Elevation Correction Factor for Absolute Pressure Measurements

Joseph W. Panek and Mark R. Sorrells
Lewis Research Center
Cleveland, Ohio

Prepared for the
42nd International Instrumentation Symposium
cosponsored by the Aerospace Industries and Test Measurement Divisions of the Instrument Society of America
San Diego, California, May 5–9, 1996
Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.
Elevation Correction Factor for Absolute Pressure Measurements

Joseph W. Panek
Electrical Operations Engineer
NASA - Lewis Research Center
Cleveland, OH 44135

Mark R. Sorrells
Electrical Operations Engineer
NASA - Lewis Research Center
Cleveland, OH 44135

KEYWORDS
Pressure Measurement, Elevation, Accuracy, Error Analysis

ABSTRACT

With the arrival of highly accurate multi-port pressure measurement systems, conditions that previously did not affect overall system accuracy must now be scrutinized closely. Errors caused by elevation differences between pressure sensing elements and model pressure taps can be quantified and corrected.

With multi-port pressure measurement systems, the sensing elements are connected to pressure taps that may be many feet away. The measurement system may be at a different elevation than the pressure taps due to laboratory space or test article constraints. This difference produces a pressure gradient that is inversely proportional to height within the interface tube. The pressure at the bottom of the tube will be higher than the pressure at the top due to the weight of the tube's column of air. Tubes with higher pressures will exhibit larger absolute errors due to the higher air density.

The above effect is well documented but has generally been taken into account with large elevations only. With error analysis techniques, the loss in accuracy from elevation can be easily quantified. Correction factors can be applied to maintain the high accuracies of new pressure measurement systems.
INTRODUCTION

The following shall be presented:

• the theoretical analysis which produces the appropriate correction factor based on elevation (assuming constant temperature);
• the effect of air temperature upon the correction factor;
• data which validates the elevation correction factor;
• the effect upon the overall accuracy of a typical PSI System 8400 with 15 PSI rackmount modules calibrated by a 15 PSIA Pressure Calibration Unit (PCU).

THEORETICAL ANALYSIS

The following derivation shows the variation of pressure with elevation in the earth's atmosphere. It is assumed that air density is proportional to air pressure, the change in gravity is negligible and the air temperature is constant at all elevations. Ref. 1 (Some derivation values were changed for consistency throughout the paper.)

The following equation shows how pressure varies with elevation in a fluid in static equilibrium.

\[
\frac{dP}{dy} = -\rho g
\]

\(\frac{dP}{dy}\) is the change in pressure per change in elevation while \(-\rho g\) is the weight density of air (air density \(*\) gravity). As the elevation, \(y\), increases, the pressure, \(P\), decreases.

At a constant temperature, air density, \(\rho\), is proportional to air pressure, \(P\), and we have

\[
\frac{\rho}{\rho_o} = \frac{P}{P_o},
\]

where \(\rho_o\) and \(P_o\) are known values of density and pressure.
Substituting \( \frac{dP}{dy} = -g \frac{\rho_o P}{P_o} \), so that \( \frac{dP}{P} = -g \frac{\rho_o}{P_o} dy \).

Integrating this from the value \( P_o \) at the elevation \( y = 0 \) to the value \( P \) at an elevation \( y \), we obtain

\[
\ln \frac{P}{P_o} = -g \frac{\rho_o}{P_o} y \quad \text{or} \quad P = P_o \exp^{-g(\rho_o/P_o)y}.
\]

At 20 DegC,

\[ g = 9.80 \text{ m/s}^2, \quad \rho_o = 1.205 \text{ kg/m}^3 \quad \text{and} \quad P_o = 1.01325 \times 10^5 \text{ Pa}, \]

so that \( g \frac{\rho_o}{P_o} = 1.16546 \times 10^{-4} \text{ m}^{-1} = 35.523 \times 10^{-6} \text{ ft}^{-1} \).

For any measured pressure, \( P_o \), the actual pressure, \( P \) (at elevation \( y \)) can be found by

\[ P = P_o \exp^{-35.523 \times 10^{-6} y}. \]

Substituting, \( P = P_o E_y \), where \( E_y = \exp^{-35.523 \times 10^{-6} y} \).

