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1. General Considerations

This document provides guidelines to recalibrate Paroscientific Intelligent Devices (with display and RS-232 serial communication) or Paroscientific Transducers (with period outputs using coefficients). Recalibration software that calculates the correct adjustment is made available with this application note.

1.1 Reason for Recalibration

Paroscientific transducers measure pressure with a force sensitive quartz crystal whose output period (or frequency) changes with applied load. For a given temperature, true applied pressure will generate a specific crystal period. In turn, a measure of the crystal period will indicate what pressure was applied, provided the relationship between crystal period and pressure is known. This relationship is usually expressed as the C,D, Tau \emptyset equation. C,D, and Tau \emptyset are coefficients that are unique to Paroscientific transducers, and are different for each transducer. In addition, these coefficients are characterized for thermal effects. For each temperature, they are expressed as polynomial expansions with coefficients C1,C2, C3,D1,D2,T1, etc. Typically, it takes between 7 and 10 coefficients to fully describe the relationship, also called the "CD thermal model", between crystal output, temperature, and pressure.

The determination of all coefficients is done at the Paroscientific Calibration Laboratory and is called "calibration". The transducers are calibrated over the full temperature and pressure range, such that the indicated pressure as calculated by the CD thermal model will agree with the true applied pressure with a typical absolute accuracy of ± 0.01 percent of transducer full scale at all temperatures and pressures.

Recalibration is necessary if a user decides that the agreement between true and indicated pressure is outside tolerances set for the particular application.

There are four basic reasons for recalibration:

1. The user's primary pressure standard differs from the Paroscientific primary pressure standard, and the user decides to adjust the transducer to another primary standard. The primary standards used at the Paroscientific Calibration Laboratory are dead weight testers with accuracies of 0.005 to 0.015 percent of reading and are traceable to NIST. It is possible within traceable accuracies of 0.015 percent that

two primary pressure standards at different calibration laboratories differ by as much as 0.03 percent. The computation of true pressure from the dead weight tester must include corrections due to local gravity, buoyancy, head effects, thermal expansion, and piston deformation.

2. The user has elected to recalibrate the transducer on a periodic schedule. Some laboratories are required to maintain current traceability of their instruments. In any case, it is a good idea to check the transducer periodically against known pressure values, and to keep a record of the results.

3. The transducer may be recalibrated for a specific application over a limited pressure and/or temperature range.

4. The transducer needs periodic recalibration to maintain an absolute accuracy of ± 0.01 percent of transducer full scale. All instruments need period recalibration, even primary pressure standards. As described in more detail below, it is usually sufficient to adjust an offset between true and indicated pressure twice a year.

1.2 Types of Recalibration

a. Offset Adjustment

The Paroscientific transducer measures a force that is generated by external pressure. Since the quartz crystal is extremely sensitive, any other small force that is transmitted to the sensing element will be added to the pressure measurement. A pressure offset generated in this way is purely additive and is the same at all pressure values. In principle, checking accuracy at a single applied pressure is sufficient to determine an offset. Of course, the offset can be calculated as the average offset of many pressure points.

In practice, all Paroscientific transducers stay within ± 0.01 percent of full scale absolute accuracy during their entire lifetime if the offset is checked and adjusted periodically. No other adjustment is necessary.

In Digiquartz[®] Intelligent Devices, an offset constant called the PA parameter can be adjusted (use program RECAL/i and consult the "Programming and Operation Manual of Intelligent Transmitter" and Appendix A). If the coefficients of transducers are adjusted directly, the T1 and C1 terms are changed (use program RECAL/c or consult Appendix B).

b. **Offset and Span Adjustment**

Span is defined here as the pressure difference from minimum pressure to full scale pressure. A span error is the difference between the indicated pressure span as measured by the transducer and the true pressure span. If a transducer is carefully adjusted at minimum pressure, the span error is simply the difference between indicated and true applied pressure at full scale.

