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Electronic measuring equipment as reference standards

Be Absolutely Assured

Electronic measuring equipment as reference standards

Technical Note 7 was first published in April 1988 to explain NATA's requirements for use of electronic measuring equipment as reference standards. This edition reflects some of the advances in electronic instrument technology since that time and addresses issues raised by the use of such instruments as reference standards. It also briefly discusses some of the difficulties and limitations in the use of such equipment and outlines a number of specific calibration requirements.

1. Introduction

Electronic measuring instruments are used universally in calibration laboratories. The quality and maturity of some electronic instruments are presently at a level where their reliability has been proven to be very high. This, combined with other attractive features associated with electronic instruments, has led NATA to accept that electronic instruments are appropriate as reference standards under certain conditions.

For the purposes of this note, a reference standard is an instrument or artefact whose calibration is performed by an appropriate NATA accredited laboratory, a calibration laboratory accredited by one of NATA’s Mutual Recognition Arrangement (MRA) partners, by Australia’s National Measurement Institute (NMI) or by a national metrology institute that is a signatory to the CIPM MRA and in terms of which another instrument or artefact may itself be calibrated. For example, a dc voltmeter calibrated by NMI could serve as a reference standard for the calibration of other dc voltmeters in a local laboratory; similarly, an electronic voltage reference certified by an appropriate NATA laboratory might, in conjunction with a calibrated reference divider, serve as a reference standard for a local calibration of a voltage source.

2. Conditions for acceptability of electronic instruments as reference standards

Electronic instruments may be used as reference standards provided the following conditions are satisfied:

1. The instrument is of high quality with an established history of performance and reliability.
2. The instrument is calibrated on a regular basis, at prescribed intervals, by an appropriate NATA accredited laboratory, a calibration laboratory accredited by one of NATA’s Mutual Recognition Arrangement partners, by Australia’s National Measurement Institute or by a national metrology institute that is a signatory to the CIPM MRA.
3. There is at least one other instrument or external reference standard of adequate quality and performance available for comparison.
4. Regular intercomparisons are made between the standard and the alternative instrument(s) at prescribed intervals in order to maintain a history of performance.
5. Where provided, 'autocal' against the instrument's internal reference is carried out to the manufacturer's recommendations.

One of the difficulties in accepting electronic instruments as standards is that no firm definition exists to characterise 'adequate calibration' and 'adequate intercomparison'. For some equipment, such as electronic voltage references, procedures are relatively straightforward and those established for the more traditional equipment may be applied directly. However, for digital multimeters, calibrators, electronic wattmeters and the like, techniques for calibrating traditional standards are not always adequate.

It is not commercially viable for laboratories to document calibration procedures for every model of electronic equipment but specific calibration procedures for each class or type of instrument, based on accumulated experience, need to be developed to assist staff in maintaining consistency of such instruments. Manufacturer's calibration procedures may be appropriate but still need to be evaluated for their adequacy.

3. Recalibration period

In the absence of more reliable information, the manufacturer's specification should be taken as a guide to the initial maximum period between recalibrations. This must be supplemented by regular intercomparisons between the standard instrument and the other instrument(s) as specified in section 2 above.

Initially, intercomparisons must be carried out at intervals which are perhaps half that specified for the external calibration. All intercomparisons must be documented.

Intervals between recalibrations may be increased as a history and confidence in an instrument's performance is established. However, these would normally not exceed a maximum of twelve months.

4. Test requirements

4.1 Direct voltage references

The most common and convenient reference is an electronic instrument based on one or several Zener diodes. The output voltages are almost always 1.000 V, 1.018 V or 10 V (nominal), or a combination of these. Some models of instruments provide only one output at a given voltage level, while others provide several. The 1.018 V output is provided for historical reasons only, since this is the voltage of saturated standard cells that were the forerunners of the modern Zener-based instruments as standards of voltage. The presence of several outputs at a given voltage level is advantageous, since intercomparisons are then possible and there is also some degree of insurance against instability or failure of one output.

