By JIM ROWE

Precision 10V DC reference for checking DMMs

Have you ever checked the calibration of your digital multimeter? Yeah, we know – you haven't because there is no easy (read cheap) way of doing it. But now you can with this precision DC voltage reference that can be built in a few hours. Without any need for adjustment, it will provide you with a 10.000V DC source accurate to within ±3mV, ie, an accuracy of ±0.03%.

MOST of us don't ever get our DMMs calibrated, though they do drift out of calibration over years of use. If you are using them in your occupation, they should be checked every year or so – otherwise, how can you trust the readings?

But it can cost quite a bit to send a DMM away to a standards lab for calibration – more than many DMMs are worth. So generally, we either hope for the best or simply buy a new DMM if we suspect that our existing meter has drifted too far out of calibration.

Voltage source

Back in the 1970s, when DMMs first became available, the only practical source of an accurately known DC voltage was the Weston cell, a wet chemical 'primary cell' that had been developed in 1893 and had become the international standard for EMF/voltage in 1911 (see panel). It produced an accurate 1.0183V reference, which could be used to calibrate DMMs and other instruments.

Unfortunately, Weston cells were fairly expensive and few people had direct access to one for meter calibration. As a result, most people tended to use a reasonably fresh mercury cell as a 'poor man's' voltage reference. Fresh mercury cells have a terminal voltage very close to 1.3566V at 20°C, and this falls slowly to about 1.3524V after a year or so. Silver oxide cells can be used for the same purpose, having a stable terminal voltage very close to 1.55V.

Of course, batteries of any kind have a tendency to obey Murphy's Law and usually turn out to have quietly expired before you need them. And although mercury and silver oxide cells have quite a long life, especially if you use them purely as a voltage reference, they certainly aren't immune to this problem. Therefore, batteries make a pretty flaky voltage reference, at best.

Fortunately, in the 1980s, semiconductor makers developed a relatively low-cost source of stable and accurately predictable DC voltage: the precision monolithic voltage reference (PMVR). This is a kind of up-market relative of the familiar 3-terminal voltage regulator IC. Like 3-terminal regulators, PMVRs produce a regulated DC output voltage when they are fed with unregulated DC power.

The Analog Devices AD588 device we're using in this new voltage reference project incorporates a number of recent advances in PMVR technology. These include an ion-implanted 'buried' Zener reference diode, plus high-stability thin-film resistors on the wafer, which are laser trimmed to minimise drift and provide high initial accuracy.

It also incorporates highly stable on-chip op amps which are configured to allow Kelvin connections to the load and/or external current boosters, for driving long lines or high current loads.

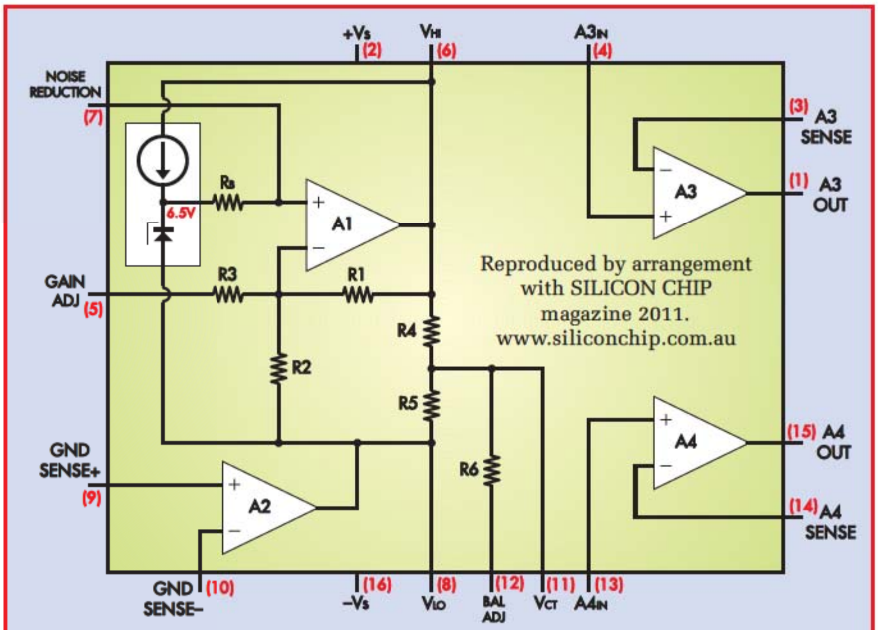


Fig.1: block diagram of the AD588 voltage reference. It contains four op amps (A1-A4) plus a 'buried' Zener and its current source to provide the voltage reference cell.

