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EPMT: A Portable Transfer Standard for Telemetry System Pressure-Transducer Calibration

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EPMT: A Portable Transfer Standard for Telemetry
System Pressure-Transducer Calibration*

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Abstract

The LLL developed electronic pressure meter (EPMT) is a portable static-pressure calibration instrument for use with the LLL telemetry transducer system at the Nevada Test Site (NTS). It is significantly more accurate and rugged than the bourdon-tube pressure gauge it replaces, and can be incorporated into a field-use, semi-automatic, pressure calibration system.

This paper discusses the process by which a transducer is selected for EPMT use from our inventory of field-service-certified transducers and subjected to an extensive preconditioning and calibration procedure. By combining this unusual calibration procedure with a unique, statistically based data-reduction routine, the total uncertainty of the measuring process at each calibration point can be determined with high accuracy.

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1.0 INTRODUCTION

In many of the nuclear events conducted by LLL, at USERDA's Nevada Test Site (NTS), pressure measurement must be made on experimental systems which are located in a "downhole" environment. These measurements are used to verify actual system performance and provide diagnostic information if there is a system failure.

The pressures of interest range from atmospheric to the thousands of PSI and are measured using aerospace quality, gauged diaphragm, integrally signal conditioned, high-level-output transducers. The high dollar value of each experiment requires that great care be taken to insure that transducers committed to a system will not fail mechanically (an absolute "no-no") or electrically (very undesirable). This is accomplished through stringent specifications, close LLL/vendor liaison, and an extensive in-house certification program.[1]

Once in the field, output signals from the transducers are hardwired from their downhole location to the surface, a distance which can range from 500 to 6,000 feet. After being digitized and encoded, the signals are multiplexed onto the LLL PCM microwave telemetry link for transmission to the remote control-room facility. There they are decoded, recorded, and displayed, as required, in appropriate engineering units.

2.0 BACKGROUND

The key to reliable accurate transducer performance is good design and quality assurance, coupled with a program of controlled mechanical and electrical "past history".

Prior to being qualified, each candidate transducer is subjected to an LLL design evaluation of both the pressure cavity[2] and signal conditioning electronics. In order to guard against the undesirable effects of free hydrogen which may be present in the system, the LLL Specification[3] requires that the pressure body and diaphragm be an integral weld-free part, machined from an H_2 compatible material. Since the associated systems are ultra-clean, the cavity design, Figure 1, must be free from any voids or spaces which could entrap particulate matter.

When a design appears promising two evaluation units are procured and tested mechanically and electrically. If successful, the transducer design is then considered as qualified. The vendor is not to make any modifications to this design without LLL approval.

Unfortunately, qualification of a design and vendor are not enough to preclude transducer failures. These failures fall into two main categories; shelf-life and infant-mortality. With the former a previously good unit, when removed from bonded storage, is found to no longer meet the required specifications. In the latter case a failure occurs after a limited number of operating hours.

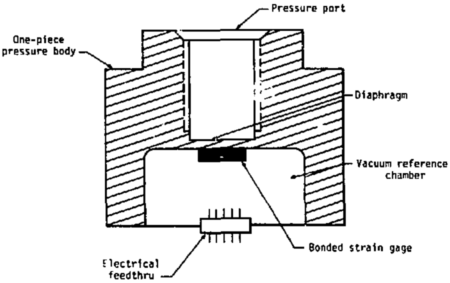

Fig. 1 Pressure Body Cross Section

Such problems are not detected by the vendor since prior to shipment the units generally experience less than ten pressure cycles and eight hours of electrical operation.

Thus, during actual use, the zero can vary as a function of strain gauge creep due to aging of the bonding adhesive, diaphragm characteristics can change due to working of the material, a gradual leak can destroy the reference vacuum, and electronic components can age.

To ameliorate the latter problem, we require that all transducers be burned-in for 168-hours at 150°F, with the maximum excitation voltage applied. This is done either at the vendor's plant or in LLL's Reliability Test Lab. Most infant-mortality failures are culled out and the subsequent overall reliability and stability are enhanced.