This gives us an elevation correction factor, \( E_y \) which can be applied to any measured pressure, \( P_o \), to correct for a positive or negative elevation, \( y \), between the transducer and the model pressure tap with applied pressure, \( P \) at 20 DegC.
TEMPERATURE EFFECTS ON THE ELEVATION CORRECTION FACTOR

It is safe to assume constant gravity for a small change in elevation. The influence of temperature on the elevation correction factor is shown in the following examples for a 20 Ft elevation.

The density of air, $\rho$, decreases with increasing temperature. The density of air is 1.293 kg/m$^3$ at 0 DegC and 0.946 kg/m$^3$ at 100 DegC. The density of air, $\rho_0$, at 14.696 Psia, for any temperature, $T$, can be calculated from the following equation.

$$\rho_0 = \frac{1.293}{(1 + (0.00367 \times T))} \text{ kg/m}^3$$

The following chart and table show the change in air density with temperature.

<table>
<thead>
<tr>
<th>Temp (DegC)</th>
<th>Air Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-200</td>
<td>4.8609</td>
</tr>
<tr>
<td>-180</td>
<td>3.8097</td>
</tr>
<tr>
<td>-160</td>
<td>3.1323</td>
</tr>
<tr>
<td>-140</td>
<td>2.6594</td>
</tr>
<tr>
<td>-120</td>
<td>2.3106</td>
</tr>
<tr>
<td>-100</td>
<td>2.0427</td>
</tr>
<tr>
<td>-80</td>
<td>1.8304</td>
</tr>
<tr>
<td>-60</td>
<td>1.6581</td>
</tr>
<tr>
<td>-40</td>
<td>1.5155</td>
</tr>
<tr>
<td>-20</td>
<td>1.3954</td>
</tr>
<tr>
<td>0</td>
<td>1.2830</td>
</tr>
<tr>
<td>20</td>
<td>1.2046</td>
</tr>
<tr>
<td>40</td>
<td>1.1275</td>
</tr>
<tr>
<td>60</td>
<td>1.0597</td>
</tr>
<tr>
<td>80</td>
<td>0.9995</td>
</tr>
<tr>
<td>100</td>
<td>0.9459</td>
</tr>
<tr>
<td>120</td>
<td>0.8977</td>
</tr>
<tr>
<td>140</td>
<td>0.8541</td>
</tr>
<tr>
<td>160</td>
<td>0.8146</td>
</tr>
<tr>
<td>180</td>
<td>0.7786</td>
</tr>
<tr>
<td>200</td>
<td>0.7457</td>
</tr>
</tbody>
</table>

Assuming $P_o = 1.01325 \times 10^5$ Pa and $g = 9.8 \text{ m/s}^2$,

For $\rho_o = 1.293 \text{ kg/m}^3$ (0 DegC),

$$\frac{g \rho_o}{P_o} = 1.25057 \times 10^{-4} \text{ m}^{-1} = 38.118 \times 10^{-6} \text{ ft}^{-1}.$$

The pressure correction, $E_y$, is

$$E_y = \exp ^{-(38.118 \times 10^{-6} \times 20)} = 0.999238.$$
For $\rho_0 = 0.946 \text{ kg/m}^3$ (100 DegC),

$$\frac{\rho_0}{P} = 0.91496 \times 10^{-4} \text{ m}^{-1} = 27.888 \times 10^{-6} \text{ ft}^{-1}.$$  

The pressure correction, $E_y$ is

$$E_y = \exp^{-\left(27.888 \times 10^{-6} \times 20\right)} = 0.999442.$$  

At 0 DegC, the correction factor, $E_y$, equals 0.999238. (-0.076%)

At 100 DegC, the correction factor, $E_y$, equals 0.999442. (-0.056%)

At 20 DegC, the correction factor, $E_y$, equals 0.999290. (-0.071%)

Assuming that $P_o$ is 14.7 PSIA, a temperature change from 0 to 100 DegC (32 to 212 DegF) would cause an additional 0.020% (0.0029 PSIA) error. A change from 0 to 20 DegC (32 to 68 DegF) would add an additional 0.005% (0.0008 PSIA).

