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APOLLO EXPERIENCE REPORT - FLIGHT INSTRUMENTATION CALIBRATION

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16. Abstract

Three types of instrumentation-calibration data were used in the Apollo Program to provide the correct engineering data for tests and mission support. The command and service module instrumentation-component procurement specifications required individual-component calibration, and calibration data for these individual components (conventional-calibration data) were always used for mission data support. A mean standard type of calibration data derived from a statistical sampling of conventional-calibration data was used for test and checkout during the latter part of the Apollo Program. The lunar module instrumentation procurement specification permitted the use of standard-calibration data. These data were applicable to similarly instrumented measurements. The definition, merit, and application of each type of data are discussed.

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APOLLO EXPERIENCE REPORT

FLIGHT INSTRUMENTATION CALIBRATION

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SUMMARY

Three types of instrumentation-calibration data were used for minimizing errors in data accruing from Apollo spacecraft instrumentation systems. The type usually specified was unique to individual instrumentation components and was termed conventional. Mean-standard-calibration data were used for most command-service module test and checkout purposes during the latter stages of the program. Advantages in the use of standard-calibration data were later recognized, and this type was permitted by lunar module instrumentation specifications to minimize the use of conventional-calibration data. It is concluded that the use of standard-calibration data is preferable for most applications; however, the requirement for the use of conventional-calibration data for critical measurements may never be eliminated.

INTRODUCTION

Instrumentation systems sense such physical conditions as the pressure in a fuel tank, the acceleration of a mass, or the mass flow of a moving fluid, and the systems represent them as numerical values. When using instrumentation system data, the analyst is concerned with how closely the measured values represent the actual values. Ideally, the output of the measurement system should be directly proportional to the input and in the same units. This condition was seldom achieved, however, because of errors associated with the measurement of the physical stimuli and the conversion of the measurements to electrical signals. Therefore, calibration data were required to convert the numerical values into usable units that could be interpreted by the analyst. The instrumentation error was normally determined by comparing the measured value to the same measurement made with an established and accepted measurement system. The terms and accuracy of the calibration data provided had to be compatible with the requirements of the analyst when interpreting test results.

TYPES OF INSTRUMENTATION SYSTEMS

A simple form of an instrumentation system is a meter that is read directly in the units of the measured stimulus. This kind of system requires minimal calibration data. Complex instrumentation systems consist of several components, including a transmission system, and require more comprehensive calibration data so that the errors are determined and the correct compensation is applied. Calibration data, usually presented as a curve, compare the output of the instrumentation system with the measured values. For a simple meter display, the curve would show actual data compared with indicated data (fig. 1).

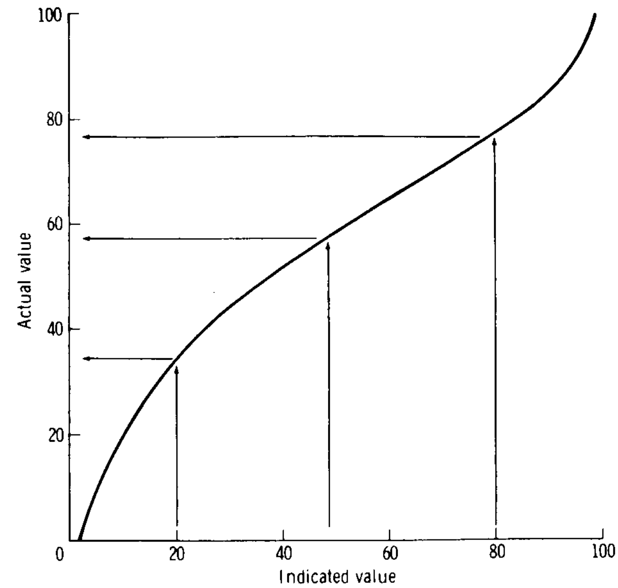

Figure 1. - Simple calibration curve.

