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TEST EQUIPMENT ACCURACY

By Glenn D. Winkler

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TEST EQUIPMENT ACCURACY

By: Glenn D. Winkler

The Bendix Corporation

The purpose of this paper is to review accuracy and error from a test equipment designer's viewpoint. An analysis of a few examples and some general guides to design will be offered.

In order that problems in semantics may be avoided, the following definitions are offered:

Accuracy - The ability of the measuring device to reproduce correctly the known value of a standard.

Precision - The ability of a measuring device to repeat readings on a specific characteristic. This is related to repeatability and resolution. A meter may be very precise in that it indicates a standard 10.501 volt voltage source is 10.103 volts 20 times out of 20 trials; yet its accuracy may be rather poor. A meter that indicates the same standard source is between 10.4 and 10.6 volts would be more accurate but less precise. High precision but low accuracy meters can be very useful as comparators or null detectors.

Percent Accuracy - The percentage deviation positive or negative from a known standard value based on the average of several readings.

Percent Precision - The percentage deviation positive or negative from the average of several readings.

$\bar{X}$ - The average of several readings or samples.

$\bar{R}$, The Average Range - The average of the ranges based on sub groups of 2 from several readings.

σ - The "standard deviation."

Range - The highest reading minus the lowest reading of 2 consecutive samples or readings. Note this is always positive.

Test equipment accuracy is traceable through a chain of calibrating standards starting with the "standard calibrating device" the calibration technician uses to verify a tester's accuracy. The "working standard" is compared at adequate intervals with standards verified by a primary standards laboratory. The standard device used by the laboratory is verified by the National Bureau of Standards. Consider for example a piece of test equipment required to perform a measurement with an accuracy of $\pm 1\%$ and let us examine the intermediate steps necessary to assure this. The test equipment designer will want to provide the most economical instrument that can make this measurement; yet, he also wants to make certain the measurement is always within his allowed accuracy specification. Suppose he chooses the most economical route and provides a 1% instrument. The working standard the calibration technician might use then would be one that has an accuracy 10 times better than the test equipment--in this case, 0.1%. This would have to be calibrated similarly with a 0.01% instrument held by primary standards laboratory. The National Bureau of Standards would require 0.001% accuracy.

By use of calibration equipment with accuracy 10 times that to which it is applied, we can assure by statistical means that most of the time we can be within the 1% accuracy required. Yet, it is possible with everything on the high side to not provide anything better than 1.111% accuracy for the example given. A safer designer's choice would have been to provide test equipment with an accuracy of 1/2% which could have been verified with the same chain of standards and "never" resulted in more than 0.611% accuracy.

When product specifications or test equipment requirements are nearer the "state-of-the-art development," or economics dictate less expensive equipment, we are placed in the position of specifying tolerances and accuracies related to absolute values. If the product specification requires a voltage to be within the range of 80 to 100 volts (a $\pm 10\%$ range), the designer will often choose a meter of $\pm 1\%$ tolerance. However, if he is confronted with assuring that a voltage lies between 98.8 and 99.2 volts (a range of $\pm 0.2\%$), he may be tempted to provide

a $\pm 0.1\%$ meter and revising his limits to 98.9 and 99.1. This can, in a few cases, accomplish his purpose. In fact, in the previous example, an experienced calibration technician will apply this same principle by not allowing more than 0.9% error when calibrating a $\pm 1\%$ instrument with a $\pm 0.1\%$ standard.

However, if the product under test has an actual voltage of 98.99 and the test equipment happens at this time to read 0.1% low, it will indicate this voltage as 98.89. We would be forced to reject the product. This practice can never pass an out-of-tolerance condition yet can cause an unduly high rejection rate and where possible, the test equipment should provide accuracy 10 times that of the tolerance range in order to avoid this condition.

