Setting New Standards for DC Voltage Maintenance Systems

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Many organizations rely on 10V DC standards as their primary DC reference. However, the routine maintenance of such devices is not only labour intensive, but requires a high degree of metrological skill to perform the measurements and analyse the accumulated historical data. This paper describes an innovative new lightweight voltage standard and integrated voltage maintenance system that fully automates the voltage measurement process from import of traceability through to certification. In this paper, the subject matter is presented in terms of the sources of voltage standard uncertainty.

Voltage Reference Standards

The most basic DC voltage reference standard typically consists of one or more zener devices together with an amplifier and gain-defining components (R1 and R2) in a temperature controlled "oven." The oven is used to provide an operating temperature higher than the local ambient, such that a known stable operating environment can be achieved. This allows the effects of the temperature coefficient of the zener and gain-defining components to be significantly reduced.

Batteries are usually provided to maintain operation of the device in the event of power failure. The device will typically have an output of 10V and an additional divided output at 1V or 1.018V. These reference devices are widely used throughout the T&M industry to not only maintain a standard of voltage, but also "transfer" or "import" a standard of voltage from one place to another.

A New Reference Standard

The Wavetek 7000 is a compact (H137mm x W85mm x D290mm), self-contained voltage standard that is smaller and lighter than any other high-stability commercially available device. A voltage standard is an important link in a "chain" of traceability that extends from national and international standards down to the working laboratories of calibration laboratories and beyond. The "chain" would typically comprise a number of standards used for transporting the "Volt" from one laboratory to another and also maintaining a particular voltage capability in a carefully maintained laboratory environment. To be able to address these varying requirements, the 7000 was designed with system compatibility in mind, this allowed some significant improvements in overall performance to be obtained as well as greatly simplifying the traceability process.

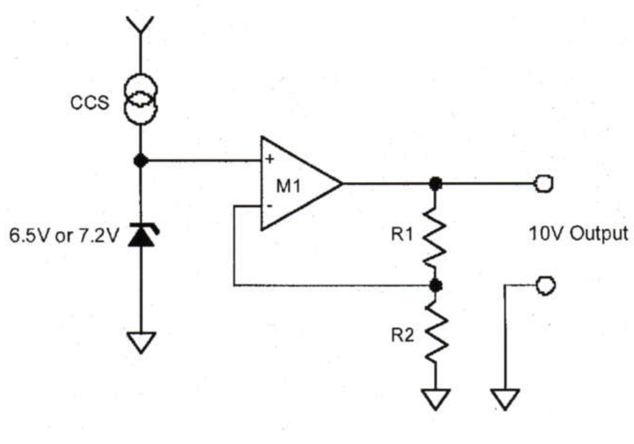
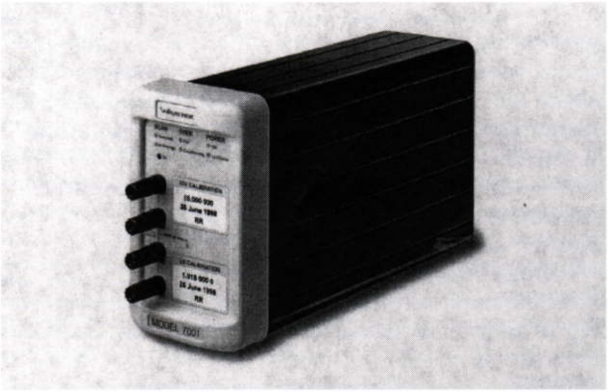


Figure 1. Basic zener voltage reference standard.

Hardware Requirements

It is generally agreed that the highest confidence is best obtained by using multiple standards. If the zeners are independent and their output voltages uncorrellated, there will be a root n improvement in the stability of their average value where n is the number of devices involved. The traditional approach would be to



Wavetek 7001 Voltage Standard

inter-connect the standards by cables to an electro-mechanical switch or "scanner." A sensitive DMM or micro-voltmeter will then be used in conjunction with a suitable program and computer to inter-compare the standards in a particular way. There are a number of potential problems with this approach, some of which are avoidable and others that are due to the nature of the individual standards. These problems are identified as:

- Power supply noise and leakage
- Interference from the computer
- Interaction between instruments
- Cable movement
- Ground loops