Once a shipment of transducers arrives at LLL, the pressure cavities are thoroughly cleaned of oil and particulate matter. Then they are routed through the following sequences:

a. Initial calibration check (gas) 2 cycles; 0/50/100%-Range
b. Burn-in (if not performed by vendor)[5]
c. Post burn-in calibration check (see a above)
d. Vibration and shock[6]
e. Calibration check (see a above)
f. Pressure Test

1) Overpressure - 150%-Range (He plus 10% O_2) for 30-minutes (110% for 20-KSI units)

2) H_2 Soak - 140%-Range - 2 hours (100% for 20-KSI units)

3) H_2 Cycle - four cycles to 90%-Range - 5 minutes

g. Pressure Calibration - two cycles, 21 points (0-to-100%-Range)

The final calibration is performed in the LLL Force and Calibration Lab, where a computer generated terminal point error plot, Figure 2, is produced for each of these field-certified units.

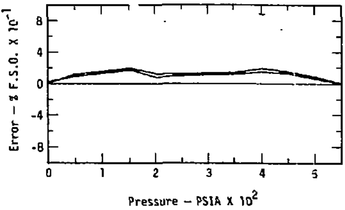

Fig. 2 Terminal Point Error Plot

When a transducer is installed in the final-use system, an end-to-end static pressure calibration is performed involving all portions of the event system. Ultra-pure inert gas, from a high pressure bottle, is manually introduced into the system until the desired calibration pressures are obtained, as observed on a bourdon-tube gauge. It is these gauges which we are replacing with the EPMT.

Consider that, following their calibration at LLL's Livermore Calibration Laboratory, the gauges are subjected to a multitude of "mechanical history" altering inputs: temperature excursions from 68°F in the Cal Lab, to 120°F in an NTS pick-up truck, to an air conditioned forward area building; ambient pressure changes from 14.7-PSIA at Livermore to subatmospheric during the plane ride to NTS with its 12.6-PSIA; physical impacts coincident with their transport. It is a wonder that they possess any accuracy at all, mirror scales notwithstanding.

3.0 ELECTRONIC PRESSURE METER WITH TRANSDUCER (EPMT)

To obtain a field calibration standard whose accuracy is in keeping with that of the transducers being checked, we have developed a rugged, portable, easy to use, transfer standard known as the EPMT.

A transducer for the required range is selected from our inventory of "well exercised" field-certified transducers. The criteria are: better than average linearity and repeatability; minimal hysteresis.

After being mounted within a blast case (see Figure 3), the transducer is installed in a small, portable, electronics enclosure (see Figure 4), with the pressure fitting brought out to the front panel. Also contained within the box are a power supply, buffer amplifier, digital voltmeter (DVM), analog voltmeter, power and shunt-calibrate switches, and power and output signal connectors. In addition, a small mechanical pressure gauge is included to provide a rough indication of the pressure. This gauge becomes very important if an electrical power or electronics failure occurr while the system is pressurized.

The high level (0-5 V DC) transducer output signal is applied, via a unity gain buffer amplifier and resistive attenuation network, to the precision, 40,000 count, auto-zeroing, DVM which displays pressure directly in PSI (refer to Figure 5). Zero adjustments are included to correct for unavoidable transducer and buffer amplifier zero shifts. The attenuator is adjusted to provide an output voltage which represents the pressure in PSI. Output from a second buffer amplifier is applied to an analog meter to permit observation of trends during periods of rapid pressure change.

Binary coded decimal (BCD) and 0-5 V DC output signals are available for use with digital and analog recording equipment.

