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NASA Technical Memorandum 107240

Elevation Correction Factor for Absolute Pressure Measurements

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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

National Aeronautics and
Space Administration

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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, ρ, is proportional to air pressure, P, and we have

$$\frac{\rho}{\rho_o} = \frac{P}{P_o},$$

where ρ_o and P_o are known values of density and pressure.

Substituting $\frac{dP}{dy} = -g\rho_o \frac{P}{P_o}$, 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

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

At 20 DegC,

$$g = 9.80 \ \ m/s^2, \quad \rho_o = 1.205 \ \ kg/m^3 \quad \text{and} \quad P_o = 1.01325x10^5 \ \ Pa,$$

so that $g\frac{\rho_o}{P_o} = 1.16546x10^{-4} \ m^{-1} = 35.523x10^{-6} \ ft^{-1}.$

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

$$P = P_o \exp^{-35.523x10^{-6}y}.$$

Substituting, $P = P_o E_y$ where $E_y = \exp^{-35.523x10^{-6}y}.$

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

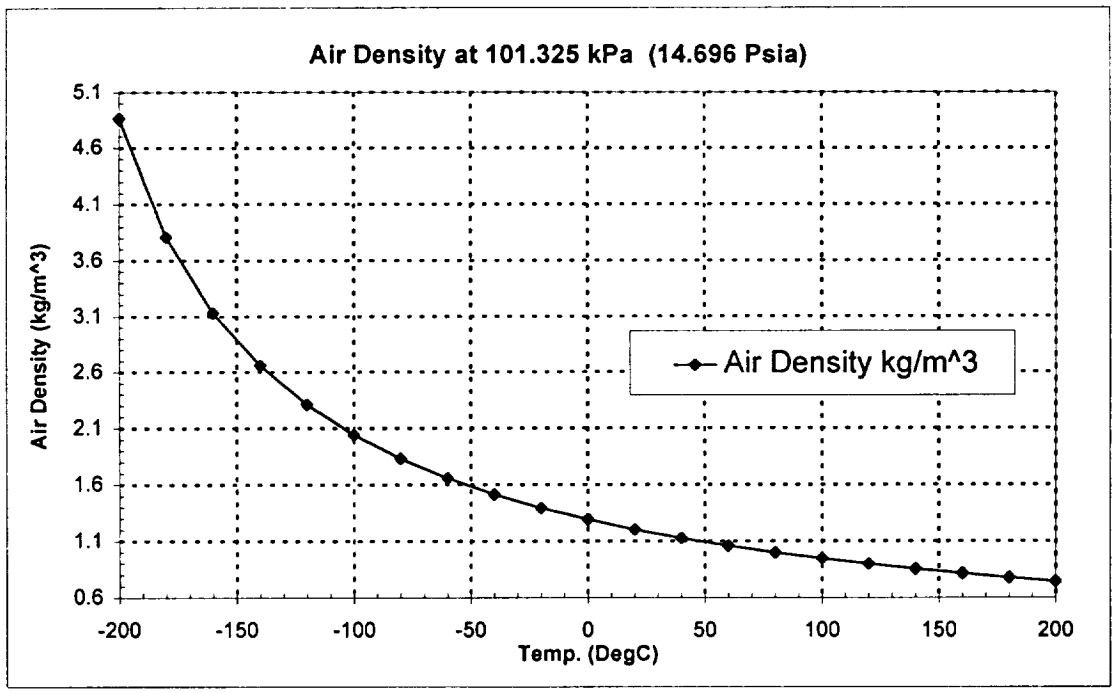
It is safe to assume constant gravity for a small change in elevation. The influence of temperature on the elevation correction factor is shown in the following examples for a 20 Ft elevation.

The density of air, ρ, 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, ρ_0, at 14.696 Psia, for any temperature, T, can be calculated from the following equation. [Ref 4]

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

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

Temp DegC	Air Density kg/m^3
-200	4.8609
-180	3.8097
-160	3.1323
-140	2.6594
-120	2.3106
-100	2.0427
-80	1.8304
-60	1.6581
-40	1.5155
-20	1.3954
0	1.2930
20	1.2046
40	1.1275
60	1.0597
80	0.9995
100	0.9459
120	0.8977
140	0.8541
160	0.8146
180	0.7786
200	0.7457



Assuming P_o = 1.01325 x10^5 Pa and g = 9.8 m/s^2,

For ρ_o = 1.293 kg/m^3 (0 DegC), $\quad g\frac{\rho_o}{P_o} = 1.25057x10^{-4}\ m^{-1} = 38.118x10^{-6}\ ft^{-1}.$

The pressure correction, E_y is $\quad E_y = \exp^{-(38.118\ x\ 10^{-6}*20)} = 0.999238.$

For ρ_o = 0.946 kg/m^3 (100 DegC), $g\frac{\rho_o}{P} = 0.91496x10^{-4}\ m^{-1} = 27.888x10^{-6}\ ft^{-1}$.