The 7000 uses a patented high-isolation DC/DC converter to reduce common-mode noise to extremely low levels. This means that it can be compared with a Josephson system directly and under line-power with no noise-related problems. Conventional parallel interfaces are grounded for data integrity. This can compromise the measurement performance of voltage monitoring systems depending on the level of bus activity. The 7000 has a duplex optical fibre serial link between the computer and the measurement system that provides total immunity from cable-borne noise. With separate system components, inter-connecting cable must be used to route the analogue signals. Ideally, they should be of low-thermal type and twisted-pair shielded construction. Where standards are to be placed in series opposition, there will inevitably be areas that cannot be effectively shielded (by twisting the wires) from external interference.

Because the 7000 scanner, detector and interconnections are integrated into a single unit, EM immunity is very high. Furthermore, the use of iso thermal planes within the integral analogue inter-connections keep thermal emfs to a minimum. Power consumption of the 7000 series system has been deliberately kept very low - for an entire system the power consumption/dissipation is less that 12 watts - this is less than most DMMs. Individual 7000 reference modules have a power dissipation of <1 watt. Such low power levels ensure minimum heating effects and thermal interaction between system elements.

Battery Considerations

All zener based voltage references known to the author rely on batteries for shipment and as a safeguard against line power failure. To allow uninhibited shipment by air, these batteries have typically been of the lead-acid type with a special non-liquid electrolyte. Unfortunately, these batteries tend to be unreliable because they are not frequently cycled, resulting in dramatic loss of capacity. Users are generally reluctant to allow the batteries to discharge completely because they believe that the traceability of the standard will be lost. This is encouraged by the voltage standard manufacturers who provide "In Cal" or "Heater Fail" indicators. These indicators are a safeguard, because if the power to the device is lost completely, it may also be subjected (unknowingly) during shipment to very low, or (less likely) very high temperatures that can cause a shift in output voltage.

Manufacturers do not usually specify their voltage standards under these conditions. There is a further consideration that, on re-application of power, the current may take a different path through the zener device resulting in a different output voltage from the standard. Whether this actually happens or not depends on the characteristics of the device concerned and the conditioning and selection processes it has passed through. However, the seed of doubt remains.

Each 7000 voltage standard uses NiMH battery technology similar to that used by mobile 'phones to overcome the "memory" effect known to exist with conventional NiCd cells. An integral pack of 10 "AA" sized cells gives a very compact power source to provide around 15 hours normal operation at room temperature. Line power for routine operation and charging is provided by an external power supply similar in size to that used by notebook computers. It produces 12V DC and is connected to the 7000 module via a locking DIN plug. When the module is located in a rack, the rack provides the 12V power via a multi-way rear panel connector.

Temperature Control

Zener devices have a significant temperature coefficient in relation to their expected performance as a voltage standard. To overcome this limitation, the zener device and associated circuits may be placed in a heated oven chamber within the instrument. Temperature control is achieved by running the oven above the expected maximum ambient temperature. Because of the current passing through the zener device, its chip temperature will be at a higher temperature than the oven, and this has an impact on the overall temporal stability of the device. There is a trade-off between oven temperature (and therefore the maximum ambient operating temperature) and the long-term drift of the zener. Increasing the temperature extends the ambient operating temperature range, but also increases the long-term drift. Furthermore, maintaining a higher operating temperature requires more power and reduces battery operation time and therefore powered shipment range. The required ambient operating range also dictates the lowest oven temperature that can be used because control is achieved by varying the heater power - there is no active cooling.

With a separate oven, it is not unusual for the zener chip temperature to exceed 80°C. Extensive research has shown that a zener chip temperature less than 50°C can double the long-term stability and easily achieve a performance of better than 1ppm/year. At the time of writing, there was only one type of device suitable for this operating range - the Lineartech LTZ1000. This device has a chip-substrate heater[1] and does not require a separate oven. Consequently, the zener current also contributes to heating the chip such that the substrate heater power can be reduced even further. This is ideal for a reference that might be shipped long-distance under battery power

Shipment Effects

A laboratory's uncertainty analysis for voltage importation must have provision for shipment effects. Typical parameters to consider would be:

- Battery failure
- Temperature/environment differences
- Line/battery power differences
- Humidity effects
- Pressure coefficients

A voltage standard is normally shipped under battery power. The zener is known to offer its best repeatability under powered conditions. This is great if the journey to the calibration centre can be completed within 8 hours or so, but what if the actual time is much longer? It is quite common for voltage standards to arrive "cold" with discharged batteries, how long will it take the zener to recover? What temperature extremes has it been exposed to? The 7000 has a "Hysteresis Safeguard", a patented conditioning process[1] that will relieve any residual stress in the chip substrate and return the zener voltage typically to within ±0.2ppm of the value maintained before battery discharge causes the eventual loss of heater control.