To determine the elevation deviation needed to induce the same 0.020% correction factor change as the 100 DegC temperature shift,

$$0.99980 = \exp^{-38.118 \times 10^{-6} \times y}$$

$$\ln 0.99980 = 38.118 \times 10^{-6} \times y$$

$$y = \frac{-0.0002000}{-38.118 \times 10^{-6}} = 5.25 \text{ ft}$$

For a 20 ft elevation differential, an additional 5.25 ft variation in elevation produces the same error as a temperature change from 0 to 100 DegC (32 to 212 DegF). For many applications, temperature effects upon pressure can be ignored since elevation produces the dominant error.
DATA TO VALIDATE THE THEORY

Data was acquired at various pressures and elevations by a 19 PSIA PSI Sonix pressure gage (Reference Pressure) and a 19 PSIA Ruska pressure gage (Elevation Pressure). The ambient temperature was 70±5 DegF. The two gages are accurate to ±0.003 PSIA but have much higher repeatability (approximately ±0.001 PSIA). Biases between the two standards were measured at the four measured pressures. These were subtracted from the elevation pressure so that a true comparison could be made of the elevation effects. Error bars of ±0.001 PSIA are shown on the data points.

It can be seen that the elevation effects are greater at higher pressures due to the higher air density.

This data matches the theoretical curves to within ±0.001 PSIA; the repeatability of our instrumentation. This error is not significant for a PSI System 8400 with 15 PSI Rackmount Modules calibrated with a 15 PSIA Digiquartz PCU.
ERROR ANALYSIS OF A PSI SYSTEM 8400 AT VARIOUS ELEVATIONS

An error analysis has been done on the PSI System 8400 to determine system performance. Samples of typical analyses are shown with 0 ft, 20 ft and 40 ft elevations from the system to the model pressure ports. The PCU has an elevation difference of 6 ft from the rackmount modules. The largest error occurs at the highest measured pressure, 15 PSIA. The following equations show the method used to calculate the uncertainty. Ref 2

\[ U_{RSS} = \sqrt{B^2 + \frac{(2 \cdot S')^2}{N}} \]

\[ U_{RSS} = \pm \text{Uncertainty (PSI)} \]

\[ N = \text{Number of Data Sets Averaged} \]

\[ B' = \text{Root-Sum-Square of all Bias (fixed) Errors} \]

\[ S' = \text{Root-Sum-Square of all Precision (random) Errors} \]

The following tables show all bias and precision errors as well as the final uncertainties.

For a system at the same elevation as the model pressure ports, the uncertainty is ± 0.05% of FS.
For a system with a 20 ft elevation to the model pressure ports, the uncertainty is ± 0.087% of FS (an increase of 74% in the uncertainty).

<table>
<thead>
<tr>
<th>DIGIQUARTZ ERRORS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cal Lab Calibration Error</td>
<td>0.0018 PSI</td>
</tr>
<tr>
<td>Temp Error</td>
<td>0.0007 PSI</td>
</tr>
<tr>
<td>Time Base Error</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Curve Fit Error</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Counter Resolution</td>
<td>0.0001 PSI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MODULE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>15 PSI</td>
</tr>
<tr>
<td>Serial Number (Ignore B)</td>
<td>2037</td>
</tr>
<tr>
<td>Temp Change between Calibs.</td>
<td>1.5 DegF</td>
</tr>
<tr>
<td>Thermal Zero Shift</td>
<td>0.02 % FS</td>
</tr>
<tr>
<td>Thermal Span Shift</td>
<td>0.02 % FS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Data Sets Averaged</td>
<td>8</td>
</tr>
<tr>
<td>Elevation from PCU to Modules</td>
<td>6.00 Feet</td>
</tr>
<tr>
<td>Elevation from Module to Ports</td>
<td>20.00 Feet</td>
</tr>
<tr>
<td>Highest Measured Pressure</td>
<td>15.00 PSI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOTAL DQ ERROR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias Errors</td>
<td>0.0022 PSI</td>
</tr>
<tr>
<td>Random Errors</td>
<td>0.0011 PSI</td>
</tr>
<tr>
<td>+/- Uncertainty (PSI)</td>
<td>0.0023 PSI</td>
</tr>
<tr>
<td>+/- Uncertainty (%)</td>
<td>0.0154 %FS</td>
</tr>
</tbody>
</table>

For a system with a 40 ft elevation to the model pressure ports, the uncertainty is ± 0.150% of FS. This error is three times larger than a pressure measurement system that has the model on the same level.