ACCURACY

The procurement of Apollo instrumentation components was based on a nominal instrumentation range that could determine system status and performance. The accuracy of each Apollo instrumentation measurement for flight evaluation was obtained by a root-sum-square summation of the allowable system-component errors. These errors were separated basically into random errors and systematic or repeatable errors. Instrumentation errors were also influenced by environmental conditions; however, for brevity, only systematic errors at ambient conditions will be discussed in detail. Other errors were considered in qualifying instrumentation and in defining overall accuracy.

A calibration curve that illustrates various types of errors is shown in figure 2, in which the data points from a number of calibration tests are represented by X's. A faired curve that best fits the data points is a mean-calibration curve. Boundary lines drawn through the outer data points define the random-error band, and the outermost dashed lines show the boundaries of the specified-error band. The offset of the mean-calibration curve from the ideal-calibration curve is the systematic error. The systematic error may be a constant bias or may vary in magnitude throughout the measurement range. The important points are that the error is repeatable and that the instrumentation-calibration data compensate for the error.

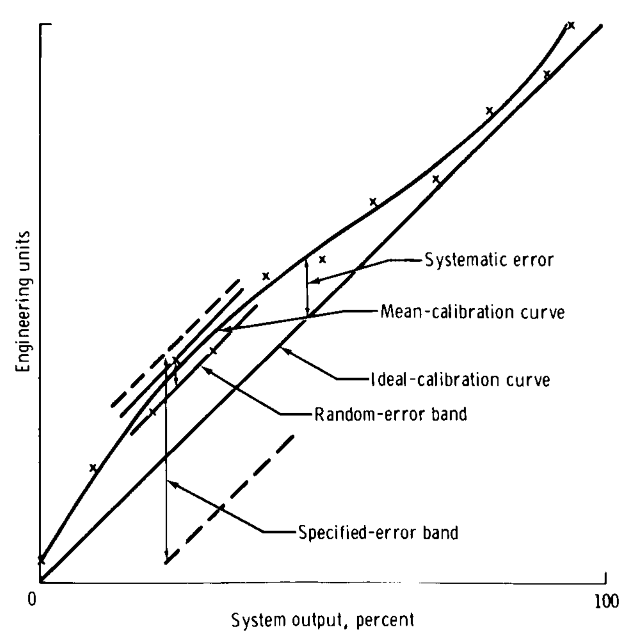

Figure 2. - Random and systematic errors.

Instrumentation accuracy was improved in two different ways: through better quality hardware and through repeated calibration of instrumentation components. However, a point was soon reached at which it was necessary to compromise to provide calibrations that best served the purpose within the practical limitations of cost and scheduling. In addition, the error magnitude was related to the design state of the art of measurement sensors and of signal-conditioning equipment.

CONVENTIONAL-CALIBRATION DATA

Individual-component calibration was required by procurement specifications for the Saturn launch vehicle and the command and service module (CSM). The type of calibration data usually specified for Apollo instrumentation systems was individual-component data and was, therefore, defined as conventional-calibration data. Apollo scientific equipment also generally required the use of conventional-calibration data.

The specified instrumentation range was equal to or greater than that required to determine system performance. Actual component-calibration data were used to eliminate systematic errors, thereby improving the accuracy of the measurement. For linear curves, end points were determined for the specific transducer, and a straight line was drawn between them. The maximum allowable deviation from this line was defined by the transducer specification. The data points for each specific transducer taken during testing were used to produce conventional-calibration curves. Systematic errors were verified by using actual data from vendor acceptance and verification testing. All these tests were conducted under ambient pressure and temperature conditions.