Some types of voltage reference exhibit different output voltages depending on whether they are line or battery powered. This is usually caused by changes to the internal power dissipation for the different operational modes. As mentioned earlier, with some designs, line powered operation can introduce noise into the measurement system resulting in erroneous values or noisy readings. Where the reference output voltage is influenced by the operational mode, systematic errors may be introduced during the importation process. These problems have been addressed in the 7000 by having a low power dissipation and using power supplies with a very high isolation and low leakage current.

Voltage standards may also be influenced by environmental effects. Some types of component are hygroscopic. In particular, the absorption of moisture can affect the dimensional stability of resistor formers or substrates, such that a humidity-dependent stress is induced. This can affect the value or ratio of gain/attenuation defining components within the reference, resulting in an apparent seasonal variation of output voltage. There may be a significant time-lag for this effect making it difficult to observe in the short-term. The 7000 uses "statistical resistor arrays" as gain-defining components. This type of device, based on tantalum-nitride technology[1], is packaged and used in such a way that it is not affected by humidity and also has an extremely low temperature coefficient and very high long-term stability.

Voltage standards can also be influenced by changes in atmospheric pressure. This is caused by a pressure dependence of certain types of zener device. It is important that pressure coefficients should be very small because there can be significant changes in pressure due not only to the weather conditions, but also to differences in elevation between standards laboratories. A Wavetek 7004T transportable voltage standard has been extensively evaluated for pressure coefficients[2] over the range 835mb to 1200mb and exhibited a linear pressure coefficient of -1.5nV/mb. This is extremely low and is

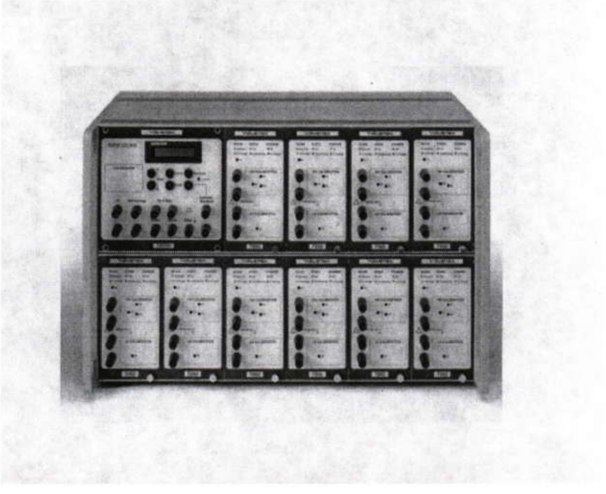


Figure 2. Wavetek 7010N System.

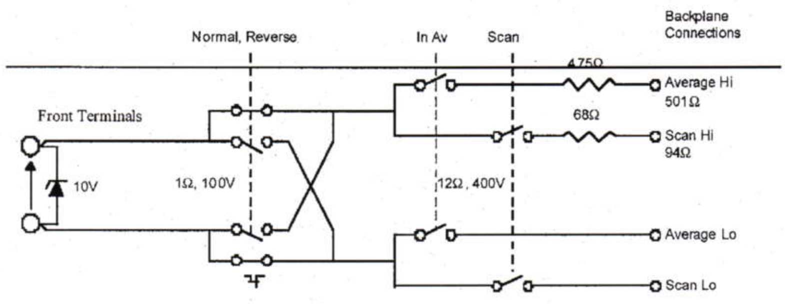


Figure 3. Wavetek 7000 integral switching.

negligible in relation to the pressure differences likely to be encountered during normal use as a traveling standard.