A voltage reference must not have any externally accessible means of adjustment of the output voltage. This implies that the output terminals must have no associated dials or switches by means of which the output voltage could be changed.

The Zener diodes and associated circuitry are invariably controlled at an elevated temperature, commonly between 28^0C and 30^0C, which in most models can be monitored by means of a built-in thermistor with connections to the front or rear panel. The instrument can then continue to function should the ambient temperature exceed by several degrees the 20^0C to 23^0C environment typical of calibration laboratories. This may happen during transport, for example. A Zener-based voltage reference always contains an internal battery which is kept at full charge through the mains connection and which, if mains power is disconnected, maintains the internal temperature and correct functioning of the circuitry. This permits transport without loss of calibration, and any mains-borne interference can then be easily eliminated, if necessary, from sensitive measurements.

The 10 V output has an output resistance normally of the order of a few tenths of an ohm, but the 1.018 V and 1.000 V outputs have much larger output resistances, of the order of a kilohm, and so there may be significant loading of these outputs if directly connected to a digital voltmeter. The long-term stability of Zener-based voltage references is generally in the range 0.2 μV/V per year to 2 μV/V per year. The changes in voltage over minutes or hours, although usually very small, are often unpredictable but have been observed to be characteristic of '1/f noise', so called because of its inverse dependence on frequency.

For very accurate work, the user should be aware of the environmental coefficients of Zeners. For one degree change in ambient temperature, the output voltages usually change by less than 0.1 μV/V. There is also a pressure coefficient, of the order of 0.001 μV/V to 0.005 μV/V per hectopascal. Changes in ambient relative humidity may have an effect which is highly variable from one Zener-based reference to another but is usually less than 0.1 μV/V for a 10% change in humidity (for example, from 50% to 60%). The changes that result from changes in humidity often take place with a time-constant that may be hours or several days.

There is an extensive literature on the use and properties of Zener-based voltage references. A key paper on noise and humidity effects is Witt et al[1]. Zener noise is further discussed by Witt[2]. Intercomparison methods and related matters are discussed by Frenkel[3]. Environmental coefficients are reported in references 4 to 6. Further references may be obtained from the National Measurement Institute.

4.2 Digital multimeters

All digital multimeters (DMMs) contain an internal reference voltage (or current) source, an analogue-to-digital converter to compare the input with the reference, means of range changing, and some form of digital display. In addition, many DMMs contain an ac-to-dc converter, current-to-voltage and resistance-to-voltage converters and an interface.

The internal reference voltage may be accessible for calibration in terms of a second stand-alone reference of the kind discussed in the previous section and, in some cases, this may require only back-to-back difference voltage measurement of low accuracy to determine the value of the internal reference in terms of the reference standard. Alternatively, and this will be the more common and more convenient case, the stand-alone reference may be directly measured by the voltmeter, just like any other unknown voltage. Although this latter method is not as direct as the former, it is suitable for establishing the stability of the DMM over time.

Analogue-to-digital (A/D) converters differ greatly among themselves in their principle of operation. Some high-end DMMs contain A/D converters whose characteristic is intrinsically monotonic, with linearity specified by the manufacturers to be significantly better than the errors caused by their dc offset and the instability of the voltage reference. Nevertheless, linearity and hysteresis of a particular A/D converter must be established by independent measurements. Calibration of a 'direct' range of the DMM, usually 1 V or 10 V, at several cardinal points including zero and full scale is a minimum requirement. In some cases, particularly for DMMs using older types of A/D converter, it might be that every possible step of the converter must be tested. NMI offers a calibration service for digital multimeters where known applied voltage that can be changed with a resolution of less than 1 microvolt. It is also possible in this system to make small increments (and decrements) around the particular step involved in an effort to establish monotonicity. Instruments of the highest accuracy can be calibrated directly against the primary Josephson Junction Array.