The span of a Paroscientific transducer is rarely adjusted since the scale factor of the sensing element is very stable. Differences are sometimes due to different calibration standards. The span of a dead weight tester used as a primary standard depends directly on the piston area and the value of local gravity. Any apparent change of span in a Paroscientific transducer should be carefully checked to ascertain that the pressure is correctly applied and calculated with the correct piston area and gravity constant, and that the piston is vertical. We recommend recording several pressure points over the entire pressure range to establish any span error. The Paroscientific calibration software program RECAL calculates the best span by a least-squares fit optimization.

In Digiquartz[®] Intelligent Devices, a pressure multiplier called the PM parameter can be adjusted (use program RECAL/i and see Programming and Operation Manual of Intelligent Transmitter and Appendix A). If the coefficients of transducers are adjusted directly, the T1 and C1 terms are changed (use program RECAL/c or see Appendix B).

1.3 **Equipment Needed for Recalibration**

The Paroscientific Calibration Laboratory uses state-of-the-art dead weight testers as primary pressure standards with current calibration and periodic cross calibration between standards. The calibration is traceable to the National Institute of Standards and Technology (NIST). For recalibration, we recommend using a primary standard with an absolute accuracy of 0.02 percent of reading or better. Special recalibration procedures are covered in Chapter 3. Differential units can be checked at 0 psig without a standard. High pressure units can be checked with a relatively more accurate barometer at ambient atmospheric pressure. Two or more transducers can be checked for relative accuracy against each other.

1.4 **Frequency of Recalibration**

Most Paroscientific transducers keep an absolute accuracy of ± 0.01 percent of full scale if the pressure offset is recalibrated twice a year. Digiquartz[®] Barometric Standards carry a guarantee of stability of better than 0.1 hPa per year. This is usually the case for laboratory applications. More stressful environments, especially at high temperature, may affect a transducer more. Systems using pressure instruments should be designed in such a way that recalibration is possible to the accuracy needed. For example, systems with differential transducers may include an option to vent both ports and “rezero” (recalibrate the indicated pressure to read 0 psig) before use. It is standard practice to increase the calibration interval if in-tolerance conditions are found.

1.5 **Accuracy of Recalibration**

The resolution and short-term stability of Paroscientific transducers routinely exceed one part per million (ppm) of transducer full scale, e.g., the resolution of a transducer with $P(\text{full scale}) = 100$ psia is $P(\text{full scale})/1,000,000$ or 0.0001 psia. Good practice dictates reading and recording the indicated and applied pressure to that resolution. As a rule, pressure values should be recorded with seven significant digits (starting with the highest digit of the full scale pressure), e.g. 5014.443 psia (6000 psia full scale), or 14.5288 psia (100 psia full scale), or 14.52886 psia (barometer).

If several indicated pressure values are recorded at the same nominal applied pressure, the difference between measurements is related to the stability of the applied “true” pressure. The stability of the pressure standard should exceed the designed accuracy by at least a factor of four. For example, if a transducer is calibrated with a standard that is certified to 0.012 percent at the transducer full scale, the stability of individual pressure points should be better than 0.003 percent of full scale (30ppm).

1.6 **Pressure and Temperature Stabilization**

The applied pressure should be kept constant for at least three minutes. This ensures that the manifold is leak-free and allows for proper stabilization of pressure. At the Paroscientific Calibration Laboratory, applied pressure is monitored during the application with a relative accuracy of parts per million. This helps greatly to detect pressure leaks and pressure instability which may originate from the primary standard, e.g. weight bounce or cleanliness of piston.

Temperature instability or lack of temperature correction will result in apparent offset errors. Transducers must be in thermal equilibrium for accurate calibration values. Sufficient insulation and stable temperature surroundings are necessary to keep the whole transducer body at the same temperature.