Fig. 3 EPMT - Inside Rear View

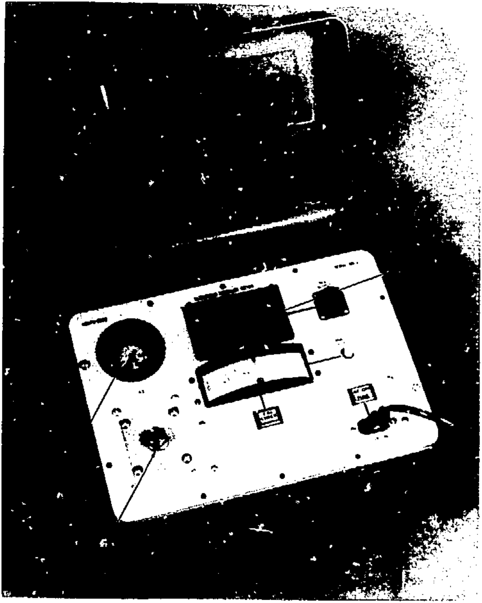

Fig. 4 EPMT - Front Panel

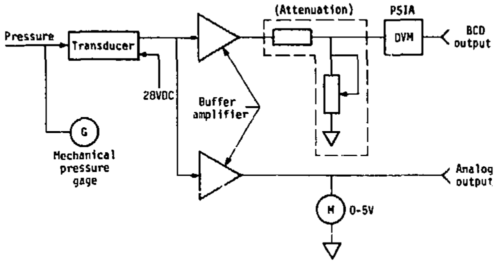

Fig. 5 EPMT - Block Diagram

4.0 CALIBRATION AND DATA REDUCTION

Use of a field certified transducer in conjunction with a high resolution digital readout does not in itself guarantee precision pressure readings. Nor does a two-cycle calibration run. Since the EPMT is intended for field rather than Lab use, the calibration process attempts to incorporate some of the less than ideal conditions to which it will be subjected.

The following states the objective of the calibration process:

> Obtain sufficient realistic data to permit computation of a number which reasonably represents the absolute accuracy of the instrument under test, including the variability of the measuring process and the uncertainty of the standard against which the instrument is being calibrated.

This objective is met by employing an uncomplicated but somewhat laborious procedure in which a moderately large number of independent measurements are made at each calibration pressure in order to enhance the confidence level of the data.

Each EPMT is preconditioned with five overpressurizations to 125%-Range. Zero is set at 0%-Range and, with a very precise 100%-Range pressure applied, the span is adjusted to provide the required readout in PSI. No further zero or span adjustments are made for the duration of the calibration process.

Next, the EPMT is subjected to two calibration cycles in 10%-Range increments. A maximum pressure of approximately 110%-Range is applied, with no data taken at that point, so that ascending and descending data at 100%-Range can be recorded. The EPMT is deenergized, pressure fittings disconnected, and the unit removed to another location where the ambient temperature differs by at least 15 to 20°F from that of the Cal Lab. After a minimum of 1-hour, it is returned to the Cal Lab where, after a 30-minute warm-up, the cycle is repeated. After a total of ten calibration cycles (220 points) have been recorded, the process is complete. Because of Cal Lab workloads, this process may extend over a period of several weeks, which lends to the statistical validity of the data.

Figure 6 shows the applied calibration pressures and the corresponding EPMT readings for a 500-PSIA EPMT. The odd sample numbers (S#) are for ascending pressures while even S#'s are for descending pressures.

	Applied pressure - PSIA										
S#	0	50	100	150	200	250	300	350	400	450	500
1	0.0	50.7	100.9	151.0	200.5	250.6	300.6	350.4	400.5	450.8	500.0
2	0.3	50.6	100.8	150.9	200.4	250.5	300.4	350.2	400.6	450.2	500.0
3	0.0	50.6	100.9	151.1	200.6	250.6	300.6	350.5	400.7	450.4	500.0
4	0.3	50.6	100.7	150.8	200.4	250.4	300.5	350.4	400.6	450.2	500.0
5	0.0	[illegible]	100.7	150.9	200.5	250.5	300.6	350.6	400.8	450.6	500.2
6	0.1	[illegible]	100.7	150.9	200.4	250.5	300.5	350.5	400.7	450.5	500.1
7	0.1	[illegible]	100.9	151.1	200.7	250.7	300.7	350.7	400.9	450.7	500.3
8	0.2	[illegible]	100.8	151.0	200.5	250.6	300.[illegible]	350.6	400.7	450.6	500.2
9	0.4	50.8	101.1	151.3	200.9	250.9	301.0	351.0	401.1	450.9	500.4
10	0.4	50.7	[illegible]	151.2	200.8	250.9	300.9	350.9	401.1	450.9	500.4
11	0.4	50.9	101.2	151.3	200.9	251.0	301.0	350.9	401.2	451.0	500.6
12	0.4	50.8	101.0	151.1	200.8	250.8	300.9	350.8	401.0	[illegible]	500.5
13	0.2	50.7	100.9	151.1	200.7	250.8	300.9	350.8	401.0	450.8	500.4
14	0.2	50.6	100.8	151.0	200.6	250.6	300.8	350.7	401.0	[illegible]	500.3
15	0.2	50.7	101.0	151.2	200.7	250.8	300.8	350.8	401.0	450.6	500.4
16	0.2	50.7	100.9	150.9	200.6	250.7	300.8	350.8	401.0	450.8	500.4
17	0.2	50.7	101.0	151.1	200.8	250.9	300.7	350.8	401.0	450.8	500.4
18	0.2	50.6	100.9	151.0	200.6	250.7	300.8	350.7	400.9	450.7	500.3
19	0.2	50.7	101.9	151.2	200.7	250.8	300.8	350.7	401.0	450.8	500.4
20	[illegible]	50.6	100.8	151.1	200.6	250.8	300.5	350.6	400.9	450.8	500.4

Fig. 6 Calibration Data
500-PSIA EPMT

Next, the data is reduced using a unique statistically based routine from which an accuracy statement for each cardinal point is obtained. In addition, a conservative overall accuracy statement (total error band) is produced.