DMMs with an ac function have an AC/DC converter, in addition to the A/D converter discussed above. AC/DC converters range from simple rectifier averaging types through various types of limited rms converters to true rms. All converters can contribute to non-linearity with input level and, in conjunction with ancillary ranging components, are frequency dependent and crest factor limited. Therefore, tests on ac voltage and current ranges are required over a number of input levels and frequencies throughout the range and specific tests are required to check for crest factor performance. An ac range of a DMM is not considered traceable if it is only calibrated at the top of the range. Separate tests are also required to validate operation with combined ac and dc, when this function is provided.

The DMMs change their voltage ranges either by means of a voltage divider or alternatively by changing a resistor in the feedback path of an amplifier. Precision amplifiers are normally used at low voltage ranges. Range changing implies the ability to measure voltage or resistance ratios at each calibration check and requires a determination, at least initially, of the load coefficient of the ratio or linearity of each range. Regardless of the particular mechanism of range changing, provided the process is constant on a particular range, these measurements are usually sufficient for calibration purposes. Resistors are susceptible to drift over time from voltage stress and humidity penetration, and must have a low temperature co-efficient in this application. The heating effect on the resistors at high voltage loading takes time to stabilise and presents non linearity in terms of voltage which needs to be carefully monitored. This is also true for current where ranges are usually changed by interchanging internal current shunts. The problems caused by low-voltage amplifiers include DC offset, non-linearity, and, for alternating voltage ranges, frequency-dependence of the input impedance. Many DMMs are equipped with an autoranging function which may have to be manually overridden to avoid ambiguity during calibration.

Automatic calibration and statistical process control are important advances in DMMs. In many instruments, no physical calibration adjustments need to be made. Correction constants are stored in the non-volatile memory. This occurs when 'autocal' is performed and also during periodic 'calibration' or 'artefact calibration' of the instrument which consists of comparing internal references with an external direct voltage standard and resistance standards, and recording in memory. It is, however, still necessary to perform a full verification of the instrument to ensure that all ranges and parameters are within the manufacturer's or user determined specifications. In some instruments it is possible to record calibration constants obtained during full verification and access the history of the recorded constants. By the use of statistical methods and appropriate algorithms, the drift trends can be anticipated and the status of the instrument measurement uncertainty for each range can be checked between calibration recalls. Internal self diagnostic routines are normally employed to continuously monitor instrument status and facilitate servicing.

The availability on many instruments of software adjustment and manually adjustable controls, commonly called 'twiddlers', gives rise to several important issues. In some areas of testing, the term 'calibration' is taken to include 'adjustment of appropriate controls to bring the instrument as close to nominal as possible'. It is preferable that, at least in the area of Electrical Testing, the term be more restrictive and be understood to mean 'determining the response of the instrument to a known stimulus or series of stimuli'. The existence or otherwise of one or more 'twiddlers' is a question separate from calibration and one which is not implicit in the terms, though it can and perhaps should be attended to in a calibration report.

Two questions are commonly asked concerning these user-adjustable controls. First, can it be confidently established that these controls are not adjusted subsequent to calibration? Second, can a satisfactory history of performance between calibrations be established?

With respect to the first question, such controls can be sealed in a simple way so that any change is obvious and renders the calibration no longer valid. The answer to the second question is essential for measurement confidence and will depend on the stability of the instrument between calibrations. The degree of stability is reflected in the amount of adjustment required to minimise errors, and this may be categorised into three possibilities:

i. Adjustments are needed to correct for errors which lie outside the required stated uncertainties,

ii. adjustments are needed to correct errors which are a significant fraction of the desired uncertainty but less than in (i), or

iii. departures from nominal (or previously calibrated values) are satisfactorily within the desired uncertainty so that adjustments may be considered unnecessary.

If (i) applies, the instrument should be considered unsatisfactory for the accuracy sought. The recommendation limit here is an adjustment of more than 60% of the desired uncertainty. The specific uncertainty should then be increased until the instrument falls into (ii) or alternatively, a 'better' instrument should be purchased.

For instruments in the second group which require adjustment, a history should be established and maintained by recording the response both before and after adjustments. Instruments in group (iii) are the most desirable and are better calibrated without any adjustments. It is recommended that instruments requiring an adjustment of less than 30% be classified in this category.

