

# A practical approach to maintaining DC reference standards

## Application Note

DC voltage standards based on Zener technology are now in widespread use in electrical standards laboratories and have brought many practical advantages over the Weston Cells they replaced. However, with the accumulated measurement data it has become obvious that solid-state references must be used with some caution if their full potential is to be realized. Careful instrument design can overcome many of the potential limitations of Zener-based voltage reference standards. This paper discusses the design considerations for a standard introduced by Fluke's Precision Measurements Division.

### 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".

Batteries are usually provided to maintain operation of the device in the event of power failure. The device will typically have an output of 10 V and an additional divided output at 1 V or 1.018 V. These reference

devices are widely used throughout the test and measurement industry to not only maintain a standard of voltage, but also "transfer" or "import" a standard of voltage from one place to another.

### Design considerations

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 are usually placed in a

heated oven chamber within the instrument. Temperature control is achieved by operating the oven above the expected maximum ambient temperature. There is a trade-off between oven temperature (and therefore the maximum ambient operating temperature) and the temporal stability 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.

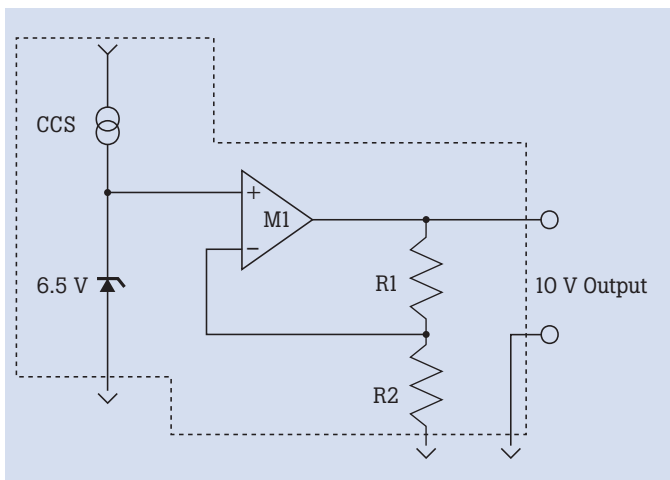


Figure 1. Basic Zener Voltage Reference Standard.

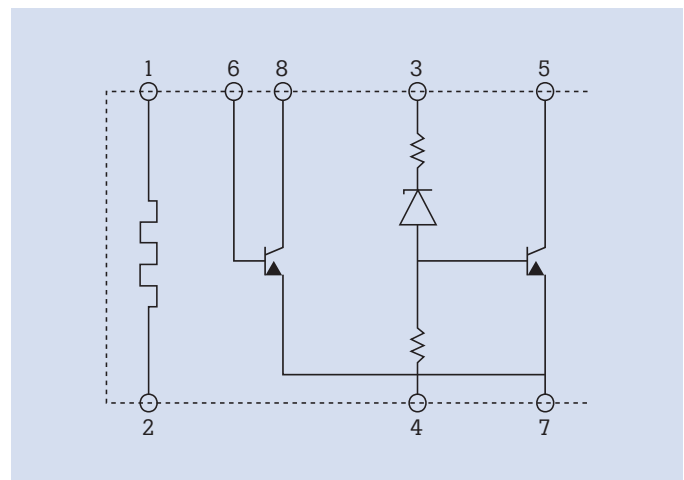


Figure 2. LTZ1000 Schematic.

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 1 ppm/year. One type of device suitable for this operating range is a LTZ1000. Figure 2 shows the chip schematic.

The LTZ1000 has a chip substrate heater 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. The reference voltage is effectively taken from pins 3 and 7 of the device. The base-emitter junction of the series transistor is used to compensate for the relatively poor temperature coefficient of the Zener. The second transistor is used as a temperature sensor to provide closed-loop control of the chip substrate heater that is connected to pins 1 and 2 of the device. A proprietary conditioning and selection process is used by Fluke to ensure maximum performance from each reference device. Devices that have been through this process can achieve a linear temperature coefficient of <0.05 ppm/°C and a TME stability of 0.7 ppm/year.

### A new reference standard

The Fluke 7001 is a compact (H137 x W85 x D290 mm), self-contained voltage standard that weighs only 2.1 kg (4.5 lb). It can be used as a single 10 V standard or used in groups of up to 10 modules in an integrated voltage maintenance system. When used in the modular system, the extruded case and front moulding are not required. In this form, the reference is known as the Fluke 7000 reference module.