SOURCES OF ERROR

1. Circuit errors - These errors arise from component inaccuracies, diode non-linearities, power supply voltage errors, etc., and will give predictable errors. When we choose a 1% meter multiplier, we must be prepared to accept at least the 1% error of the multiplier. These errors can easily be corrected by proper calibration and remain relatively constant for a given group of physical components. Circuit errors generally will not lower an instrument's precision.
2. Stability errors - This class of errors is less predictable or repeatable. The precision of the instrument is seriously affected by such things as thermal changes, humidity, hysteresis, aging, friction, and line voltage fluctuation.
3. Readout errors - Assuming the operator does not make "total errors" by reading the number 5 as 8, he still may make an error in reading an instrument. This group includes parallax, averaging, and the mental process of dividing the distance between two scribed marks into equal divisions. A meter that fluctuates between 96 and 100 will often be averaged at 98, but its true average could conceivably be 97 if it reads periodically 96 for 3 seconds and 100 for 1 second. The digital voltmeter will eliminate this error if we are reading battery voltages. However, if the voltage in a circuit is actually varying from 96 to 100 volts, the DVM will have just as much trouble making a decision as the operator

reading a panel meter. This type of error makes it difficult to apply the oscilloscope to quantitative testing.

A meter manufacturer publishes a rather lengthy discussion of an AC meter that is analyzed as having a possible 7.63% error. Let us examine a DC meter application with a similar attack. Consider a basic 1 ma meter to be used to measure a voltage of 9 volts. We will want to select a meter multiplier that will give a deflection near full scale. The following items can act to destroy our accuracy:

Multiplier resistance error	0.50%
Multiplier heating	0.10%
Meter resistance error	0.10%
Full scale meter error	1.50%
Repeatability	1.00%
Drift error (long term)	0.20%
Parallax error	0.40%
(0.2 div of 50 div)	
Estimating error	0.40%
(0.2 div of 50 div)	
TOTAL	4.80%

The statistician will of course not add these individual errors for a total, but will take some weighted average and assume the designer will not have all of the errors against him at any given time. On the average, the statistician is right, but there are those days when the wheel comes up black 10 times in a row! The test equipment designer must take the pessimistic approach and add directly all of his individual errors. It is obvious that a good calibration technician can eliminate a good many of the individual errors and may allow an accuracy of better than 1% at any one given point.

The purpose of all measurements is to take some type of action. This in the case of electrical "in-process" test equipment means to accept or reject a product. In making a measurement, we will nearly always arrive at a specific number as an answer. We will usually imply an accuracy by the number of significant digits in the answer. For example, a voltage measurement of 10.52 implies that it has an accuracy of ± 0.005 volts unless otherwise stated. The measurement of 201.00 volts implies the same type of accuracy. Often, when we are not convinced of a measurement, we may repeat it. If we are really stubborn, we may repeat it 10 times and take the one measurement out of 10 that best satisfies our desires. The repetition of a measurement can give important data as to the precision given. We may repeat a measurement in order to examine drift or noise. A continuing record of a measurement taken at

one month intervals can reveal any long term drift and warn of future trouble. A series of readings that plot as shown in figure 5 must be interpreted as drift and should seldom be averaged. However, a series of readings as shown in figure 6 can be analyzed with more success according to statistics. Adjustments or error corrections arising from an averaging operation must always have as their source random measurements as shown in figure 6. With this data we can usually assume that if we average the 20 readings, we can arrive at a fairly precise value. We are always tempted to delete any "wild" points that are obviously in error and are not repeated values. The one high point on this series of observations could be wisely dropped from the averaging calculation.

The degree of repeatability is usually of importance. A short method of getting accurate and precise data is shown in figure 7. Twenty different readings are taken on a standard resistor which is certified to $0.875 \text{ K}\Omega \pm 0.1\%$. The average is taken of the 20 readings to obtain $\bar{X} = 0.8735 \text{ K}\Omega$. If we now divide the 20 readings into 10 sub groups, each containing 2 readings, and take the difference between the 2 readings in each sub group, 10 values of "Range" are obtained. The Range column is averaged for an R value of $0.007 \text{ K}\Omega$. This means that on the average, if we take 2 consecutive readings on the same parameter, they will differ by $0.007 \text{ K}\Omega$. It is just as correct to divide the 20 readings into 5 sub groups each containing 4 readings. Within each of these sub groups, the smallest reading is subtracted from the largest reading to obtain range. In figure 7 the average range R for $N=4$ is $0.014 \text{ K}\Omega$. This can be interpreted to mean that on the average, if 4 consecutive readings are taken on the same device, they will be within a range $0.014 \text{ K}\Omega$ wide.