4.3 Calibrators

The main function of a calibrator is to generate electrical signals with known values of a particular quantity or quantities. Calibrators are used in many laboratories to calibrate DMMs. Being a source, as opposed to a meter, a calibrator is susceptible to the influence of the load that is connected to its output. This is especially true for alternating voltage and current ranges, particularly at high frequencies. Therefore, unless the loading presented to a calibrator during its own calibration, using a high-end DMM or a thermal transfer standard, is the same as the loading of the DMM being calibrated, the output of the calibrator may change significantly. The above condition is almost impossible to achieve, particularly for current where a fuse and a fuse holder with highly varying inductance are connected in series with the current input of the DMM. Also, at millivolt ranges, the output resistance of the calibrator is typically between 30 and 50 ohms due to the use of an internal resistive voltage divider. Therefore, the loading effect on the calibrator must be investigated and a corresponding uncertainty component included in the uncertainty analysis.

Similarly to DMMs, some calibrators are provided with 'autocal' or 'artefact calibration' against external standards. Although these processes must be performed as per manufacturers' specifications, they are not a replacement for the full verification of the calibrator.

4.4 Other instruments

There are many other electronic instruments whose purpose is to measure a wide variety of parameters. Most of these will comprise a calibrator and/or a voltmeter ahead of which is a transducer and/or some signal conditioning circuitry to transform the quantity to be measured into a voltage of suitable magnitude so that it may be measured by the dc voltmeter. Some examples include electronic thermometers using a thermocouple as the transducer, Multifunction Transfer Standards and solid state AC/DC Transfer standards. In principle, the test requirements related to such instruments include but are not limited to those discussed above and below.

4.5 General measurement considerations

Operation of digital instruments under bus control is now widespread. However, this introduces additional problems which must be checked. For example, faults in the decoding circuitry used to drive the digital display can lead to some digits in the display differing from corresponding digits appearing on the bus. Also, command signals and spurious signals entering the instrument from the bus can lead to false display and/or false bus outputs digits. Faults of this nature are often insidious and may require tests over the full range of bus control functions. Such an extensive check may not be practical but as a minimum test requirement, the effect of connecting and disconnecting the bus should be observed. Also, the bus read-out should be checked against the display, on each range.

The digital display is an important consideration, since there exists the possibility of gigantic errors with otherwise minor faults, for example, failure of one or more digits of the display. In many cases, such a fault will give rise to an illegal character, and no difficulty is experienced in detecting such errors. On the other hand, a fault which omits the middle segment from the digit 8 and so displays a zero, may easily pass undetected.

All digital displays must provide, at least, for a display of all digits showing the digit 8 in every position. It is desirable that the ability for all segments to be switched OFF is also provided, and that the behaviour of the decimal points can be tested. It is also useful to compare the displayed readings with those obtained using the remote interface, if it is available. Provided such checks can be performed both before and after use, the digital display per se is considered satisfactory.

The total operating environment for electronic equipment used as reference standards needs to have adequate protection against factors such as air currents, heat, line borne and radiated electromagnetic interference. Although equipment is designed to meet strict EMI specifications, unwanted signals can upset the operation. By removing fluorescent lights, electrometers, soldering irons etc from the vicinity of the set up, one can essentially eliminate this problem. Care needs to be taken with the stabilisation of the operating temperature of both the equipment transferring the calibration and the equipment being calibrated, particularly on the shop floor. Some items of equipment need recalibration or 'autocal' for temperature changes ± 1°C, some equipment compensates for predictable warm up errors, and some equipment employs thermal ovens for critical components to extend the thermal range. In some cases, temperature coefficients need to be added to the specified limits. Note that relative specifications are often given which are relative to the equipment, not the standard. Therefore both the relative uncertainty and the test uncertainty of the standard need to be combined in the uncertainty analysis to give the true uncertainty.

Further information on the contents of this section can be obtained from Budovsky[7] and by contacting the Australian National Measurement Institute.

5. Acknowledgements

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6. References

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