Each component was calibrated throughout its operational range in increments of 10 or 20 percent. The results of two tests that were conducted over the full range of the sensor at ambient temperatures are shown in figure 3, in which various components of instrumentation error are exaggerated. The number of data points for each instrumentation sensor varies with the instrumentation type and the ease of calibration. For example, it was easier to calibrate a spacecraft-cabin temperature sensor than a cryogenic-helium-tank temperature sensor because the latter data points ranged from -425° to -200° F, and sensor characteristics change at these low temperatures. When off-ambient calibrations were conducted, multiple calibration curves were supplied and annotated in terms of the secondary variable. The secondary variable was normally a function of the environmental conditions; temperature was the most common variable.

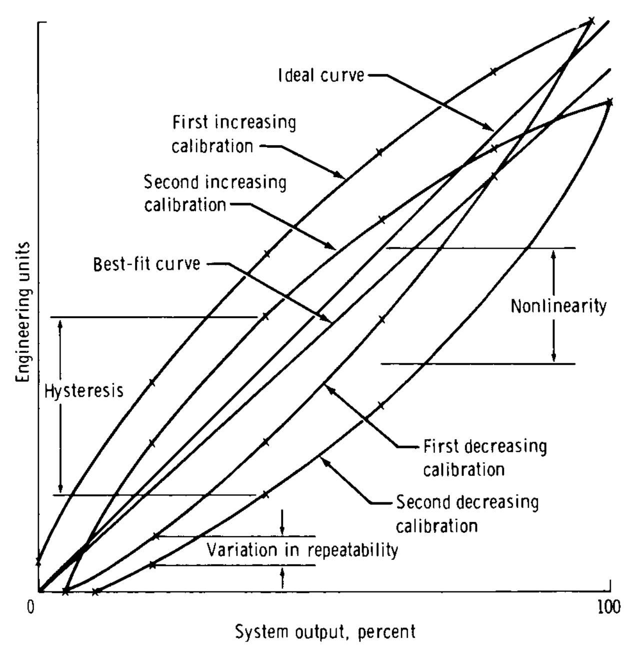

Figure 3. - Calibration errors (exaggerated).

Excerpts from Apollo CSM instrumentation-component specifications are included in this report to demonstrate how conventional-calibration data were specified. The following pressure-transducer specification MC 449-0005 (dated May 11, 1964, and revised February 12, 1968) is presented as an example.

3.3 PERFORMANCE

3.3.10 Output Voltage. - The output voltage shall be zero volts (plus 0.15 volts, minus 0 volts) to 5.0 volts (plus 0 volts, minus 0.15 volts) dc floating and directly proportional to the specified pressure range. The output noise shall not exceed 10 millivolts peak-to-peak to 10 000 cps.

3.3.14 Long-Term Stability. - Combined sensitivity and long-term zero drift under continuous operation for 360 hours, at any point within the specified pressure range, shall be less than plus or minus 0.5 percent of full scale. For intermittent operation over a period of 90 days, the above drift shall be less than plus or minus 1.0 percent full scale.

3.3.15 Hysteresis. - Maximum hysteresis shall not exceed plus or minus 0.15 percent of full scale.

3.3.16 Repeatability. - Repeatability error shall not exceed plus or minus 0.1 percent full scale.

3.3.18 Error Band. - The algebraic sum of the total combined errors from hysteresis, linearity, repeatability, regulation, and all environmental parameters shall not exceed 4.5 percent full scale.

(End of specification)

In an interpretation of these specifications, the error bands in figure 4 are 3 percent of full scale for the end-point tolerance and 4.5 percent for the specified-error band. The instrumentation-component-procurement acceptance test required that two calibration tests, each consisting of 11 data points, be provided over the instrumentation range. These test data confirmed acceptable performance and provided conventional-calibration data points.

