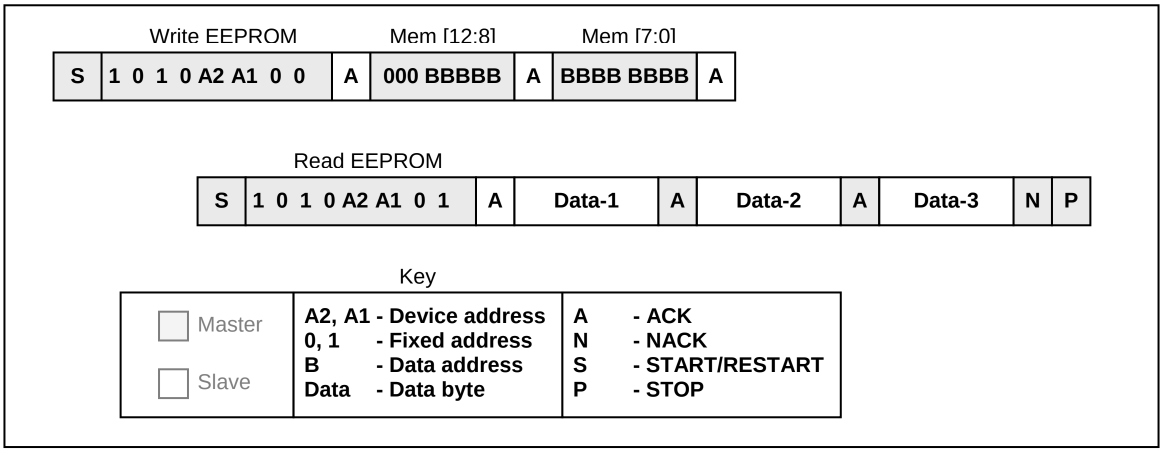
☐ Master	**A2, A1 - Device address**	**A - ACK**
	01 - Fixed address	**N - NACK**
☐ Slave	**Data - Data byte**	**S - START/RESTART**
		P - STOP

4.2 EEPROM Read - Specific Address

The Specific-Address Read requires a Write command to load the Data Address. The device address byte is sent with the R/W bit set low (WRITE) and is acknowledged by the EEPROM. The two Data Address Bytes are then sent and acknowledged by the EEPROM, following which the master generates a repeated START condition. The device is addressed again, this time with the R/W bit set high (READ). The EEPROM acknowledges, and transmits sequential data as long as the master acknowledges each byte. After the last byte is read, the master terminates the read with NACK followed by STOP.

Warning: this command may fail if it is the first command issued after a power-on reset. See Section 2.4.

Figure 16. EEPROM Specific Address Read



4.3 Data Retention

Original testing at Quartzdyne confirmed data published by Ramtron regarding data retention at elevated temperatures. The data retention time was found to be limited to approximately 400 hours at 200°C, with an activation energy of 0.94 eV (1000 hours at 180°C). Unfortunately, more recent testing has produced contrary results above 180°C.

Corruption can be expected after a few minutes at 200°C. Reading the device at temperatures above 180°C may also contribute to data corruption. The user is advised to provide alternate storage for coefficients once the unit has been deployed. Always verify the checksum prior to using coefficients. Coefficients may be retrieved from our website.

Beginning January, 2010, four redundant copies of the coefficient file are stored in the FRAM at memory locations 0x000, 0x100, 0x200 and 0x300. If an invalid checksum is detected in the first block, the host may read successive blocks to improve the probability of obtaining valid coefficients. This feature has been established as a temporary stop-gap measure while we pursue alternate options for coefficient storage.