Figure 3. 7001 Voltage Standard.

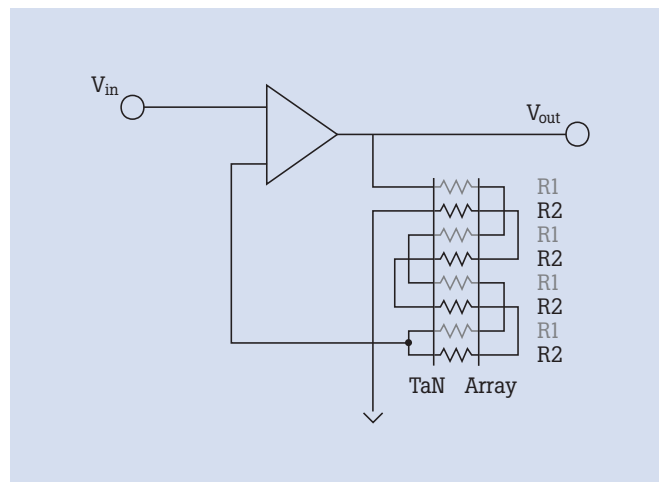


Figure 4. TaN Resistor Array.

As can be seen from Figure 1, the stability of a Zener-based voltage standard is dependent not only on the Zener device but also on the gain-defining components and amplifier required to produce a 10 V output from a nominal 7 V reference. In the Fluke 7000, individual gain defining resistors have been replaced by Taitanium-Nitrate “statistical” resistor arrays. With this technology, special packs of thin-film resistors with identical properties are used in a special way to maximize their ratio stability with time and temperature. The basic principle is shown in figure 4.

The individual resistor elements of the array(s) are interleaved such that temperature gradients across the array affect the elements comprising R1 and R2 equally. Interleaved multiple array packages are used to achieve the required ratios. Although the amplifier gain is controlled by resistor arrays, a means of adjusting the output to the nominal 10 V is required. This is achieved by using two 8 bit DACs configured for coarse and fine adjustment. Rather than adjust the amplifier gain, the DACs are configured to provide an additional voltage (stabilized by the Zener) with a span of some 20 mV and a resolution of 0.4 ppm.

This means that the 10 V output can typically be adjusted to within 0.2 ppm of the nominal 10 V. The advantage of this system is that there are no electro-mechanical trimmers—the adjustment is made using 8 bit binary switches that are not part of the reference analogue circuit. TaN resistor arrays are also used to provide the low voltage output. These are set by links to give initially either 1.018 V or 1 V as required by the customer, and also to provide basic adjustment of the nominal output value.

### Battery considerations

Zener based voltage references rely on batteries for shipment and as a safeguard against line power failure. To allow uninhibited shipment by air, the batteries have typically been of the Lead-Acid type with a special non-liquid electrolyte. Unfortunately, their capacity can reduce dramatically if they are not frequently cycled.

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

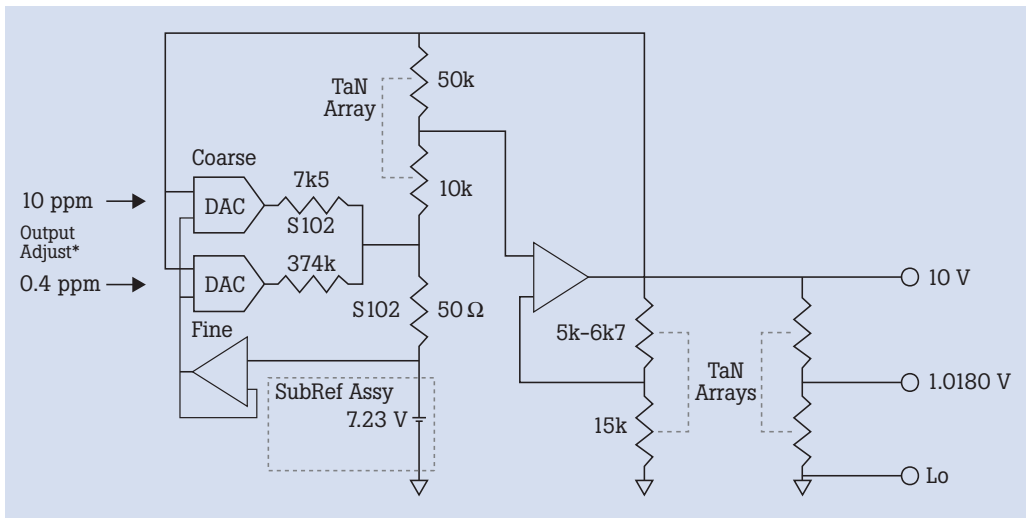


Figure 5. Output voltage adjustment of the 7000.