Data Reduction Procedure

The arithmetic mean ($\bar{x}$) and standard deviation (s) for all 20 observations are found for each value of applied pressure (P_A).

$$\bar{x} = \frac{\Sigma x_i}{n}$$

$$s = \sqrt{\frac{\Sigma x_i^2 - \frac{1}{n}\left(\Sigma x_i\right)^2}{n - 1}} = \sqrt{\frac{\Sigma \delta^2}{n - 1}}$$

Where x_i = The EPMT reading at a particular applied pressure, P_A

n = The total number of observations (20 for this process)

δ = $(\bar{x} - x_i)$, the deviation of each observation from the mean of the set of data.

Determination of Uncertainty

Since the EPMT is to be used as a working standard, it is desirable to know how closely a particular reading can be trusted. If a random pressure is applied, the resulting reading can be believed, with a stated probability known as the "confidence level", to represent the true absolute value of the applied pressure within a band of uncertainty known as the "confidence interval" (C_s).

The standard deviation, $\pm$ s, defines a range about the mean within which it is reasonable to expect 68% of the observed data to lie, assuming normal distribution.

To obtain the confidence interval, the standard deviation is multiplied by a coefficient which takes into account the number of observations and the desired confidence level. For 20 observations and a confidence level of 95%, the coefficient extrapolated from the referenced table[7] is equal to 2. Thus, $C_s = 2s$, and may have a different value for each value of P_A.

Next, the uncertainty of the mean must be considered. For the confidence level stated above the confidence interval, $C_{\bar{x}}$, is

$$C_{\bar{x}} = \frac{C_s}{\sqrt{n}} = 0.224\ C_s$$

Likewise, the value of applied pressure, P_A, produced by the primary calibration standard, possesses some uncertainty. This value, U_S, (expressed in PSI) is the stated accuracy of the standard. Note that $U_S = 0$ for P_A = 0-PSIA if 100%-Range of the test transducer is much greater than vacuum.

The total uncertainty, $\pm U_T$, of the EPMT, at each value of P_A, is

$$\pm U_T = \pm (C_s + C_{\bar{x}} + U_S)$$

A substitution of terms yields

$$\pm U_T = \pm (2.448s + U_S)$$

Zero Corrected Mean

During the period of the full calibration cycle, the EPMT readings at 0%-Range also vary. Thus, the mean of those readings, $\bar{x}_O$, should be subtracted from the mean pressure reading at each observation point to obtain a zero corrected mean, $\bar{x}_C$.

$$\bar{x}_C = \bar{x} - \bar{x}_O$$

Correction Factor

Taking the difference between the zero corrected mean and the applied pressure provides a correction factor, C_F.

$$C_F = \bar{x}_C - P_A$$

When obtaining a precise pressure (P), the correction factor is added to the value of P to determine what EPMT reading (P_M) should be observed.

$$P_M = P + C_F$$

Note that for the above to be valid, the EPMT zero must be adjusted to provide a reading of 0-PSIA at 0%-Range

It can be stated:

> when the applied pressure produces an EPMT reading equal to P_M, the actual pressure present equals the desired pressure P, within the stated uncertainty, $\pm U_T$.

When the greatest accuracy is required of the EPMT, it should be used at the specific calibration pressure points, with readings appropriately corrected.

Determination of the Error Band

For more general use, an overall accuracy statement can be used. At each value of P_A, calculate the sum and difference of the correction factor and total uncertainty to obtain an error term, $\varepsilon(\pm)$.

$$\varepsilon(\pm) = C_F \pm U_T$$

Using the above equations the calibration data has been reduced to the final form shown in Figure 7. Note that all values are in units of PSIA.