The indicated pressure must be temperature corrected. This is automatically done in the Digiquartz[®] Intelligent Devices. A quartz crystal temperature sensor, characterization equation, and coefficients necessary to generate thermally-compensated, linearized pressure outputs are provided with each Digiquartz[®] Transducer. The residual temperature error is less than 0.0008 percent f.s. per deg C. Without temperature correction, the indicated pressure can be erroneous by 0.005 percent f.s. per degree C (low pressure units), and up to 0.02 percent f.s. per degree C (high pressure units), hence thermal compensation is recommended to achieve the best absolute accuracy.

1.7 **Keeping Records**

We recommend keeping a record of the coefficients supplied by the Paroscientific Calibration Laboratory and keeping a record of recalibration changes. For Intelligent Devices, it is best to maintain the original coefficients and only adjust PA (and PM), if necessary.

1.8 **Checking the Result**

The result of a recalibration can be easily checked. One method is to make sure that the transducer reads ambient pressure correctly (if a barometer is available) and that differential transducers are correctly rezeroed (read 0 psig with both ports open).

2. **Recalibration Software**

Paroscientific, Inc., has a software program called RECAL available to calculate the proper offset (and span) adjustment. As input, the true applied and the indicated pressure values of one or many pressure measurements are entered. The values entered can be saved as a file, edited with a word editor (e.g. EDIT), and rerun again. The program calculates pressure errors as entered, which can also be displayed graphically. The data are then summarized as:

- a. Average pressure error as entered.
- b. Average pressure offset and remaining error after offset adjustment.
- c. Offset and span error and remaining error (also called conformance) after both offset and span adjustment.

The user makes a selection among:

- (N) No adjustment,
- (O) Offset adjustment only,
- (S) Span and offset adjustment.

The data are then shown after adjustment. The remaining error is referred to as pressure conformance to the calibration data after adjustment. If three or more pressure points are entered, the optimal offset and span are found with a linear least-squares fit to all points.

The computer program RECAL is a proprietary product of Paroscientific, Inc., and is protected by copyright law.

2.1 **Program RECAL/i for Paroscientific Intelligent Devices**

If the program is loaded as RECAL/i or simply as RECAL, the program calculates PA (and PM) parameters to be loaded into the device.

2.2. **Program RECAL/c for Paroscientific Transducers**

If the program is loaded as RECAL/c the program calculates new C1 and T1 coefficients.

2.3 Examples of Recalibration

a. Single Point Recalibration

(Choice "Ø" for offset adjustment)

As an example, assume that a 15 psia full scale transducer with C,D,TauØ coefficients indicates pressure as 15.00155 psia when true pressure of 15.00000 psia is applied. The transducer reads high by 0.00155 psia or 0.0103 percent of full scale (%f.s.). Invoke the calibration software as RECAL/c and enter one pressure measurement. Choose "Ø" for offset adjustment when prompted. Finally calculate new C1,T1 coefficients. (Example: if old coefficients were C1=83.20394, D1=0.0392875, T1=25.27268, the new recalibrated coefficients will read C1(new)=83.20228, T1(new)=25.27292).

b. Two Point Offset and Span Adjustment

(Choice "S" for offset and span adjustment)

Again, as an illustration, assume that a 30 psig full scale transducer with an Intelligent Transmitter indicates -0.00330 psig with both ports open (-0.0110 percent f.s.). At full scale with true pressure of 30.00000 psig applied, the transducer indicates a pressure equal to 30.00610 psig (0.0204%f.s.). Enter both pressure measurements into program RECAL/i. The data summary will indicate that the average RMS error is 0.0164% f.s., and that the average offset was only 0.0047% f.s. with a large remaining error. The proper adjustment would be to apply an offset of -0.0110% f.s. and a span error of 0.0314% f.s. (the program will caution that the span error is unusually large). If PA = 0 and PM = 1 before recalibration, the new values are PA = 0.003300 and PM = 0.999686. Note that PA is in pressure engineering units (psig in this example) and that the Intelligent Transmitter must be programmed to the same engineering units (e.g. UN=1).

c. Conformance Calibration

With three or more points, the optimal offset and span adjustments are calculated with a least-squares fitting routine. As an example of this technique, a sample data file called RECAL.DAT is included. Start program RECAL and load this file. Even though most measured errors are as large as 0.05% f.s. in this example, the pressure conformance is on average only 0.0015 percent of full scale after offset and span recalibration. In Appendix C, this sample printout summary is shown.