These data points were then used to generate calibration-curve expressions for data processing. Using x for the independent variable (instrumentation output) and y for the dependent variable (engineering units), the polynomial expression for the calibration curve is

$$y = a_0 + a_1x + a_2x^2 + \ldots + a_nx^n \qquad (1)$$

For a linear curve, the data end points established a straight-line curve expressed by the polynomial

$$y = a_0 + a_1x_1 \qquad (2)$$

Here, the constant a_0 establishes a bias and a_1 establishes a slope. These data points were tested to establish whether the variance from a straight line was equal to or less than 0.5 percent. If the variance was less than 0.5 percent, a straight line was used. A polynomial approximation curve was fitted through the calibrated data points when the variance was greater than 0.5 percent. This curve was based on an orthogonal polynomial least-squares fit. A second- through fifth-order polynomial was tried, and the residuals of each order were established. The proper polynomial was then selected on the basis of a statistical test to establish the best fit (F-ratio test of 1-percent significance). The selected polynomial was compared with the test-calibration data to ensure that the variance did not exceed 0.8 percent.

If a curve exceeded the 0.8-percent criterion, a piecewise linear fit was then used. This type of curve is shown in figure 5. The curve is produced by vectoring a line between calibration data points. This type of data fit was used for vehicle testing with the Apollo acceptance checkout equipment. The number of acceptance-checkout-equipment input data points was held to six (20-percent increments) because of equipment limitations. Additional data points (as many as 14) were used with special equipment modifications.

Data processed in support of mission control and postmission data evaluation used a polynomial fit whenever possible. A limited number of measurements could not be fitted to a polynomial. These measurements were expressed as piecewise fits and were the least accurate.

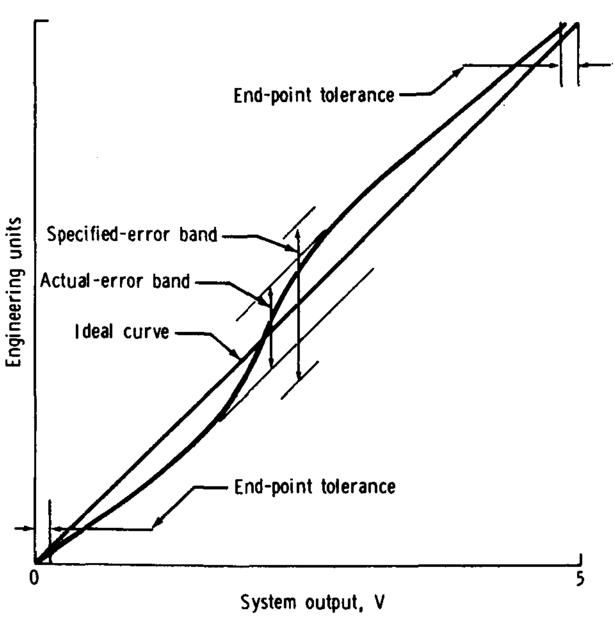

Figure 4. - System calibration curve.

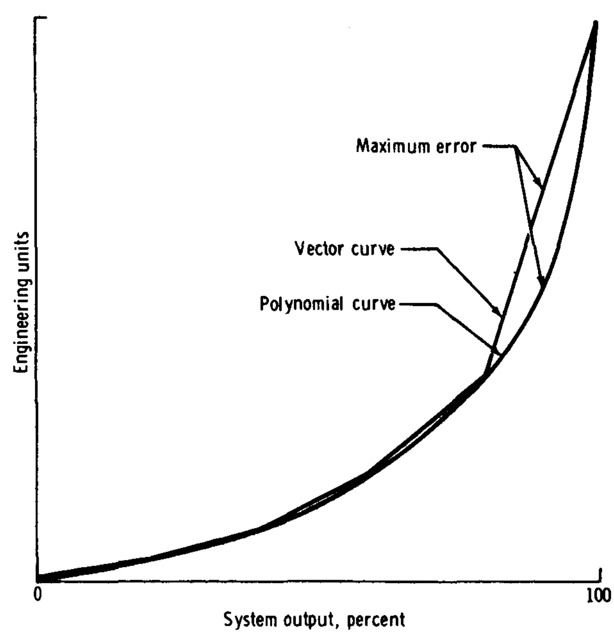

Figure 5. - Vector- and polynomial-curve-fit comparison.