P_A	$\bar{x}$	s	C_s	$C_{\bar{x}}$	U_S	U_T	$\bar{x}_c$	C_F	$C_F + U_T$	$C_F - U_T$
0.00	0.21	0.129	0.259	0.058	0.00	0.32	0.00	0.000	0.317	-0.317
50.00	50.67	0.099	0.198	0.044	[illegible]	0.34	50.46	0.455	0.797	0.113
100.00	100.95	0.263	0.525	0.117	0.10	0.74	100.74	0.740	1.483	-0.003
150.00	151.06	0.139	0.278	0.062	0.10	0.44	150.85	0.850	1.291	0.409
200.00	200.64	0.157	0.313	0.070	0.10	0.48	200.43	0.425	0.908	-0.058
250.00	250.71	0.164	0.328	0.073	0.13	0.53	250.50	0.495	1.021	-0.031
300.00	300.72	0.177	0.353	0.079	0.15	0.58	300.51	0.510	1.092	-0.072
350.00	350.67	0.198	0.395	0.088	0.18	0.66	350.46	0.460	1.119	-0.199
400.00	400.89	0.193	0.385	0.086	0.20	0.67	400.68	0.675	1.347	0.003
450.00	450.68	0.227	0.454	0.101	0.23	0.78	450.47	0.465	1.245	-0.315
500.00	500.29	0.181	0.363	0.081	0.25	0.69	500.08	0.075	0.769	-0.619

Fig. 7 Analysis of Calibration Data
500-PSIA EPMT

Select the maximum positive and negative value of ε (+ 1.48 and - 0.62 PSIA for the data shown). Next, using the terminal-end-point straight line (passing through 0%, 0% and 100%, 100%-Range) as a reference, the pair of parallel lines passing through $\varepsilon(+)_{max}$ and $\varepsilon(-)_{max}$ define the limits of the total error band (T.E.B.).

Figure 8 depicts the T.E.B. for the example 500-PSIA EPMT. In order to obtain adequate resolution, the abscissa represents the error, in PSIA, between the zero-corrected EPMT reading and the corresponding applied pressure. The terminal-end-point straight line corresponds to zero error.

Also shown are the normal distribution curves associated with $\epsilon(\pm)_{max}$.

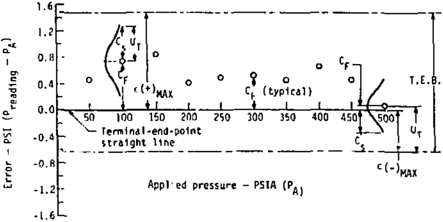

Fig. 8 Total Error Band Plot - Partial 500-PSIA EPMT

The result of this process can be stated as follows:

> There is a 95% probability that any EPMT reading will represent the true applied pressure within the uncertainty expressed by the T.E.B.

The preceding calculational procedure is presented in the Appendix for use with a programmable pocket calculator (HP55). A programmable desktop calculator (HP9830) was used to obtain the tabulated data and data analysis shown in Figs. 6 and 7. The latter program is available from the author upon request.

5.0 THE OVERALL CALIBRATION SYSTEM

To achieve and maintain the accuracy of the EPMT requires the availability of a hierarchy of field and laboratory pressure standards. (Refer to Figure 9).

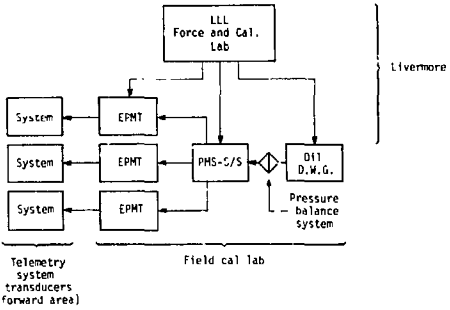

Fig. 9 Block Diagram - Overall Calibration System

The LLL Force and Calibration Lab utilizes a Gilmore 10-KSI automatic gas dead weight system and a Ruska 40-KSI oil dead weight gauge, (DWG). A field calibration facility has been established, at NTS, which incorporates a Ruska 12-KSI oil DWG as a local "primary" standard, plus a working standard, the Pressure Measurement System - Secondary Standard (PMS-S/S). The latter system incorporates oven-mounted, precision, diaphragm-type, pressure transducers, in conjunction with linearization electronics. The pressure is displayed digitally in engineering units.

The EPMT functions as the transfer standard used for calibration of the "downhole" telemetry-system transducers.