Specifications

Output voltage: 10.000V DC

Sensing: internal or remote sensing to compensate for output cable voltage drop

Basic accuracy: ±0.03% (±3mV) without adjustment, ±0.002% after optional trim adjustment and calibration

Long term drift: <15ppm per 1000 hours, mostly in first year of operation

Temperature coefficient: 3ppm/°C between –25°C and +85°C

Maximum output current: 10mA

Noise on output: less than 6mV RMS

Load regulation: less than ±50µV/mA for loads up to 10mA

Supply line regulation: less than 200µV/V

Power supply: 12V AC, current drain <60mA

Block diagram

You can see what's inside the AD588 in the block diagram of Fig.1. The voltage reference cell is at upper left, consisting of the 'buried' Zener (6.5V) and its current source, together with op amp A1. All the resistors (R1 to R6) are high-stability thin-film resistors, laser trimmed to allow the gain of A1 to be set to a high degree of precision – so the cell's basic output voltage (between pins V_{HI} and V_{LO}) is initially set to 10.000V ±3mV (for the AD588JQ/AQ version we use here), without any external adjustment.

Temperature compensation inside the cell also gives the basic voltage reference a very low temperature drift coefficient: typically ±2ppm/°C. In addition, resistors R4 and R5 can be configured to provide a very accurate 'centre tap' for this voltage, allowing the chip to be used as a precise source of ±5.000V ±1.5mV.

Although this basic untrimmed initial accuracy of the AD588 (10.000V ±0.03%) is good enough for calibrating the majority of low-cost DMMs, the chip can also be trimmed very easily to improve its accuracy by a factor of greater than 10 times – ie, to an accuracy around ±0.002%.

This is done by connecting the GAIN ADJ pin to a 100kΩ trimpot, connected between the V_{HI} and V_{LO} terminals. The pot allows the gain of A1 to be adjusted for a very small output voltage range (approximately -3.5mV to +7.5mV) without any adverse effect on temperature stability. Of course, in order to take advantage of this trimming feature, you must have access to an even higher precision voltage reference, to compare it with.

Op amp A2 is used to allow accurate 'ground sensing', ensuring that the external system ground is accurately held at the same potential as V_{LO}. Op amps A3 and A4, which are internally compensated, act as output buffers for the V_{HI} and V_{LO} voltages, as well as providing for a full Kelvin (ie, remote sensing) output connection.

Circuit details

As you can see from the full circuit diagram in Fig.2, there's not a great deal in our new precision voltage reference apart from the all-important AD588 chip (IC1) – the heart of the project.

All that we need to do in the rest of the circuit is provide it with a moderately regulated and filtered power