Conventional-calibration data were used for preflight test and checkout operations at the launch site, at mission control, and during postmission-evaluation data processing. The data-presentation technique is shown in figure 6 and table I. The calibration curve (fig. 6) includes information concerning the measurement identification, title, equation coefficients, and acceptance-checkout-equipment data points that were used. This presentation indicates the general curve characteristic (nonlinearity) and is also used for approximate scaling of strip-chart recordings and meter displays. The digital-to-analog conversion for each telemetry count value is shown in table I. This tabulation provides specific engineering-unit values and indicates the resolution capability of the instrumentation system.

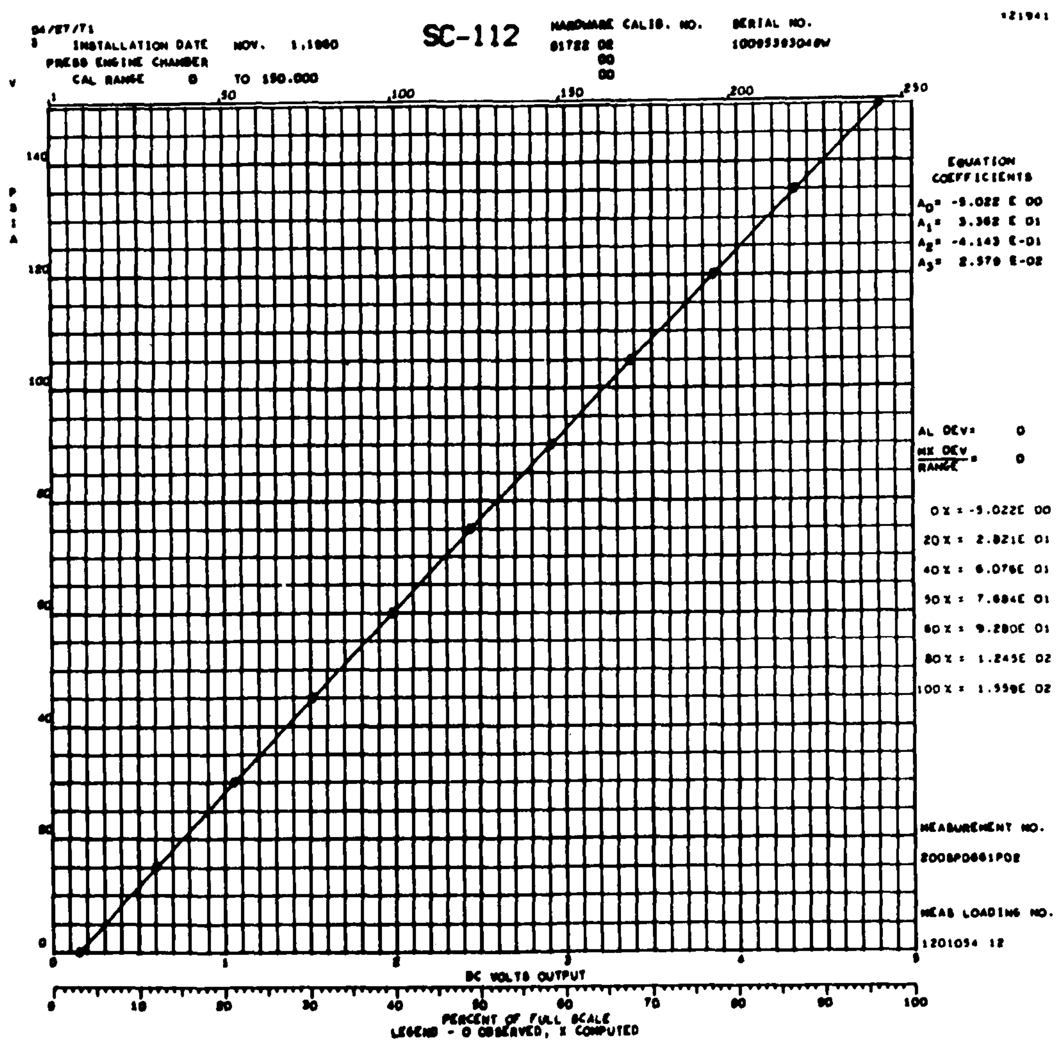

Figure 6. - Typical calibration data used for mission-evaluation data analysis.