The pressure correction, E_y is $E_y = \exp^{-(27.888x10^{-6}*20)} = 0.999442.$

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,

$$0.99980 = \exp^{-38.118x10^{-6}*y}$$

$$\ln 0.99980 = 38.118x10^{-6}*y$$

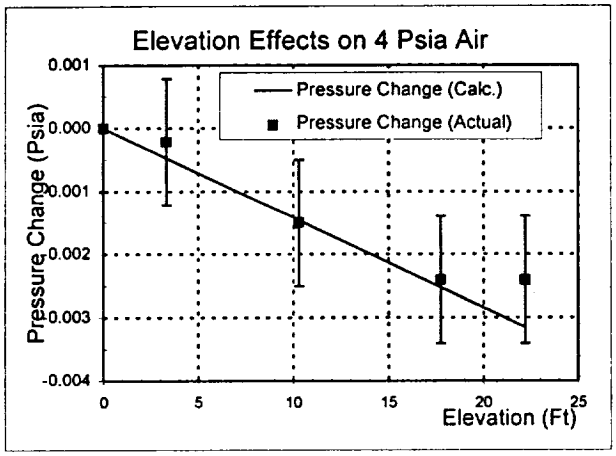
$$y = \frac{-0.0002000}{-38.118x10^{-6}} = 5.25\ ft$$

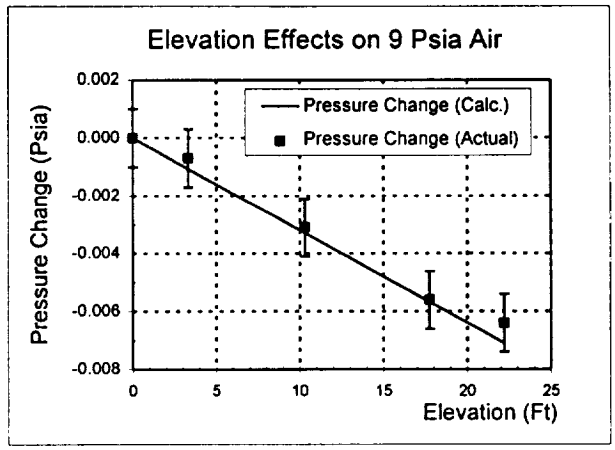
For a 20 ft elevation differential, an additional 5.25 ft variation in elevation produces the same error as a temperature change from 0 to 100 DegC (32 to 212 DegF). For many applications, temperature effects upon pressure can be ignored since elevation produces the dominant error.