A System Approach to Volt Maintenance

Although DC voltage is one of the fundamental measurement parameters in electrical metrology, no single vendor has previously taken a fully integrated approach to the problem of volt maintenance, particularly in a commercial laboratory environment. Often, the solution is to simply automate the existing equipment to make the required inter-comparison measurements, whereas a total solution should take a holistic approach considering full integration of compatible hardware and automate not only the measurements, but also the whole voltage importation and maintenance process.

The complete Wavetek 7000 Volt Maintenance System comprises the following components (model number in parenthesis):

- Nanoscan Controller/Detector and Rack (7004N/7010N)
- Basic Array of 4 to10,10V zener Modules (7000)
- Optional Switch Modules (7000S)
- Separate Transportable 10V zener Module (7001), "Transref" Transportable Standard (7004T/7010T)

The "Nanoscan" is a combined scan-controller and high-sensitivity digital detector mounted in a special 19" rack capable of taking up to 4 or 10 independent zener modules depending on rack height. The detector has a very high input impedance ($>10^9$), a resolution of 0.01ppm and an operational range of ±10mV. The zener modules each have 10V and 1.018V front panel outputs and an integral electronic (PhotoMOS) switching system to route the 10V output to a Hardware Average and the Nanoscan detector.

Electronic, rather than electromechanical switches were chosen to improve reliability and reduce thermal emfs. This was made possible by the availability of very low "on" resistance devices from the telecom industry. These have proved to be very effective and require very little stabilisation time after switching. They also provide a high isolation and very low capacitance between the control and measurement circuits and benefit from not having the heating effects that can result from energising relay coils. The "on" resistance has no significant effect on the performance of the system. The Nanoscan detector has a very high input impedance so the series resistance of the switches does not introduce any errors. The "on" resistance is also quite stable in relation to the hardware averaging circuit and does not significantly effect the accuracy of the average output. The switching time (typically 2 ms) is much faster than relays and minimises the time that measurement circuits are left open during the scan process. Separate switches are used for voltage reversals (to eliminate any residual thermal emfs) and for switching the zener module outputs to the scan-bus and hardware average.

The switching arrangement is such that the detector Lo may be connected to the hardware average (HAV), while the detector Hi may be connected to any individual 10V module output Hi under scan control (up to a maximum of 20 modules). There is also provision for automatic reversal of the connections throughout the system to eliminate any spurious thermal offset voltages. In addition to the zener modules, the system can also use modules that contain only the electronic switching system. This allows existing external standards to be included in the

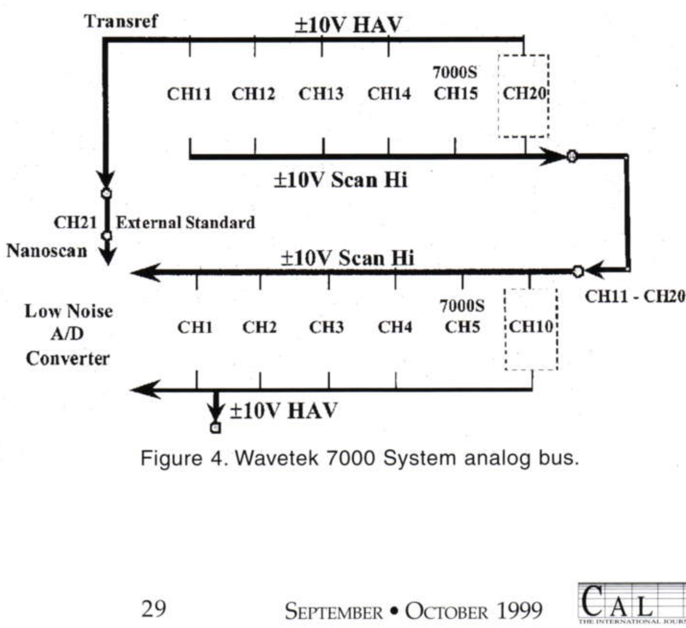


Figure 4. Wavetek 7000 System analog bus.

measurements. An external standard may be connected to the front panel terminals of the Nanoscan. This allows the system to be calibrated - either against a 10V Josephson system or another zener-based standard. Where a Josephson system is used, the Nanoscan provides a switch-closure to control the polarity switching of the array as part of the scanning process. The Nanoscan also provides the 10V average output, 4-wire output (taken from the buffered average) for driving external loads and 1V output.