TABLE I. - SAMPLE CALIBRATION DATA PRINTOUT

**** CALIBRATION TABLE OF 8-BIT COUNTS VS ENGINEERING UNITS ****

PRESS ENGINE CHAMBER

MEASUREMENT NO. 200SP0661P02
VEHICLE SC-112
TRANSDUCER SERIAL NO. 10095393048W
SIGNAL CONDITIONER SERIAL NO.
AUXILIARY COMPONENT SERIAL NO.
CALIBRATION DATE 11/01/60

CNT	PSIA	CNT	PSIA	CNT	PSIA	CNT	PSIA	CNT	PSIA	CNT	PSIA	CNT	PSIA
1	-5.022	38	19.349	75	43.338	112	67.005	149	90.410	186	113.613	223	136.677
2	-4.358	39	20.003	76	43.982	113	67.640	150	91.039	187	114.238	224	137.299
3	-3.694	40	20.655	77	44.625	114	68.276	151	91.668	188	114.863	225	137.921
4	-3.030	41	21.308	78	45.268	115	68.911	152	92.298	189	115.488	226	138.542
5	-2.367	42	21.960	79	45.911	116	69.546	153	92.927	190	116.112	227	139.164
6	-1.704	43	22.612	80	46.554	117	70.181	154	93.556	191	116.737	228	139.786
7	-1.041	44	23.264	81	47.196	118	70.816	155	94.184	192	117.361	229	140.408
8	-0.379	45	23.915	82	47.838	119	71.451	156	94.813	193	117.986	230	141.029
9	0.283	46	24.567	83	48.480	120	72.085	157	95.442	194	118.610	231	141.651
10	0.945	47	25.217	84	49.122	121	72.719	158	96.070	195	119.234	232	142.272
11	1.606	48	25.868	85	49.764	122	73.354	159	96.698	196	119.858	233	142.894
12	2.267	49	26.518	86	50.405	123	73.987	160	97.326	197	120.482	234	143.515
13	2.928	50	27.169	87	51.046	124	74.621	161	97.954	198	121.106	235	144.137
14	3.588	51	27.818	88	51.687	125	75.255	162	98.582	199	121.730	236	144.758
15	4.249	52	28.468	89	52.328	126	75.888	163	99.210	200	122.353	237	145.379
16	4.908	53	29.117	90	52.968	127	76.521	164	99.837	201	122.977	238	146.000
17	5.568	54	29.766	91	53.608	128	77.154	165	100.465	202	123.600	239	146.622
18	6.227	55	30.415	92	54.248	129	77.787	166	101.092	203	124.224	240	147.243
19	6.886	56	31.064	93	54.888	130	78.420	167	101.719	204	124.847	241	147.864
20	7.545	57	31.712	94	55.528	131	79.052	168	102.346	205	125.470	242	148.485
21	8.203	58	32.360	95	56.167	132	79.685	169	102.973	206	126.094	243	149.106
22	8.861	59	33.008	96	56.806	133	80.317	170	103.600	207	126.717	244	149.727
23	9.519	60	33.655	97	57.445	134	80.949	171	104.227	208	127.340	245	150.348
24	10.176	61	34.302	98	58.084	135	81.581	172	104.853	209	127.963	246	150.969
25	10.833	62	34.949	99	58.722	136	82.212	173	105.480	210	128.586	247	151.590
26	11.490	63	35.596	100	59.361	137	82.844	174	106.106	211	129.208	248	152.211
27	12.147	64	36.243	101	59.999	138	83.475	175	106.732	212	129.831	249	152.832
28	12.803	65	36.889	102	60.637	139	84.106	176	107.359	213	130.454	250	153.453
29	13.459	66	37.535	103	61.274	140	84.737	177	107.984	214	131.076	251	154.073
30	14.114	67	38.181	104	61.912	141	85.368	178	108.610	215	131.699	252	154.694
31	14.770	68	38.826	105	62.549	142	85.999	179	109.236	216	132.321	253	155.315
32	15.425	69	39.471	106	63.186	143	86.629	180	109.862	217	132.944	254	155.936
33	16.080	70	40.117	107	63.823	144	87.260	181	110.487	218	133.566		
34	16.734	71	40.761	108	64.460	145	87.890	182	111.113	219	134.188		
35	17.388	72	41.406	109	65.096	146	88.520	183	111.738	220	134.811		
36	18.042	73	42.050	110	65.733	147	89.150	184	112.363	221	135.433		
37	18.696	74	42.694	111	66.369	148	89.780	185	112.988	222	136.055		