<table>
<thead>
<tr>
<th>DIGIQUARTZ ERRORS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cal Lab Calibration Error</td>
<td>0.0018 PSI</td>
</tr>
<tr>
<td>Temp Error</td>
<td>0.0007 PSI</td>
</tr>
<tr>
<td>Time Base Error</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Curve Fit Error</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Counter Resolution</td>
<td>0.0001 PSI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MODULE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>15 PSI</td>
</tr>
<tr>
<td>Serial Number (Ignore B)</td>
<td>2037</td>
</tr>
<tr>
<td>Temp Change between Calibs.</td>
<td>1.5 DegF</td>
</tr>
<tr>
<td>Thermal Zero Shift</td>
<td>0.02 % FS</td>
</tr>
<tr>
<td>Thermal Span Shift</td>
<td>0.02 % FS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Data Sets Averaged</td>
<td>8</td>
</tr>
<tr>
<td>Elevation from PCU to Modules</td>
<td>6.00 Feet</td>
</tr>
<tr>
<td>Elevation from Module to Ports</td>
<td>40.00 Feet</td>
</tr>
<tr>
<td>Highest Measured Pressure</td>
<td>15.00 PSI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOTAL DQ ERROR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias Errors</td>
<td>0.0022 PSI</td>
</tr>
<tr>
<td>Random Errors</td>
<td>0.0011 PSI</td>
</tr>
<tr>
<td>+/- Uncertainty (PSI)</td>
<td>0.0023 PSI</td>
</tr>
<tr>
<td>+/- Uncertainty (%)</td>
<td>0.0154 %FS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RACKMOUNT MOD. ERRORS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability</td>
<td>0.0015 PSI</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>Thermal Zero Shift</td>
<td>0.0045 PSI</td>
</tr>
<tr>
<td>Thermal Span Shift</td>
<td>0.0045 PSI</td>
</tr>
<tr>
<td>Non-Linearity Curve Fit Error</td>
<td>0.0008 PSI</td>
</tr>
<tr>
<td>A/D Converter Resolution</td>
<td>0.0005 PSI</td>
</tr>
<tr>
<td>Computer Output Resolution</td>
<td>0.0010 PSI</td>
</tr>
<tr>
<td>SP/Module Elev. Span Error</td>
<td>0.0032 PSI</td>
</tr>
<tr>
<td>Module/Port Elev. Span Error</td>
<td>0.0107 PSI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOTAL DQ ERROR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias Errors</td>
<td>0.0130 PSI</td>
</tr>
<tr>
<td>Random Errors</td>
<td>0.0023 PSI</td>
</tr>
<tr>
<td>+/- Uncertainty (PSI)</td>
<td>0.0130 PSI</td>
</tr>
<tr>
<td>+/- Uncertainty (%)</td>
<td>0.0869 %FS</td>
</tr>
</tbody>
</table>
CONCLUSIONS

It has been shown that the elevation between a transducer and the test article pressure port causes an error in the absolute pressure measurement. The derivation for an elevation correction factor has been shown and proven to be valid from the acquired data. Temperature effects have been presented. The effects upon the accuracy of a typical PSI System 8400 Pressure Measurement System have been demonstrated.

This can also be used to correct errors from elevation differences from a pressure standard to a transducer being calibrated. This would be the case for a PSI System 8400 using remote miniature ESP Modules. (The modules would be on the same elevation as the pressure taps with the pressure calibrator at a different elevation.)

This information can be easily integrated into future testing or be used to re-process old data to yield higher accuracy pressure measurements.
REFERENCES


ACKNOWLEDGMENT

We would like to thank Phil Blumenthal for his assistance with the error analysis portion of this paper.
**Title**: Elevation Correction Factor for Absolute Pressure Measurements

**Authors**: Joseph W. Panek and Mark R. Sorrells

**Abstract**: With the arrival of highly accurate multi-port pressure measurement systems, conditions that previously did not affect overall system accuracy must now be scrutinized closely. Errors caused by elevation differences between pressure sensing elements and model pressure taps can be quantified and corrected. With multi-port pressure measurement systems, the sensing elements are connected to pressure taps that may be many feet away. The measurement system may be at a different elevation than the pressure taps due to laboratory space or test article constraints. This difference produces a pressure gradient that is inversely proportional to height within the interface tube. The pressure at the bottom of the tube will be higher than the pressure at the top due to the weight of the tube's column of air. Tubes with higher pressures will exhibit larger absolute errors due to the higher air density. The above effect is well documented but has generally been taken into account with large elevations only. With error analysis techniques, the loss in accuracy from elevation can be easily quantified. Correction factors can be applied to maintain the high accuracies of new pressure measurement systems.

**Subject Terms**: Pressure measurement; Elevation; Accuracy; Error analysis