All three field instruments were initially calibrated at Livermore, with both the EPMT and PMS-S/S receiving the 220 point calibration described above.

The PMS-S/S is used to perform regular calibration checks of EPMT's, transducers, and gauges. Periodically, the PMS-S/S is checked against the DWG and adjusted, as required, to correct for zero and span errors.

Note that the oil DWG is isolated from PMS-S/S by a differential pressure cell operated in conjunction with an electronic pressure-balance readout. This is done to avoid the introduction of oil into the clean systems which are to be calibrated. Extensive testing has been done in order to determine the null uncertainty introduced by ΔP-cell null shift at high line pressures. The resulting term must be added to the PMS-S/S uncertainty in order to define the total uncertainty, or variability, of the measuring process.

6.0 A PROPOSED SEMI-AUTOMATIC CALIBRATION SYSTEM

Currently, when an end-to-end static pressure calibration is performed, pressure is metered into the system via a hand-operated valve. The EPMT can be easily incorporated into a semi-automatic system as seen in Figure 10.

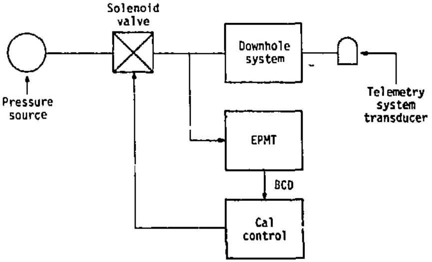

Fig. 10 Proposed Semi-automatic Calibration System

Gas from the high pressure source passes through a fast acting, normally-closed, solenoid actuated valve.

The pressure is sensed by the EPMT and the resulting BCD output signal is fed into the portable calibration control box. Having selected the number of calibration points desired and the appropriate EPMT pressure range, the START switch is activated. The solenoid valve opens and the pressure rises until the EPMT BCD output equals the value of the first calibration point set into the control box digital counter. The valve closes and following a suitable delay, to permit temperature equilibration, the time-of-day and EPMT pressure readings are printed out. The telemetry system transducer output can also be recorded locally, on a second printer, as well as at the remote control-room facility. Again, the valve opens and the calibration run continues. A preliminary study indicates that all of the necessary control can be accomplished using either a few discrete logic components or a microprocessor.

7.0 SUMMARY

The key to reliable accurate pressure transducer performance is careful control over both the design and accumulated "mechanical and electronic past history". From an inventory of such transducers it is possible to select units which exhibit better than specified linearity, repeatability, and hysteresis characteristics. Incorporation of such a unit into a safe, convenient, portable enclosure and coupling it with a digital electronic readout provides the basis for an excellent transfer standard, the EPMT.

Next, by performing a rigorous precision calibration, it is possible to obtain a meaningful, statistically based, accuracy statement. The validity of the EPMT's accuracy is based on the existence of a hierarchy of pressure calibration standards.

The end result is an easy to use, rugged, transfer standard, suitable for the end-to-end static pressure calibration of telemetry-system pressure-transducers. In addition, the EPMT can provide a significant portion of a semi-automatic calibration system.

Acknowledgement

Design and fabrication of the transducer portion of the EPMT, plus the extensive transducer qualification testing was provided by A. W. Hampton and his High Pressure Lab crew. The laborious precision calibration procedure was done by J. Kimberling and J. Phair of the Force and Calibration Lab. Finally, special thanks go to C. Miks of the Ruska Instrument Corporation, who introduced me to the concept of the "variability of the measuring process", and P. Stein who acquainted me with the significance of "past mechanical history".

Appendix

Data Reduction Routine for HP-55 Calculator

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS				OUTPUT DATA/UNITS
1	ENTER PROGRAM						
2	STORE U_s FOR 0%-RANGE	0	STO	0			
3	STORE $1/\sqrt{m}$	0.224	STO	1			
4	CALC. $\bar{X}$, s @ PA = 0% RNG	$P_Ø$	Σ+				
5	FETCH $\bar{X}_o$		f	$\bar{x}$			$\bar{X}_o$
6	STORE $\bar{X}_o$	$\bar{X}_o$	STO	2			
7	FETCH $\bar{X}$		f	$\bar{x}$			
8	STORE $\bar{X}$	$\bar{X}$	STO	3			$\bar{X}$
9	FETCH s		g	s			
10	STORE	s	STO	4			s
11	STORE PA & COMP.	PA	STO	5	BST	R/S	
12	FETCH X_c		RCL	6			X_c
13	FETCH C_F		RCL	7			C_F
14	FETCH U_T		RCL	8			U_T
15	FETCH E(+)		RCL	9			E(+)
16	FETCH E(-)		RCL	.	0		E(-)
—	END OF RUN —						
17	CLEAR Σ+ REG'S		g	CL.R			
18	ENTER U_s IF ≠ STEP 2 VALUE	U_s	STO	Ø			
19	CALC. $\bar{X}$, s FOR NEXT CAL. RANGE	P_N	Σ+				
20	GO TO STEP 7 &						
	CONTINUE THRU STEP 19 UNTIL DONE						