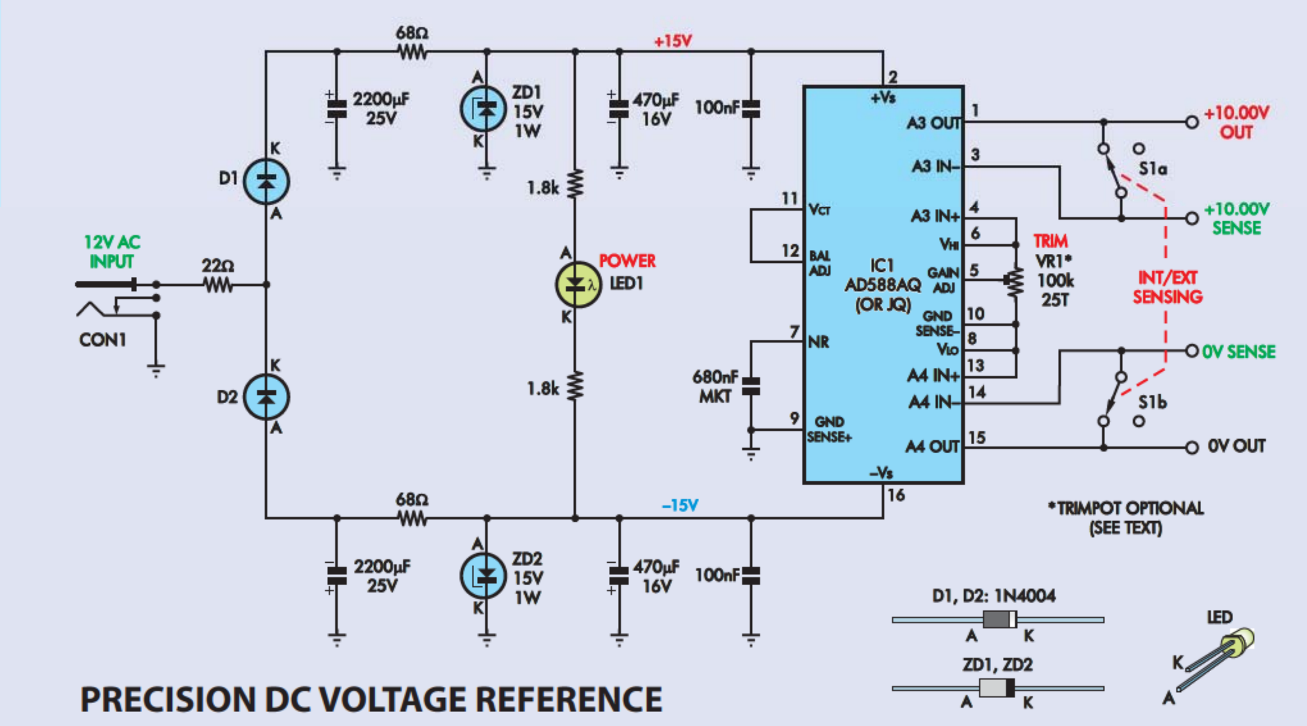


Fig.2: the circuit uses the AD588 precision voltage reference (IC1) and not much else. Diodes D1 and D2 function as half-wave rectifiers and feed Zener diodes ZD1 and ZD2 to provide ±15V rails for the IC.

source of ±15V, and also make its buffered output voltage available, either at the main local terminals, or at the end of a cable connected to a remote load.

The power supply configuration is quite straightforward, and uses a half-wave rectifier circuit to produce each DC supply rail from a 12V AC input (which can be a 12V 500mA AC plugpack). Diodes D1 and D2 form the rectifiers, with filtering provided by two 2200µF electrolytic capacitors. Zener diodes ZD1 and ZD2 (both 15V types) then provide moderate regulation for the two supply rails, in conjunction with the two 68Ω series resistors.

A small amount of additional filtering is provided by two 470µF electrolytics, together with 100nF bypass capacitors at the supply pins for IC1. Note that power indicator LED1 is connected directly between the two supply rails, in series with two 1.8kΩ current-limiting resistors.

The connections for IC1 itself are fairly easy to follow. The 680nF capacitor connected to ground from the NR pin (7) is included to provide additional low-pass filtering of any noise generated by the AD588's buried Zener. It works in conjunction with series resistor RB, as shown in Fig.1.

Op amp A3 inside IC1 is used as the positive voltage output buffer, with its non-inverting input (pin 4) connected directly to V_{HI} (pin 6). The inverting input (pin 3) is brought out to the external positive sense terminal (for remote sensing) and also to S1a, which allows it to be connected directly to the positive output (pin 1) for local sensing.

Op amp A4 is connected in the same way, as the negative output voltage buffer. Here, the op amp's non-inverting input (pin 13) is connected directly to the reference cell's V_{LO} output (pin 8), while the inverting input (pin 14) is brought out to the negative sense terminal for remote sensing and also to S1b, to connect it directly to the negative output (pin 15) for local sensing.

So what is the purpose of the 'optional' trimpot VR1? It is for trimming the AD588's output voltage to higher

What this voltage reference cannot do

This 10V DC reference is very handy if you want to check the DC accuracy of your digital multimeter, but it cannot tell you anything about your DMM's accuracy in its other modes, such as DC and AC current, AC voltage and resistance. So, just because you have done a simple check on the DC voltage accuracy, don't let it lull you into a false sense of security that everything is well with your DMM.

In fact, it is possible that this 10V DC reference may alert you to the fact that your DMM has drifted well away from its initial calibration, which may have been pretty good when you purchased it. How many years ago was that?

If you are using DMMs in your occupation, they should be calibrated every year or so, otherwise you cannot really trust the readings. Moreover, if you have dropped your multimeter, it definitely should be suspected, particularly if its internal calibration is performed by tweaking potentiometers. Let's face it, most DMMs get dropped from time to time – that's just normal.

If you need a full performance verification of all functions and ranges for your work then that is best performed by an accredited calibration laboratory.