The Nanoscan unit has a status display to allow individual readings to be monitored, including the difference between any module and the hardware average, as well as the zener chip temperature of each module. The Nanoscan also contains the fibre-optic serial interface for connection to the serial port of a PC. Proprietary software (generated with National Instruments Lab Windows™ CVI) is used to control the measurement process, capture the data, and process it via a special macro used in conjunction with Microsoft Excel™. The macro makes use of the graphing and statistical functions of Excel to determine the historical and future performance of the system.

Software Control

The 7000 Series reference modules were designed to facilitate system operation. Each reference module has a rear panel connector that carries not only the analogue signals, but also operation status information about the module. This information includes the module electronic ID (type and serial number), correct zener heater operation and temperature, power supply status, zener conditioning and hardware average enabled. The status information is read each time the module is scanned by the Nanoscan controller/detector and stored together with the other measurement results in a "CSV" (comma separated variable) ASCII file. This file is automatically imported into Microsoft Excel using a special macro that is part of the Wavetek 7050 Excel "Add-In."

To make a series of measurements, the user selects options from a "scan-base" dialogue box. The scan-base may be the same as used previously or a new one for a specific measurement type. The scan-base determines the following:

- Start date and time
- Number of scans
- Delay between scans
- Storage action (append/overwrite)
- Scan base file name/path
- Channels to be included
- Number of samples
- Delay Between channels
- Measurement Mode (normal/reversal)

Unless a preliminary scan has already been made, completion of the scan-base dialogue box will initiate a scan of the system to determine which modules are connected. It will check each channel in turn and report the module ID against the 22 available channels. Channel 0 is always the Nanoscan module and system zero while channel 21 is the external reference input/output. Check boxes are used to select whether a fitted module is to be included in the measurement scan.

Once a measurement scan is in progress, a measurement status dialogue box appears showing the following:

- Channel number
- Module difference w.r.t HAV in µV
- Module ID
- Percent total scans completed
- Percent current scan completed

The measurement process benefits from the fact that a hardware average (HAV) is continuously available. Each 10V module output is sequentially compared against the 10V average and its µV difference relative to the average is stored. The process can include full reversals of the system inter-connections to eliminate the effects of thermal emfs. The measurement sequence is also designed to remove the effects of any drift or changing offsets within the system. When reversals are made, the Nanoscan detector is required to operate over a 20V common-mode range. Careful design of the detector zero circuit and measurement process can eliminate any potential common-mode errors.

It's worth mentioning that the scan-control software can be run in the background while the PC is used for other tasks. On completion of the measurements, the results can be imported into Excel for analysis. The data is stored in Excel as a series of worksheets arranged by process and channel number. The worksheets include a summary of all the measurements of all the channels, import results, export results and detailed data for each specific channel individually.

The import and export options are for calibrating the system (import of traceability) and calibrating external

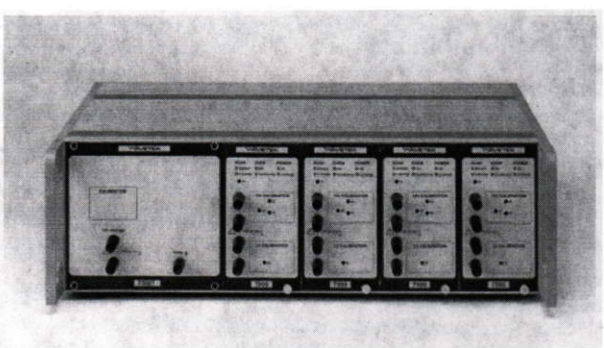


Figure 5. Wavetek 7004T 4 Cell Transfer Standard.

references (exporting traceability). The latter would normally be connected to channel 21 (external standard), but could be an individual module within the system, or an external standard connected to a 7000S scan module. The process of importing traceability and determining the on-going voltage capability of the system is called voltage maintenance.

The Volt Maintenance Process

In a volt-maintenance system the expanded uncertainty is determined by the following:

- Import standard calibration uncertainty
- Importation process
- Number of standards in group
- Time stability of reference standards
- Temperature stability of reference standards
- System inter-comparison noise and UUT

The uncertainty available from national laboratories is usually based on a 10V Josephson Array standard and is very dependent upon the performance of the UUT zener device. Typically, the expanded uncertainty quoted on a calibration certificate will be around ±0.1ppm.