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 12 V 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 12 V power via a multi-way rear panel connector.

### Shipment effects

A laboratory’s uncertainty analysis for voltage importation<sup>[1,4]</sup> must have provision for shipment effects. Typical parameters to consider would be:

- Effect of 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. If the journey to the calibration center can be completed in a few hours, a voltage standard may be kept

fully energized—but if the journey takes much longer, power to the Zener and oven may be lost completely. It is quite common for voltage standards to arrive “cold” with discharged batteries. Under these circumstances it can be difficult to know how long it will take the Zener to recover and what temperature extremes it may have been exposed to. Over a relatively narrow operating ranges A Zener will exhibit a “normal” temperature coefficient, but if the device is exposed to very low (or high) temperatures, mechanical stress within the device may cause its output

voltage to step. The Fluke 7000 has a patented<sup>[2]</sup> “Hysteresis Safeguard” that allows the temperature hysteresis to be “reset” by cycling the Zener chip temperature in a particular way. This function can be triggered manually at any time, or set to run automatically in the event of complete (battery) power failure.

The control voltage to the LTZ1000 substrate heater is modulated to produce a decaying temperature cycle that will remove the internal mechanical stress and return the Zener voltage typically within  $\pm 0.2$  ppm of the original value.

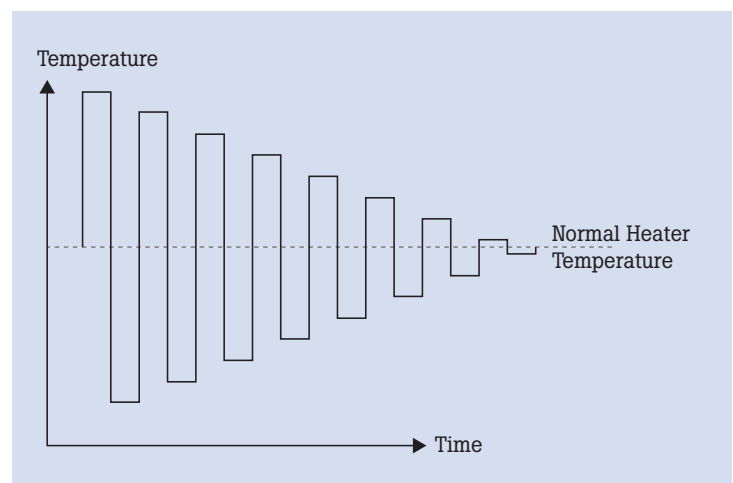


Figure 6. LTZ1000 heater temperature modulation.

### Line power supply

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. Additionally, 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.

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. The power dissipation of a single 7000 reference module is <1 Watt. This ensures minimal internal heating effects and thermal interaction between system elements.

### Environmental considerations

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<sup>[2]</sup>, 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 longterm stability.

Voltage standards can also be influenced by changes in atmospheric pressure. This is caused by a pressure dependence of certain types of Zener devices. 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 Fluke 7004T "Transref" transportable voltage standard has been extensively evaluated for pressure coefficients<sup>[3]</sup> over the range 835 mb to 1200 mb and exhibited a linear pressure coefficient of -1.5 nV/mb. This is extremely low and is negligible in relation to the pressure differences likely to be encountered during normal use as a travelling standard.

### Multiple references

A single 7000 10 V module has a measured noise level of <0.10 ppm rms. Combining four or more modules can make further improvements to the noise level resulting in very low type "A" uncertainty contributions for the measurement system. The Fluke 7004T contains four 7000 reference modules and is designed specifically for transportation.

### Volt-maintenance system

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 7000 Volt-Maintenance system comprises the following components:

- "Nanoscan" Controller/ Detector and Rack
- Array of 4 to 10, 10V Zener Modules
- Optional Switch Modules
- "Transref" Transportable Standard



Figure 7. 7010N Integrated Volt-Maintenance System.