An accepted short cut to the "standard deviation" (σ) is to divide the average range by a constant factor that has been given by statistical tables.

$$\sigma = \frac{\bar{R}}{K}$$

The factor K is dependent upon the number of elements in the sub group:

$N = 2$	$K = 1.128$
$N = 3$	$K = 1.693$
$N = 4$	$K = 2.059$

As shown in figure 7, the σ computed from $N=2$ and $N=4$ is almost identical.

The "standard deviation" (σ) can be interpreted to mean that for repeated experiments, 68% of the measurements will not vary more than $\pm 0.0062 \text{ K}\Omega$ from the average value ($\bar{X}$) obtained. The "2 standard deviations" (2σ) means that 95% of the time on repeated experiments, the value obtained will not vary more than $\pm 0.0124 \text{ K}\Omega$. In figure 7 the resistance readings lie within the range " $0.8673 \text{ K}\Omega$ to $0.8797 \text{ K}\Omega$ " 12 times and exceed this limit 8 times for a 60% versus the 68% figure. The (2σ) band is " $0.8611 \text{ K}\Omega$ to $0.8859 \text{ K}\Omega$ " and all but 2 readings fall within this bank for a 90% versus theoretical 95% figure.

Percent accuracy is computed as shown and assures us that on the average, our "average measurement" $\bar{X}$ is not more than 0.27% in error.

Percent precision gives us a feeling for repeatability and in figure 7 shows that 95% of the time an individual reading will not differ from the average of several readings by more than $\pm 1.42\%$.

SPECIFICATION OF TOLERANCES

Calibration and operation procedures can include statements as to limits or tolerances. One of the safest methods is to generalize early in the procedure by saying, "All tolerances and limits are absolute and the error of the calibrating meter must be taken into account." This will alert the technician to use extra caution in setting or checking a value. In the previous example given, the calibration of a 1% meter with a 0.1% standard would then alert the technician to not allow more than 0.9% difference in reading between the 2 meters. The other alternative is a statement such as, "Accuracies of the suggested equipment listed in this procedure have been considered in tolerances and limits. No extra guard band need be allowed." This second type of statement will perhaps in the long run facilitate calibration by the technician but complicate procedure writing. Whichever method is selected, some statement should be made so as to clarify the intent. Operating procedures will sometimes refer the reader to a product specification for a limit or "pass band." The product specification will include tolerance specifications to which the test equipment should be designed.

The present trend is to now include complete limits and values in the operating procedure. When this is done, the procedure will require change a little more often but it is felt that completeness is worth the extra effort. If limits are

included, the basic tester accuracy must be included in a determination of these limits. The philosophy for setting limits in an operating procedure should be so that an out-of-limits condition will always be rejected. If a "gamble" is to be made, arrange it so that in a few cases "good product" may be rejected but never "bad product" accepted. For example, if a product specification reads that V_1 should be less than 100 volts and a 1% meter is to be provided, the calibration procedure can insure the meter is calibrated at the 100 volt point to an accuracy of $\pm 1\%$ using a standard voltmeter. The operating procedure should then call as a limit 99 volts in order to insure that V_1 is less than 100 volts.

There are occasions when no tolerance is given, although it may be implied. When adjusting a meter multiplier in a piece of test equipment, it is often necessary to use the procedure of the following example:

Example: Calibrate a basic 0-100 volt, 1% meter at its 50 volt point as close as possible and verify that it has no more than $\pm 1\%$ error at 100 volt point. Assume that a 0-100, $\pm 1/2\%$ full scale accuracy meter is to be used as the "standard calibrating meter." The technician would be instructed to adjust the input voltage to 50 volts as read on the standard meter and turn the meter multiplier pot until the tester panel meter read 50 volts. (Note: No tolerance specified.) The technician would then set the voltage supply for 100 volt (no tolerance) indication of the standard meter and verify that the tester panel meter read between 99.5 and 100.5 volts. The absolute values that could be allowed here (99-100) must be changed to allow for the $1/2\%$ of the calibrating meter.