INSTRUCTIONS

Press ■ in RUN mode, switch to PRGM mode. Then key in the program.

Line	Code	Key Entry	X	Y	Z	T	Comments
00	//////	//////					
01	34	RCL					
02	03	3	$\bar{X}$				
03	34	RCL					
04	02	2	$\bar{X}_o$	$\bar{X}$			
05	51	−	$\bar{X}_c$				$\bar{X}_c = \bar{X} - \bar{X}_o$
06	33	STO	$\bar{X}_c$				CORRECTED MEAN
07	06	6	$\bar{X}_c$				
08	34	RCL	$\bar{X}_c$				
09	05	5	P_A	$\bar{X}_c$			
10	51	−	CF				$CF = \bar{X}_c - P_A$
11	33	STO	CF				
12	07	7	CF				
13	34	RCL	CF				
14	04	4	Δ	CF			
15	02	2	2	Δ	CF		
16	71	×	C_Δ	CF			$C_\Delta = 2\Delta$
17	41	ENT	C_Δ	C_Δ	CF		
18	41	ENT	C_Δ	C_Δ	C_Δ	CF	
19	34	RCL	C_Δ	C_Δ	C_Δ	CF	
20	01	1	.224	C_Δ	C_Δ	C_Δ	
21	71	×	$C\bar{X}$	C_Δ	C_Δ	C_Δ	$C\bar{X} = .224\, C_\Delta$
22	61	+	$C\bar{X}+C_\Delta$	C_Δ	C_Δ	C_Δ	
23	34	RCL	$C\bar{X}+C_\Delta$	C_Δ	C_Δ	C_Δ	
24	00	0	U_S	$C\bar{X}+C_\Delta$	C_Δ	C_Δ	
25	61	+	U_T	C_Δ	C_Δ	C_Δ	$U_T = U_S + C\bar{X} + C_\Delta$
26	33	STO	U_T	C_Δ	C_Δ	C_Δ	
27	08	8	U_T	C_Δ	C_Δ	C_Δ	
28	34	RCL	U_T	C_Δ	C_Δ	C_Δ	
29	07	7	CF	U_T	C_Δ	C_Δ	
30	61	+	E(+)	C_Δ	C_Δ	C_Δ	$E(+) = CF + U_T$
31	33	STO	E(+)	C_Δ	C_Δ	C_Δ	
32	09	9	E(+)	C_Δ	C_Δ	C_Δ	
33	34	RCL	E(+)	C_Δ	C_Δ	C_Δ	
34	08	8	U_T	E(+)	C_Δ	C_Δ	
35	02	2	2	U_T	E(+)	C_Δ	
36	71	×	$2 \cdot U_T$	E(+)	C_Δ	C_Δ	
37	51	−	E(−)	C_Δ	C_Δ	C_Δ	$E(+) - 2U_T$
38	33	STO	E(−)	C_Δ	C_Δ	C_Δ	$= (CF + U_T) - 2U_T$
39	83	.	E(−)	C_Δ	C_Δ	C_Δ	$= CF - U_T$
40	00	0	E(−)	C_Δ	C_Δ	C_Δ	$= E(-)$
41	84	GTO 0					
42	-00	R/S					
43							◇ STORE FOR EACH RUN
44							
45							
46							⬡ RESULTS OF RUN
47							

Registers	
◇ R0	U_S
R1	0.224
R2	$\bar{X}_o$
◇ R3	$\bar{X}$
◇ R4	Δ
◇ R5	P_A
⬡ R6	$\bar{X}_c$
⬡ R7	CF
⬡ R8	U_T
⬡ R9	E(+)
⬡ R.0	E(−)
R.1	
R.2	
R.3	
R.4	
R.5	
R.6	
R.7	
R.8	

PROGRAM

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