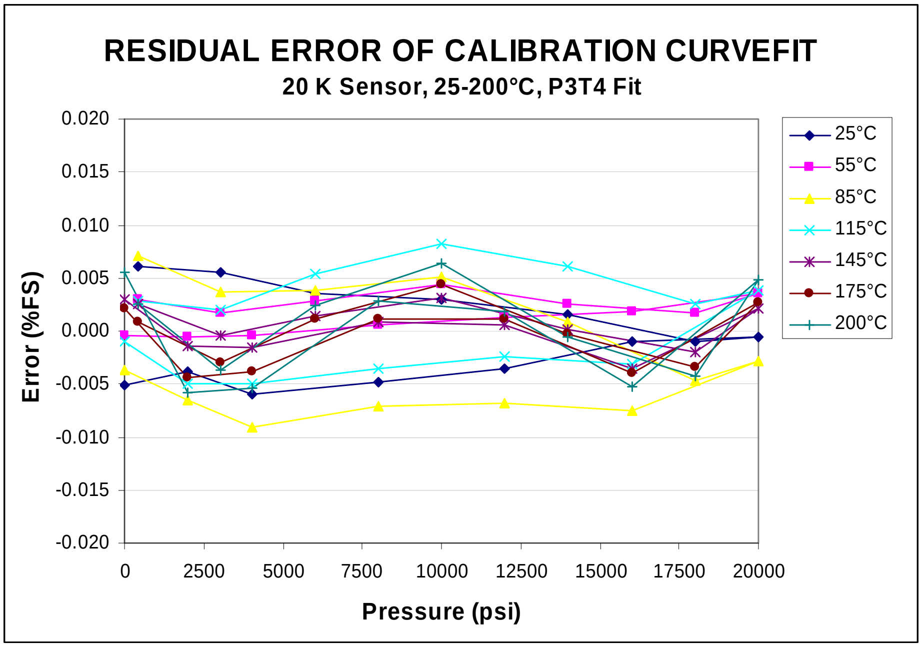
5 Calibration

The unique coefficients for each transducer are determined in calibration. The pressure and temperature counts are read at a number of known pressures at several different temperatures. The coefficients are computer-generated using an LMS (least mean squared) algorithm from the counts and the pressure data recorded during the calibration. Calibration coefficients are then stored in the transducer's EEPROM. Additionally, coefficients may be distributed on a floppy disk along with the original calibration data and several demonstration programs. Among these is a program for generating new coefficients from the user's data.

5.1 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 17 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 ±0.01% of reading.

Figure 17 . Calibration curve typical of QUARTZDYNE® Pressure Transducers.



5.2 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).

5.3 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 error in calibration are identified. In the Quartzdyne calibration laboratory the atmospheric pressure reference is either a Mensor 2104 or 1550D 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 5306 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_{atm} = 12.6 psi [869 mbar] (measured continuously during calibration)
P_{head} = 0.033 psi/in [0.897 mbar/cm]
Local gravity = 9.797930 m/s^2 (interpolated from National Geodetic Survey data http://www.ngs.noaa.gov/)
air density = 1.015 gm/cm^3 (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

5.4 Pressure Control Required for Calibration

QUARTZDYNE® Pressure Transducers measure absolute pressure. The pressure that the transducer senses during 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.

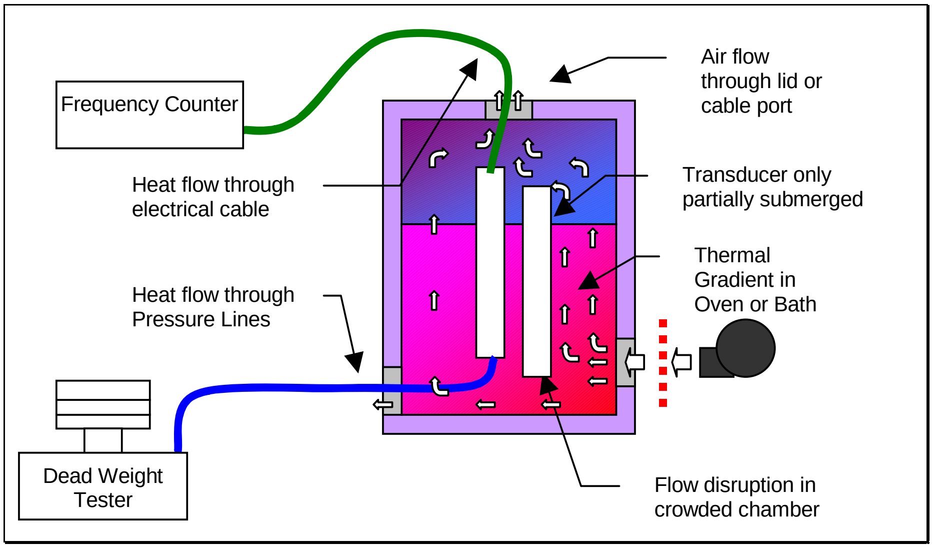
5.5 Temperature Control Required for Calibration