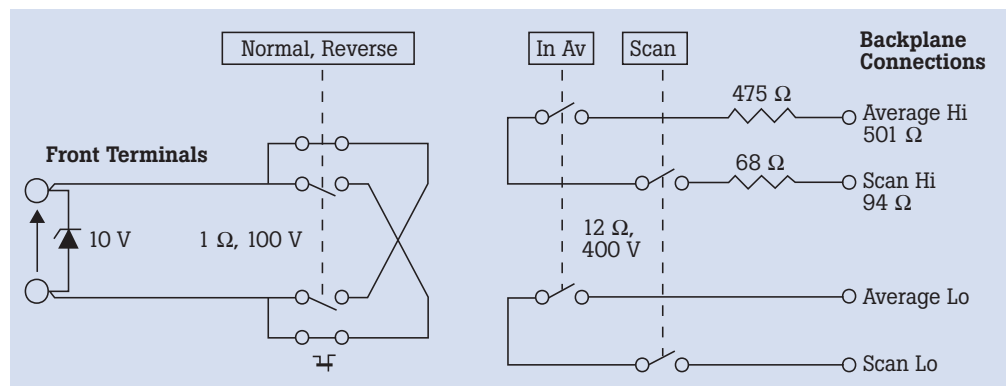


Figure 8. 7000 integral switching.



The “Nanoscan” is a combined scan-controller and high-sensitivity digital detector mounted in a special 19 inch 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<sup>9</sup> Ω), a resolution of 0.01 ppm and an operational range of ± 10 mV. The Zener modules each have 10 V and 1.018 V front panel outputs and an integral electronic (Photo- MOS) switching system to route the 10 V output to a Hardware Average and the Nanoscan detector.

Electronic, rather than electromechanical switches were chosen to improve reliability and reduce thermal e.m.f.s. 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 stabilization 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 energizing relay coils. The “on” resistance has no significant effect on the performance of the system. The Nanoscan detector has 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 minimizes the time that measurement circuits are left open during the scan process. Separate switches are used for voltage reversals (to eliminate any residual thermal e.m.f.s), and for switching the Zener module outputs to the scan-bus and hardware average.

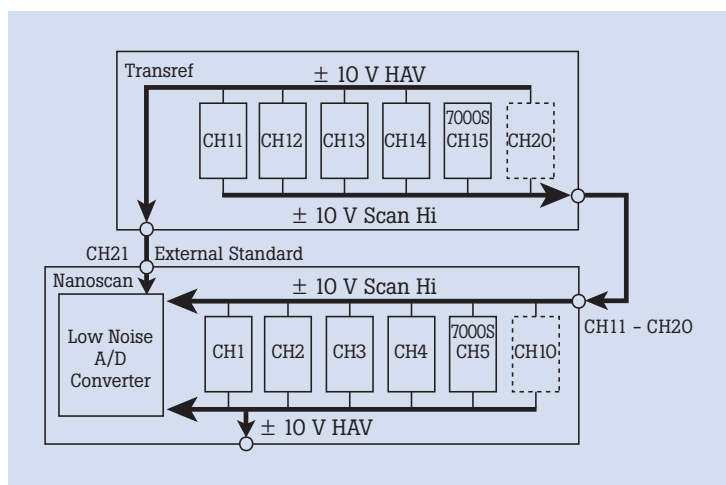


Figure 9. 7000 system analog bus.

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 10 V 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 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 10 V Josephson system, or another Zener-based standard, like the Fluke 732B. 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 10 V Average output, 4-wire output (taken from the buffered average) for driving external loads, and 1 V 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 Fiber-optic serial interface for connection to the serial port of a PC. Proprietary software (generated with National Instruments LabWindows™) 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 analog 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 (Hysteresis Safe-guard) 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 Fluke 7050 Excel "Add-In."

**References**

- [1] "Uncertainty Analysis for Laboratory Accreditation". Author: P.B. Crisp, Fluke Precision Measurement Ltd.
- [2] "A Solid-State Reference System". Author: John R. Pickering, Metron Designs Ltd., Norwich, UK.
- [3] Evaluated by Sandia National Laboratories, Albuquerque, New Mexico, USA.
- [4] "Setting New Standards for DC Voltage Maintenance Systems". Author: P.B. Crisp, Fluke Precision Measurement Ltd.

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