Tolerances can be specified by one of the three following methods:

Nominal value	$\pm Y\%$
Nominal value	+X Units -Y Units
As a Range	X to Y

Each of the three ways has application and should be suited to the manner in which the technician will utilize it. For example, it is desirable to call the tolerance of "suggested calibration equipment" as:

Voltmeter, 0-100 volts $\pm 0.1\%$

When instructing the technician to adjust a power supply, it may be simpler to say:

"Adjust R1 for a nominal reading of 28 volts and within the range of 27 to 29.5 volts."

or:

"Adjust R1 for a reading of 28 $+1.5$
volts. -1.0 "

If the nominal value is of no significance, then the range alone is better:

"Adjust R1 for a reading of 27 to 29.5 volts."

Either of these methods is obviously better than:

"Adjust R1 for a reading of 28
volts $+5.4\%$
 -3.5% "

Oscilloscopes are normally considered as "3%" instruments in that deflection accuracies, sweep speeds, attenuator accuracies, etc. allow at least this much error. In addition, there is approximately a 1% reading error contributed by the observer. If better than 5% accuracy is required from an oscilloscope, special methods must be employed.

If the scope is used as a null detector only, with a chopper applying first the signal voltage then an accurate reference voltage to the same oscilloscope deflection channel, an accuracy of from $\pm 0.5\%$ to $\pm 1\%$ can be obtained with a 5 cm high trace.

Time measurements can be similarly improved by the use of calibrating markers from an accurate time generator.

The Z plug-in made by Tektronix may be used for voltage measurements and will allow a 100 volt signal to effectively be displayed on a 2000 cm high screen. This plug-in operates as a slide-back potentiometer with an accurate voltage source provided in the plug-in. The weakest link in this system is the attenuator in the plug-in which is guaranteed to only $\pm 2\%$. The slide-back voltage source has accuracies of full scale:

0-100 volt	0.15%
0-10 volt	0.2%
0-1 volt	0.5%

A reading accuracy of ± 0.1 cm can be safely assumed. Attenuator accuracies become significant when the voltage to be measured exceeds 100 volts. At a gain setting of 50 mv/cm (X1), the attenuator does not add any errors; but at other settings, one may expect the following attenuator errors if not corrected for:

Attenuation	Deflection Sensitivity Volts/CM	Attenuator Error	Maximum Signal Volts
X1	0.05	0	100
X2	0.1	$\pm 1\%$	200
X5	0.25	$\pm 1.5\%$	500
X10	0.5	$\pm 2\%$	1000
X20	1.0	$\pm 2\%$	1000
X50	2.5	$\pm 2\%$	1000
X100	5.0	$\pm 2\%$	1000
X200	10.0	$\pm 2\%$	1000
X500	25.0	$\pm 2\%$	1000

Additional reference voltage errors can exist due to helipot linearity of $\pm 0.05\%$ of full scale. The helipot can be read only to $\pm 1/2$ division out of 1000 adding another $\pm 0.05\%$ of full scale reference voltage.

Consider the total accuracy involved in measuring a 20 volt signal. The 20 volts will produce a screen deflection of:

$$\frac{20 \text{ volts}}{0.05 \text{ volts/cm}} = 400 \text{ cm}$$

The ± 0.1 cm visual error contributes, then:

$$\frac{0.1}{400} = 0.025\%$$

The reference voltage is 0.15% accurate on the 100 volt range and will contribute an additional 0.15%. Linearity of the helipot contributes 0.05% of full scale (100 volts). The error in reference voltage due to non-linearity is then: $(0.0005)(100) = 0.05$ volts. This 50 mv will have to be referenced to the 20 volt signal giving:

$$\frac{0.05}{20} \times 100 = 0.25\%$$

The helipot will read $\pm 1/2$ division out of 200 and contribute:

$$\frac{0.5}{200} (100) = 0.25\%$$

If we add all of these errors for the total pessimistic error, we obtain:

Attenuator error	0.0%
Oscilloscope reading error of zero point	0.025%
Oscilloscope reading error of signal after slide-back	0.025%
Reference voltage error	0.15%
Helipot non-linearity	0.25%
Helipot reading error	0.25%
TOTAL ERROR	0.700%

The rather large errors that develop for signal voltages of 100 volts or greater are due to attenuator error and could in special cases be minimized by calibration of the plug-in at these particular attenuation settings.

GENERALIZED DESIGN GUIDES

The following guides are offered for consideration in the early stages of test equipment design. There will be plausible exceptions where they cannot be followed, but on the average will contribute to overall tester accuracy.

1. Resistors.

The $\pm 5\%$ composition resistor should not be used in applications requiring more than $\pm 15\%$ accuracy. MIL-R-11 for example allows a 10% change from -55°C to $+105^\circ\text{C}$ for values of resistance of 1000 ohms. It also allows a 20% change over the same temperature range for 1 megohm resistors. MIL-R-11 allows a 10% change over 1000 hours 70°C life. Humidity can contribute 2% to 4% change. Voltage coefficient may contribute an additional 0.05%. If an actual 5% total tolerance is required, the use of 1% metal film or 3% wire-wound resistors should be considered.

For reliability and stability of value, the following guides are offered on applications:

Type	Max. Wattage	Max. Voltage
1/4 watt fixed composition	0.1	250
1/2 watt fixed composition	0.2	350
1 watt & 2 watt fixed composition	0.4 & 0.8	500
2 watt carbon potentiometer	1.5	500
Metal film	0.8 rating	

(continued)

<u>Type</u>	<u>Max. Wattage</u>	<u>Max. Voltage</u>
1% wirewound precision	0.5 of rating	
1% wirewound precision	0.25 of rating	
Wirewound power	0.6 of rating	

2. Capacitors.

Precision or accuracy is not often required in capacitors, but when it is, temperature effects and long term drift should be considered. Refer to table 1.

3. Panel Meters.

If more than 2% accuracy is required, a knife-edged pointer and mirrored scale should be specified. If meters are plastic cased and unshielded, consideration of

adjacent meter spacing on a panel should be given according to the following table:

<u>Type</u>	<u>Center to Center Spacing of Meter in Both Horizontal and Vertical Planes</u>
2%, 3-1/2" meter	5 inches
1% or 1/2%, 4-1/2" meter	9 inches

CONCLUSION

The test equipment designer will consider his accuracy requirements at least twice during a design; once in initial design phases and then again at the verification of the prototype. With recognition of some of the foundations upon which accuracy is built, the verification will only prove the design and not require a quick change to high accuracy components.

Table 1

Capacitor Type	Nominal Range of Values	Ins. Res.	Leakage Current	Temp. Coeff. ppm/°C	Max. Cap. Temp. °C	Power Factor at 1 kc	Other Characteristics
Tantalum, Liquid Electrolytic	10 to 250 μf	Low	High (<500 μa)	Typically +500	85	0.10 - 0.25	Will deform if stored 2-3 years OR if used at <0.6 rated voltage.
Paper-Plastic Film per MIL-C-14157B	0.0068 to 1.0 μf	High	Low	Positive & Small	125	<0.01	High reliability.
Dura-Mica	1 to 50,000 $\mu\mu f$	High	Low	1 - 24 $\mu\mu f$ ± 200 24 $\mu\mu f$ ± 100	125	0.001 - 0.005	Temp. coeff. if non-linear.
Tantalum, Solid	0.047 to 100 μf	Relatively High	<10 μa	+1000	85	0.08	High reliability. Will not deform. Can be used at +125°C if derated to 66% of 85° voltage.
Oil Filled Paper	0.5 to 15 μf	High	Low	+650	85	0.005 at 60 cps	
Metallized Paper	0.047 to 1.0 μf	High	Low	0 to +1000	125	0.01	Low noise. Self-healing for low current arcs.
Aluminum Electrolytic, Computer Grade	35 to 150 μf	Relatively Low	Relatively High	+1000 to +2000	85	0.15 - 0.18 at 120 cps	Shelf life <3 years at +40°C. Will be much less at higher temperatures.
Aluminum Electrolytic, Minature	5 to 250 μf	Relatively Low	Relatively High	+1000 to +2000	85	Approx. 0.2 at 120 cps	Shelf life <3 years at -40°C. Will be much less at higher temperatures.
Mylar	0.0068 to 1.0 μf	High	Low	Positive varies with temp.; approx. 0 from 0° to +50°C	125	<0.01	Capacitance stable with life. AC corona may be problem.
Polystyrene	0.010 to 0.10 μf 1.0, 5.0, 10.0 μf	Very High	Very Low	-80 to -110	85	<0.002	Highly stable. Will hold charge for long periods (several days).