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 counts 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 68000 counts/°C at -40°C to 150000 counts/°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 18 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 6.

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- or 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 18. Possible sources of temperature gradients in a calibration oven or bath.



6 Calibration Coefficients

6.1 File Format

Quartzdyne Digital Pressure Transducers include binary coefficients stored in EEPROM. The format of these coefficients is different from the coefficient file format distributed with frequency output transducers. The coefficients occupy the lower 256 bytes of EEPROM, leaving the remaining memory available for the end user's application. All numeric data is stored with the most significant byte at the lowest numbered address (MSB first). As some programming environments expect integer and floating point numbers in an LSB first format, translation may be required. Coefficient files may also be supplied separately using Intel HEX coding. This is an industry standard format used by most device programmers, and is described later in this section.

Table 5. 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 6. Calibration Type Coding

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

Table 7. Prescale Type Coding

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

6.2 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.

6.3 Pressure and Temperature Calculations

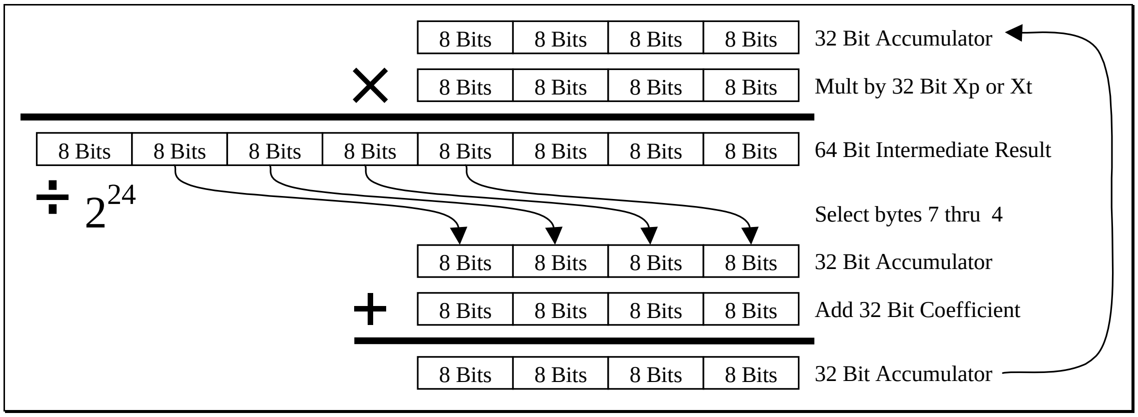
Pressure and Temperature are calculated using a polynomial in the two variables X_P and $X_{T,}$ as read from the counter. Each combination of powers (X_P^i, X_T^j) from i=0 to N1and j=0 to N2 is represented in the equation. The calculation method for either is identical except for the polynomial order. It is recommended that a generic routine be used for both, since the fit order may change with new product enhancements, or over various pressure and temperature ranges.

$$Z_{OUT} \text{ (Standard Units)} = S1 \times \sum C_{ij} \bullet (X_P/2^{24})^i \bullet (X_T/2^{24})^j$$

$$Z_{OUT} \text{ (Alternate Units)} = S2 \times \left\{ OFS2 + \sum C_{ij} \bullet (X_P/2^{24})^i \bullet (X_T/2^{24})^j \right\}$$

The polynomial may be expanded using 32-bit signed integer math if it is factored as shown in the pseudo-code example below. The multiplication and 2^{-24} scaling is accomplished by computing the 64 bit result of X_P or X_T times the previously accumulated value, and then selecting bytes 7 thru 4 as the result. If the eighth byte is non-zero, an overflow has occurred. Coefficients are added directly to the accumulator.