2.4 **Device Configuration Software DQI**

Paroscientific, Inc., provides a device configuration software program called DQI (Digiquartz Interactive) with intelligent RS-232 transmitters. It can be used to view and change all configuration parameters (especially the pressure adder PA and the pressure multiplier PM), and to print out a record of the change. PA and PM can also be reconfigured from the previously described RECAL/i program directly. Alternatively, a serial communication program (e.g. PROCOMM or TERMINAL) can be used to communicate with intelligent devices and change parameters. Consult the transmitter programming manual for details.

3. **Special Considerations**

Paroscientific, Inc., produces a wide range of pressure transducers for many special applications. The need for recalibration depends on the application. Some of the more commonly encountered cases are listed here.

3.1 **Recalibration for Specific Applications**

In some cases, the calibration can be somewhat improved if the transducer is recalibrated over a selected pressure and temperature range. In any case, recalibration should be done over the pressure range and temperature range of interest. It does not make sense to recalibrate a 15 psia transducer at 0 psia (vacuum) if the instrument is exclusively used as a barometer in the range 13 to 15 psia. Also, an instrument that is used exclusively in a laboratory setting should not be exposed to temperatures above 50 deg C or below -10 deg C.

Recalibration also acts as a check on performance whether or not the calibration is changed. A high pressure unit used to measure water depths should be checked at typical ocean temperatures, whereas a high pressure unit used to measure pressure in a hot oil well should be checked at relatively high temperatures.

3.2 Oil-filled Transducers

Some applications require oil-filled transducers, often for depth measurements in water. Oil-filled transducers may not be pressurized with gas since the gas may diffuse into the oil and foam out after pressure release. Oil-filled units can be checked at ambient pressure against a high precision barometer or against a primary standard with gas lines at a pressure close to ambient.

Oil can safely be removed with special techniques only in 2000 series transducers (contact Paroscientific, Inc.), but not in high pressure units.

Oil in vertical pressure lines will add pressure called "head effects". Head effects are pure pressure offsets if the pressure medium is incompressible. The transducer should be positioned as in the intended application. The exit of the oil-filled pressure line is the reference height at which the pressure is compared to ambient pressure. Program RECAL calculates the proper adjustment of calibration coefficients from one or more measurements. It works with both frequency output transducers and Intelligent Devices.

If there is a question whether oil is present in the unit, ambient pressure can be measured with the pressure port up and then with the pressure port down. Differences in indicated pressure would indicate oil since the acceleration sensitivity of air-filled units is very small (less than 0.0038% f.s./g).

3.3 Differential Transducers

Differential transducers can easily be checked at 0 psid with both ports open to ambient air.

3.4 High-Pressure Transducers

Transducers above 200 psia full scale are most conveniently checked under ambient conditions against a barometric standard with 1 mbar reading accuracy or better. As mentioned above, a simple offset check will correct the absolute accuracy at all pressures since the span is very stable.

Note that oil-filled units may not be pressurized with pneumatic (gas filled) pressure lines. A complete conformance check requires a hydraulic primary standard.

Note that air-filled pressure units need additional time for pressure stabilization, since the expansion and contraction of gas induces adiabatic cooling or heating. After full scale pressure changes above a few hundred psia, the transducer should be stabilized for at least 5 minutes before taking dat

Appendix A

PA.PM Adjustment Equation

Use Paroscientific recalibration software RECAL/i to calculate PA (and PM) adjustment. As a technical reference, the PA and PM adjustment equation for Digiquartz® Intelligent Devices is given here.

a. Offset (PA) Adjustment

The “calculated” pressure is determined from the frequencies of the pressure and temperature crystals with C, D, Tau0 coefficients. The “indicated” (displayed) pressure is:

$$\text{Indicated P} = \text{PM} * (\text{Calculated P} + \text{PA})$$

Default values are PA = 0 and PM = 1, in which case, the indicated pressure is simply the calculated pressure based on C, D, Tau0 coefficients.