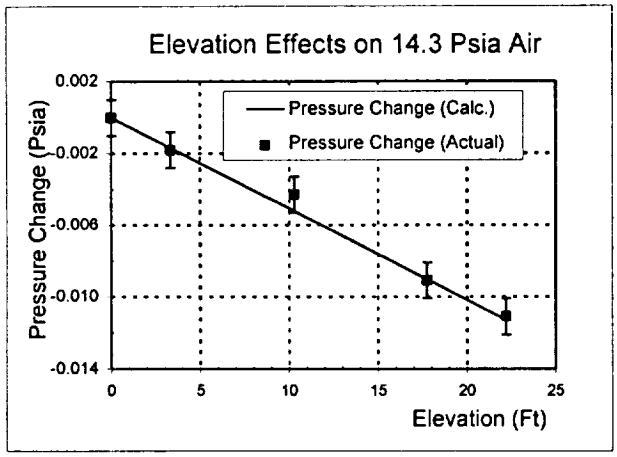
DATA TO VALIDATE THE THEORY

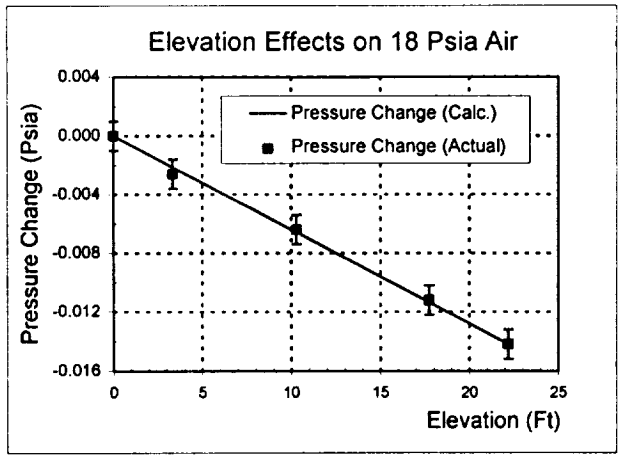
Data was acquired at various pressures and elevations by a 19 PSIA PSI Sonix pressure gage (Reference Pressure) and a 19 PSIA Ruska pressure gage (Elevation Pressure). The ambient temperature was 70±5 DegF. The two gages are accurate to ±0.003 PSIA but have much higher repeatability (approximately ±0.001 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]

$$U_{RSS} = \sqrt{B'^{2} + \left(\frac{2 * S'}{N}\right)^{2}}$$

U_{RSS} = ±Uncertainty (PSI)
N = Number of Data Sets Averaged
B' = Root-Sum-Square of all Bias (fixed) Errors
S' = 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.

DIGIQUARTZ		
Range	15	PSI
Temp Change from Calib.	10.0	DegF
Calibration Lab Error	0.0120	% FS

MODULE		
Range	15	PSI
Serial Number (Ignore B)	2037	
Temp Change between Calibs.	1.5	DegF
Scale Factor	1000	Cnts/PSI
Thermal Zero Shift	0.02	% FS
Thermal Span Shift	0.02	% FS

SYSTEM		
Number of Data Sets Averaged	8	
Elevation from PCU to Modules	6.00	Feet
Elevation from Module to Ports	0.00	Feet
Highest Measured Pressure	15.00	PSI

TOTAL DQ ERROR		
Bias Errors	0.0022	PSI
Random Errors	0.0011	PSI
+/- Uncertainty (PSI)	0.0023	PSI
+/- Uncertainty	0.0154	% FS

DIGIQUARTZ ERRORS			
Cal Lab Calibration Error	B1	0.0018	PSI
Temp Error	B2	0.0007	PSI
Time Base Error	B3	0.0008	PSI
Curve Fit Error	B4	0.0008	PSI
Repeatibility	S1	0.0008	PSI
Hysteresis	S2	0.0008	PSI
Counter Resolution	S3	0.0001	PSI

RACKMOUNT MOD. ERRORS			
Repeatability	S4	0.0015	PSI
Hysteresis	S5	0.0008	PSI
Thermal Zero Shift	B6	0.0045	PSI
Thermal Span Shift	B7	0.0045	PSI
Non-Linearity Curve Fit Error	B8	0.0008	PSI
A/D Converter Resolution	S6	0.0005	PSI
Computer Output Resolution	S7	0.0010	PSI
SP/Module Elev. Span Error	B9	0.0032	PSI
Module/Port Elev. Span Error	B10	0.0000	PSI

Total Bias Errors	B'	0.0075	PSI
Total Random Errors	S'	0.0023	PSI

+/- Uncertainty (PSI)	0.0075	PSI
+/- Uncertainty (% Module FS)	0.0501	%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).

DIGIQUARTZ		
Range	15	PSI
Temp Change from Calib.	10.0	DegF
Calibration Lab Error	0.0120	% FS

MODULE		
Range	15	PSI
Serial Number (Ignore B)	2037	
Temp Change between Calibs.	1.5	DegF
Scale Factor	1000	Cnts/PSI
Thermal Zero Shift	0.02	% FS
Thermal Span Shift	0.02	% FS

SYSTEM		
Number of Data Sets Averaged	8	
Elevation from PCU to Modules	6.00	Feet
Elevation from Module to Ports	20.00	Feet
Highest Measured Pressure	15.00	PSI

TOTAL DQ ERROR		
Bias Errors	0.0022	PSI
Random Errors	0.0011	PSI
+/- Uncertainty (PSI)	0.0023	PSI
+/- Uncertainty	0.0154	% FS

DIGIQUARTZ ERRORS			
Cal Lab Calibration Error	B1	0.0018	PSI
Temp Error	B2	0.0007	PSI
Time Base Error	B3	0.0008	PSI
Curve Fit Error	B4	0.0008	PSI
Repeatibility	S1	0.0008	PSI
Hysteresis	S2	0.0008	PSI
Counter Resolution	S3	0.0001	PSI