Figure 19. Integer Polynomial Computation



After the polynomial has been computed, the result may be converted to engineering units by multiplying by the floating- point scalar S1. The standard units are Pressure in psi and Temperature in °C. Alternate units (bar, °F) may be computed by adding the integer offset OFS2 to the polynomial result prior to multiplying by the alternate floating point scalar S2. The following pseudo-code illustrates a typical computation routine.

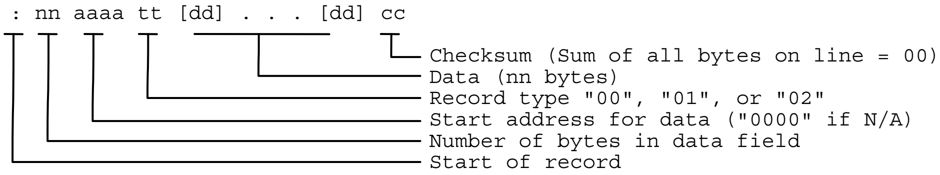
6.4 Example Calculation Routine Pseudo-Code

```
Inputs:
Unsigned[32] Xp, Xt
Integer[8] N1, N2
Float[32] S1, S2
Integer[32] OFS2, C( (N1+1) * (N2+1) )
Boolean AltUnits

Output:
Float[32] Zout

Variables:
Integer[32] Zint, Temp
Integer I, J, N

Method:
Zint = 0
N = (N1+1) * (N2+1)
For I = 0 to N1
  Temp = 0
  Zint = ( Zint * Xp ) >> 24
  For J = 0 to N2
    Temp = ( Temp * Xt ) >> 24
    Temp = Temp + C(N)
    N = N -1
  Next J
  Zint = Zint + Temp
Next I
If ( AltUnits ) Then
  Zint = Zint + OFS2
  Zout = Zint * S2
Else
  Zout = Zint * S1
End If
```

6.5 Intel HEX File Coding

Quartzdyne Digital Transducer Coefficient files are distributed using the Intel HEX file format. This allows viewing of the object file with standard tools and makes for easy file transfer from one computer system to another.

The Intel Hexadecimal Object file record format has a four-field prefix that defines the start of record, byte count, load address and record type. This is followed by the actual data and a 2-character checksum. Each 2-character pair is a Hex representation of an eight-bit byte with the most significant nibble (4-bits) first. The checksum is the 2's compliment of the sum of the preceding bytes in the record (excluding the start character). The sum of all bytes, including the checksum, will be 00. Records are separated by an end-of-line delimiter (CR/LF).



```
: nn aaaa tt [dd] . . . [dd] cc
Checksum (Sum of all bytes on line = 00)
Data (nn bytes)
Record type "00", "01", or "02"
Start address for data ("0000" if N/A)
Number of bytes in data field
Start of record
```

Record Types

Record type 00, the data record, is the record that contains the data of the file. The data record begins with the colon start character (":") followed by the byte count, the address of the first byte and the record type ("00"). Following the record type are the data bytes and the checksum. The following are examples of data records (spaces are included for clarity only and are not included in the actual object file).

:10 0040 00 137DF401CFADAAFFA38FB5FEDF13E001 4E
:05 0010 00 0102030405 AA

Record type 01, the end record, signals the end of the data file. The end record starts with the colon start character (":") followed by the byte count ("00"), the address ("0000"), the record type ("01") and the checksum ("FF").

:00 0000 01 FF

Record type 02, the extended segment address record, defines bits 4 through 19 of the segment base address. It can appear anywhere within the object file and it affects the absolute memory address of all subsequent data records in the file until it is changed. The extended segment address record starts with the colon start character (":"), followed by the byte count ("02"), the address ("0000"), and the record type ("02"), followed by bits 4 through 19 of the segment base address and the 2 character checksum. Record type 02 is not used in Quartzdyne HEX coefficient files

:02 0000 02 1000 55