Define the current PA setting as “Old PA”, the current pressure multiplier as “Old PM”. Define the pressure “offset” = true pressure minus indicated pressure.

Evaluate the new PA variable as:

$$\text{PA} = (\text{Old PA}) + (\text{Offset}/\text{Old PM})$$

b. Span (PM) Adjustment

Adjust PA as described above such that the transducer indicates pressure correctly at minimum scale (or close to it).

Now measure true “ref” pressure at full scale which is displayed as “indicated” pressure. If the indicated pressure disagrees with the reference pressure, evaluate:

$$\text{PM} = (\text{Old PM}) * (\text{Ref P})/(\text{Indicated P})$$

and load the PM parameter.

Program RECAL uses a more sophisticated method of extracting the span error from a series of pressure measurements.

Appendix B

C1, T1 Adjustment Equation

Use Paroscientific recalibration software RECAL/c to calculate C1 and T1 adjustment. As a technical reference, the C1 and T1 adjustment equation for Paroscientific transducer coefficients is given here.

a. **Offset Adjustment**

Calculate pressure “offset” true “reference” pressure minus “indicated” pressure (calculated with C, D, Tau0 coefficients):

$$\text{Offset} = (\text{RefP}) - (\text{Indicated P})$$

Define:

$$x = 0.2 \text{ if C1 coefficient is positive}$$

$$x = -0.2 \text{ if C1 coefficient is negative}$$

Define current C1, D1, and T1 coefficients as “Old C1, D1, and Old T1”.

The new recalibrated C1 and T1 coefficients are:

$$T1 = \text{Old T1} - \text{Offset} * \text{Old T1} / (2 * \text{Old C1})$$

$$C1 = \text{Old C1} + \text{Offset} * (1 + 2 * D1 - 2 * D1 * x) / (1 - D1 * x)$$

b. **Span Adjustment**

Express the “span correction” as the ratio of “true” applied divided by “indicated” (measured) pressure range from minimum to full scale.

$$(\text{Span Correction}) = (\text{True P Range}) / (\text{Indicated P Range})$$

Adjust the offset error as described above in Section a. which results in a C1 (offset adjusted) term.

Evaluate a new span adjusted C1 term as:

$$C1(\text{Span Adjusted}) = C1(\text{offset adjusted}) * (\text{Span Correction})$$

Appendix C

Printout using data file RECAL.DAT Date: 06-07-1990

Full scale pressure: 100
Pressure engineering units: psia

Data as found:

	Applied Pressure	Indicated Pressure	Difference %f.s.
1	1.5005	1.4446	-0.0559
2	10.0012	9.9505	-0.0507
3	20.0000	19.9453	-0.0547
4	29.2183	29.1684	-0.0499
5	39.2144	39.1640	-0.0504
6	49.2124	49.1650	-0.0474
7	59.2115	59.1650	-0.0465
8	69.2119	69.1653	-0.0466
9	79.2123	79.1697	-0.0426
10	89.2123	89.1722	-0.0401
11	99.2126	99.1742	-0.0384

Offset error: -0.0556 percent of full scale
Span error: 0.0163 percent of full scale

Data as left (after offset and span adjustment):

	Applied Pressure	Corrected Pressure	Residual Error % f.s.
1	1.5005	1.5000	-0.0005
2	10.0012	10.0045	0.0033
3	20.0000	19.9977	-0.0023
4	29.2183	29.2193	0.0010
5	39.2144	39.2133	-0.0011
6	49.2124	49.2126	0.0002
7	59.2115	59.2110	-0.0005
8	69.2119	69.2097	-0.0022
9	79.2123	79.2124	0.0001
10	89.2123	89.2133	0.0010
11	99.2126	99.2137	0.0011

RMS Conformance: 0.0015 percent of full scale