RACKMOUNT MOD. ERRORS			
Repeatability	S4	0.0015	PSI
Hysteresis	S5	0.0008	PSI
Thermal Zero Shift	B6	0.0045	PSI
Thermal Span Shift	B7	0.0045	PSI
Non-Linearity Curve Fit Error	B8	0.0008	PSI
A/D Converter Resolution	S6	0.0005	PSI
Computer Output Resolution	S7	0.0010	PSI
SP/Module Elev. Span Error	B9	0.0032	PSI
Module/Port Elev. Span Error	B10	0.0107	PSI

Total Bias Errors	B'	0.0130	PSI
Total Random Errors	S'	0.0023	PSI

+/- Uncertainty (PSI)	0.0130	PSI
+/- Uncertainty (% Module FS)	0.0869	%FS

For a system with a 40 ft elevation to the model pressure ports, the uncertainty is ± 0.15% of FS. This error is three times larger than a pressure measurement system that has the model on the same level.

DIGIQUARTZ		
Range	15	PSI
Temp Change from Calib.	10.0	DegF
Calibration Lab Error	0.0120	% FS

MODULE		
Range	15	PSI
Serial Number (Ignore B)	2037	
Temp Change between Calibs.	1.5	DegF
Scale Factor	1000	Cnts/PSI
Thermal Zero Shift	0.02	% FS
Thermal Span Shift	0.02	% FS

SYSTEM		
Number of Data Sets Averaged	8	
Elevation from PCU to Modules	6.00	Feet
Elevation from Module to Ports	40.00	Feet
Highest Measured Pressure	15.00	PSI

TOTAL DQ ERROR		
Bias Errors	0.0022	PSI
Random Errors	0.0011	PSI
+/- Uncertainty (PSI)	0.0023	PSI
+/- Uncertainty	0.0154	% FS

DIGIQUARTZ ERRORS			
Cal Lab Calibration Error	B1	0.0018	PSI
Temp Error	B2	0.0007	PSI
Time Base Error	B3	0.0008	PSI
Curve Fit Error	B4	0.0008	PSI
Repeatibility	S1	0.0008	PSI
Hysteresis	S2	0.0008	PSI
Counter Resolution	S3	0.0001	PSI

RACKMOUNT MOD. ERRORS			
Repeatability	S4	0.0015	PSI
Hysteresis	S5	0.0008	PSI
Thermal Zero Shift	B6	0.0045	PSI
Thermal Span Shift	B7	0.0045	PSI
Non-Linearity Curve Fit Error	B8	0.0008	PSI
A/D Converter Resolution	S6	0.0005	PSI
Computer Output Resolution	S7	0.0010	PSI
SP/Module Elev. Span Error	B9	0.0032	PSI
Module/Port Elev. Span Error	B10	0.0213	PSI

Total Bias Errors	B'	0.0226	PSI
Total Random Errors	S'	0.0023	PSI

+/- Uncertainty (PSI)	0.0226	PSI
+/- Uncertainty (% Module FS)	0.1506	%FS

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

1. Physics, Parts I and II; David Halliday and Robert Resnick, Copyright 1978, John Wiley and Sons, New York, NY.

2. NASA Contractor Report 198361, AIAA-95-3072, "A PC Program for Estimating Measurement Uncertainty for Aeronautics Test Instrumentation"; Philip Z. Blumenthal, July, 1995.

3. The Bell and Howell Pressure Transducer Handbook; CEC/Instruments Division, Copyright 1974, Bell and Howell Company.

4. CRC Handbook of Chemistry and Physics, 66th Edition 1985-1986; Editor-in-Chief, Robert C. Weast, Ph.D., Copyright 1985, CRC Press, Inc., Boca Raton, Florida.

ACKNOWLEDGMENT

We would like to thank Phil Blumenthal for his assistance with the error analysis portion of this paper.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1996	Technical Memorandum

4. TITLE AND SUBTITLE

Elevation Correction Factor for Absolute Pressure Measurements

5. FUNDING NUMBERS

WU-505-62-82

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-10285

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-107240

11. SUPPLEMENTARY NOTES

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. Responsible person, Joseph W. Panek, organization code 2850, (216) 433-5670.

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Unclassified - Unlimited
Subject Categories 35, 38, 33, 35, and 09

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12b. DISTRIBUTION CODE

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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.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Pressure measurement; Elevation; Accuracy; Error analysis	12
	16. PRICE CODE A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

National Aeronautics and
Space Administration

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