MEAN-STANDARD-CALIBRATION DATA

Mean-standard-calibration data are derived from a statistical sampling of conventional-calibration data. The use of mean-standard-calibration data simplified the test and checkout of each vehicle because individual instrumentation records were not required. Replacement of hardware did not require the suspension of testing for the specific purpose of updating calibration data. The time and effort required for calibration updating and data-processing verification were usually greater than the time and effort required for actual component replacement.

Mean-standard-calibration data were derived for each specific type of hardware contained within each measurement system. Data points were compiled and combined statistically by a computer to obtain the calibration-data curve. As additional instrumentation was procured, these data samples were used to update the mean-calibration data. Though use of mean-standard-calibration data reduces test and checkout time, additional computer programing and data-processing time are required. If large numbers of components are involved, the resulting mean standard curve will approach the specification curve. In that case, the interim step of generating mean data should be avoided because of the expense.

The use of mean-standard-calibration data relieved the computer updating problem for test and checkout during initial vehicle buildup, when the incidence of instrumentation failure was highest. As more vehicles were fabricated, the instrumentation installation and test procedures were improved, resulting in a decreased instrumentation-component failure rate. Computer updates became less frequent, and mean-standard-calibration data were no longer desirable.

Mean-standard-calibration data were used for factory checkout of analog measurements on the CSM on which the tolerance band (nominally ± 5 percent) was not critical. For those few critical measurements, such as the amounts of consumables and flow rates, conventional-calibration data were used.

STANDARD-CALIBRATION DATA

The procurement of instrumentation components for the lunar module (LM) was made to minimize or eliminate individual-component calibration data. This effort was achieved by instrumentation-component specifications that specified a greater accuracy of data end points and greater linearity of instrumentation-component performance.

The use of standard-calibration data was based on the assumption that the errors associated with a measurement are all random errors. Standard calibration was defined in the instrumentation hardware specification by a curve that connected the zero and full-scale points. The calibration was bounded by a specified-error band that was derived by a root-sum-square calculation of the typical sensor and signal-conditioner errors. Test data were not used in these calibrations and correction for systematic errors was not made.

The following excerpt from the LM instrumentation component specification indicates how standard-calibration data were obtained. The example used is pressure-transducer specification LSP-360-624A (dated April 25, 1966, and revised May 5, 1967).

3.3 PERFORMANCE

3.3.4 Signal Output Requirements. -

(a) Form and Mode. - The signal output shall be an analog voltage, unipolar and ungrounded. The magnitude shall vary between zero (0) and five (5) Vdc and shall be directly proportional to the pressure over the range and within the accuracy specified.

(b) Ripple and Noise. - The internally generated ripple and noise content of the output shall not exceed 5 millivolts peak-to-peak into a load of 1 megohm or greater.