Where a conventional one-way, top-down importation process is used, the uncertainty allowance for the importation process may be greater than the calibration uncertainty. Careful choice of the process and type of import standards used can generally reduce the uncertainty to less than 0.1ppm — particularly when an AVT process is used.

The noise and short-term stability of any UUT offered up to the system for calibration will contribute to the overall uncertainty. A single 7000 10V module has a measured noise level of < 0.04ppm rms. Combining 4 or more modules can make further improvements to the noise level resulting in very low type A uncertainty contributions for the measurement system. The Wavetek 7004T is designed specifically for this purpose and can be linked to the Nanoscan system to provide a fully automated transfer.

AVT Process

In the UK, laboratories with an accredited expanded uncertainty of 1ppm or better are expected to participate in an Audit Via Traceability (AVT)[3]. This process uses the laboratory's own transfer standard to audit the laboratory's technical competency. This is significantly different from the "round-robins" often used in the USA and has evolved from the large number of long-established accredited laboratories. Generally, in the European Accreditation system, accredited laboratories are expected to "own" all of their reference standards and maintain the history. Furthermore, the technical competency on which the accreditations are based requires the laboratories to be able to maintain all aspects of their traceability systems. Briefly, the AVT process is as follows:

1. The originating laboratory measures its transfer standard before shipment against the rest of the working reference group and declares a value (V1) for each of its outputs.
2. The transfer standard is sent to the national laboratory together with its assigned value.
3. The national laboratory measures the transfer standard against the national standard over a 10 day period.
4. The transfer standard is collected from the national laboratory and returned to the originating laboratory.
5. The originating laboratory measures the transfer standard after shipment against the rest of the working reference group and declares a value (V2) for each of its outputs.
6. The national laboratory, on receipt of the declared values, informs the laboratory of the certified values (Vref).
7. From the 3 sets of results, the originating laboratory can determine the error in its "Volt" (and make a correction) and remove the effects of drift in the importation process.

This process has been in place since 1985 and gives a reliable indication of a laboratory's whole capability - including management of the import from national standards. It also allows the accreditation body to monitor (via the national laboratory) the laboratory's real capability - without having to maintain or manage a large number of their own audit devices. The importation process used by Wavetek's 7000 series voltage maintenance system is based on this very successful method.

A laboratory must be able to determine its measurement

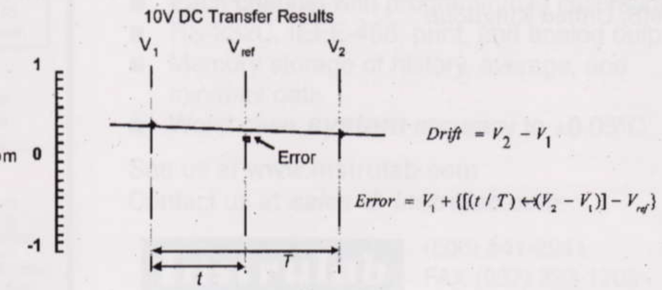


Figure 6. AVT importation process.

capability at all times. With voltage standards, it is important to know their stability between calibrations to an external standard. The calibration interval may be as long as a year, so knowledge of the drift characteristic of the standard is essential. Voltage standards of a particular type tend to have similar characteristics - particularly if they have been subjected to special selection and conditioning processes designed to optimise stability and remove potentially bad devices. The LTZ1000 is no exception to this, and its employment in the 7000 series voltage reference is the result of many years of testing and evaluation. Initially, stability predictions are based on the expected -0.7ppm/year drift rate.

Once historical data from successive calibrations has been accumulated, the 7050 software can be used to curve-fit the data to determine the actual drift rate for each reference module within the system. The drift rates are then used to make predictions of the future values of the hardware average over the next calibration cycle. As more data is accumulated, the drift rates can be revised and applied as corrections to the values used in the volt maintenance process. All the data processing is performed by Wavetek's 7050 Excel "add-in." This provides all the analysis tools, graphing, report and certificate templates necessary to allow the user to perform routine volt maintenance tasks. This approach was chosen so that users could perform data analysis to their own specific requirements (within the extensive functionality of Excel).

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