<u>Trial No.</u>	<u>Meter Indication</u>	<u>Actual Value</u>
1	10.103	10.501
2	10.103	10.501
3	10.101	10.501
4	10.104	10.501
5	10.103	10.501

Figure 1. Good Precision, Poor Accuracy

<u>Trial No.</u>	<u>Meter Indication</u>	<u>Actual Value</u>
1	10.6	10.501
2	10.5	10.501
3	10.4	10.501
4	10.6	10.501
5	10.6	10.501

Figure 2. Poor Precision, Fair Accuracy

Figure 3. Calibration Chain

Figure 4. Rejection of Good Product

Figure 5

Figure 6

<u>Trial Number</u>	<u>Resistance</u>	<u>Range (N=2)</u>	<u>Range (N=4)</u>
1	0.875 KΩ		
2	0.865 KΩ	0.010 KΩ	
3	0.855 KΩ		
4	0.875 KΩ	0.020 KΩ	0.020 KΩ
5	0.880 KΩ		
6	0.875 KΩ	0.005 KΩ	
7	0.875 KΩ		
8	0.875 KΩ	0	0.005 KΩ
9	0.875 KΩ		
10	0.875 KΩ	0	
11	0.875 KΩ		
12	0.880 KΩ	0.005 KΩ	0.005 KΩ
13	0.890 KΩ		
14	0.875 KΩ	0.015 KΩ	
15	0.865 KΩ		
16	0.860 KΩ	0.005 KΩ	0.030 KΩ
17	0.880 KΩ		
18	0.875 KΩ	0.005 KΩ	
19	0.870 KΩ		
20	0.875 KΩ	0.005 KΩ	0.010 KΩ
TOTALS	17.470 KΩ	0.070 KΩ	0.070 KΩ

$$\bar{X} = \frac{17.470 \text{ K}\Omega}{20} = 0.8735 \text{ K}\Omega$$

$$\frac{\bar{R}}{N=2} = \frac{0.070}{10} = 0.007 \text{ K}\Omega$$

$$\frac{\sigma}{N=2} = \frac{\bar{R}}{1.128} = \frac{0.007}{1.128} = 0.0062 \text{ K}\Omega$$

$$\frac{\bar{R}}{N=4} = \frac{0.070}{5} = 0.014 \text{ K}\Omega$$

$$\frac{\sigma}{N=4} = \frac{\bar{R}}{2.059} = \frac{0.014}{2.059} = 0.0068 \text{ K}\Omega$$

$$\begin{aligned} \text{Percent Accuracy} &= \left(\frac{\bar{X} - \text{Actual Value}}{\text{Actual Value}} \right) 100 \pm \text{Accuracy of Actual Value} \\ &= \left(\frac{0.8735 - 0.875}{0.875} \right) 100 \pm 0.1 = -0.171 \pm 0.1 = -0.27\% \text{ or } -0.07\% \end{aligned}$$

$$\text{Percent Precision} = \frac{\pm 2\sigma}{\bar{X}} \times 100 = \frac{\pm 2(0.0062)}{0.8735} \times 100 = \pm 1.42\%$$

Figure 7