(c) Noise Feedback. - The ripple or noise feedback into the primary power source shall not be greater than 10 millivolts peak-to-peak measured across a network consisting of a 0.5-ohm resistance in series with a 20-microhenries inductor over a frequency range of 20 cps to 15 KC/s.

3.3.5 Theoretical Curve. - The theoretical curve used to determine the magnitude of errors shall be a straight line terminated by 0.000 volts and +5.000 volts and shall be directly proportional to the pressure from 0.0 percent to 100.0 percent of the measurand. Any deviation from this theoretical straight line is the unit output error.

3.3.6 Static Error Band. - Any data point shall not be greater than the percent of full scale as specified from a corresponding parameter point on the theoretical curve and shall include the effects of linearity, hysteresis, repeatability, excitation regulation, and end points. The static error band shall be determined at the standard ambient conditions specified herein.

3.3.7 Total Error Band (Dynamic Error Band). - The total error band shall include all deviations from the theoretical curve due to environment, electrical characteristics, unit performance, and any other requirements stated herein that would contribute to the errors in the unit. Any data point shall not be greater than the percent of full scale specified from its corresponding parameter point on the theoretical curve.

ACCURACY SPECIFICATION

Contractor Part Number	Static Error Band (3.3.6)	Total Error Band (3.3.7)
LSC360-624-207	±1.5% FS	±2.5% FS
LSC360-624-205	±1.5% FS	±2.5% FS
LSC360-624-203	±1.25% FS	±2.0% FS
LSC360-624-107	±1.0% FS	±1.8% FS
LSC360-624-105	±1.0% FS	±1.8% FS
LSC360-624-201	±1.0% FS	±1.8% FS
LSC360-624-209	±1.0% FS	±1.8% FS
LSC360-624-103	±1.0% FS	±1.8% FS
LSC360-624-101	±1.0% FS	±1.8% FS
LSC360-624-1	±1.0%	±2.0% (0-200° F)
LSC360-624-3	±1.0%	±2.0% (0-200° F)

(End of specification)

In a comparison of standard-calibration data with conventional-calibration data (fig. 4), the end-point tolerance is zero and the specified-error band is the total error.

The use of standard-calibration data offered two advantages. First, very little calibration-data updating was required. During the vehicle test cycle, any component in the instrument system (sensor or signal conditioner) could be replaced with a like component and no calibration change was required. The second advantage benefited the analyst. Because numerous standard calibrations were straight lines, the instrumentation output was directly proportional to the input over the full-scale range of the measurement. The analyst made simple, direct conversions from percent of full-scale output to engineering units. For example, if a measurement with a range of 0 to 500 psia indicated 10-percent deflection on a meter or strip chart, the corresponding engineering-unit value was 50 psia.

The disadvantage of using standard-calibration data is that no corrections are made to the measurement output for systematic error. When actual test-calibration data were compared with standard-calibration data for a representative sample of measurements, the systematic errors were usually less than 1 percent.

Because of the advantages previously discussed, standard-calibration data were used for the majority of LM measurements. However, certain LM measurements required correction for systematic errors because of the need to achieve the greatest degree of obtainable accuracy for mission-evaluation purposes (for example, measurements used to calculate critical systems performance or determine consumables status). These components were individually calibrated and conventional calibration data provided.

CONCLUDING REMARKS

The use of standard-calibration data is preferable to the use of mean-standard- and conventional-calibration data for most applications. The effective use of standard-calibration data, however, may be achieved only when the instrumentation procurement specifications are designed to require standard-calibration data. When requirements of this type are levied, the procurement cost will be greater, but the overall program cost may be less because of the reduced data-processing requirements. Mean-standard-calibration data offer no advantage over standard-calibration data. The requirement for the use of conventional-calibration data for a critical measurement may never be eliminated, but the number of applications can be minimized. Scientific and experimental equipment will still require the use of conventional-calibration data because of the limited number of such equipment, the high degree of accuracy required, and peculiar design characteristics.

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