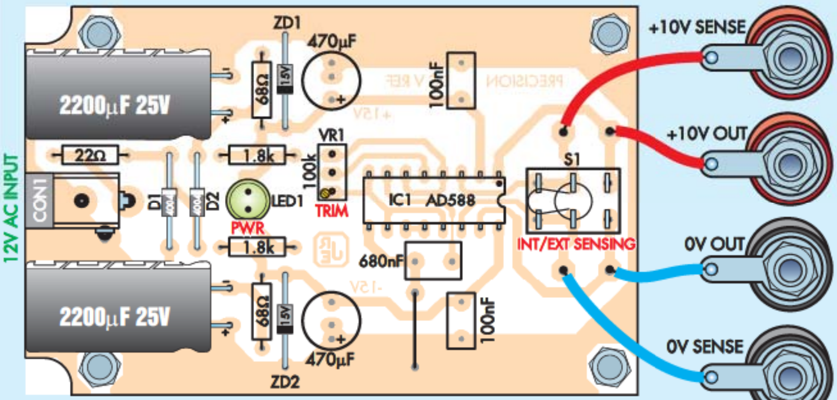
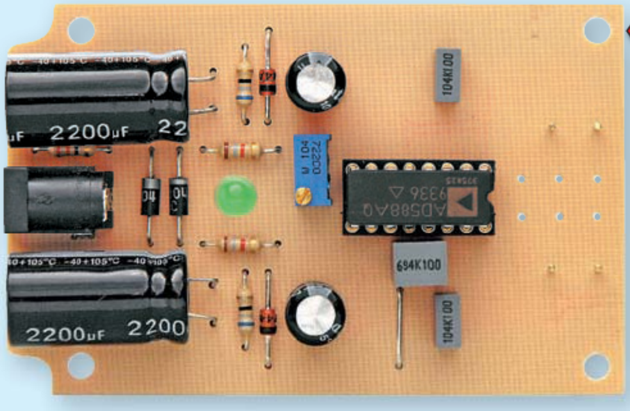


Fig.3: follow this diagram to install the parts on the PC board and complete the external wiring. Note that switch S1 actually mounts on the lid of the case and not directly on the PC board – see text.



This view shows the completed PC board with the optional trimpot (VR1) in position. Install VR1 only if you intend calibrating the unit against a high-precision 10V reference.

Parts List

1 diecast aluminium box, size 111mm × 60mm × 54mm (Jaycar HB-5063 or similar)
1 PC board, code 805, available from the *EPE PCB Service*, size 84mm × 53.5mm
1 DPDT on-on mini toggle switch (S1)
1 2.5mm PC-mount DC power socket (CON1)
1 16-pin machined IC socket
2 binding post terminals, red
2 binding post terminals, black
4 M3 × 25mm tapped metal spacers
4 M3 × 6mm screws, countersink head
4 M3 × 6mm screws, pan head
1 100kΩ 25T top adjust trimpot (optional – see text)
1 150mm length blue hookup wire
1 150mm length red hookup wire
1 100mm length 0.7mm tinned copper wire

Semiconductors
1 AD588AQ or AD588JQ voltage reference (IC1) – available from Farnell UK, part no. 411700 (see: **http://uk.farnell.com**)
2 15V 1W Zener diode (ZD1,ZD2)
1 5mm green LED (LED1)
2 1N4004 1A diodes (D1,D2)

Capacitors
2 2200µF 25V radial electrolytic
2 470µF 16V radial electrolytic
1 680nF MKT metallised polyester
2 100nF MKT metallised polyester

Resistors (0.25W 1%)
2 1.8kΩ 1 22Ω 2 68Ω

precision than its 'out of the box' ±3mV rating. We have made provision for the trimpot to be added to the PC board for this purpose, but there is no point in fitting the trimpot unless you have access to a very high precision 10V reference.

AD588 availability

That's about it regarding circuit operation. However, before we move on to discuss the project's construction, a quick word about versions of the AD588 chip and its availability.

Analog Devices apparently make five different versions of the AD588, one in a small outline (SOIC-W) SMD package and the others in 16-pin ceramic DIL packages. The four CERDIP devices have different initial error, temperature range and temperature coefficient values. They range from the AD588BQ with 1mV of initial error, a -25°C to +85°C range and 1.5ppm/°C tempco, down to the AD588JQ with 3mV of initial error, 0-70°C range and 3ppm/°C tempco. The AD588BQ is the most expensive (as you would expect), while the AD588JQ is the least expensive.

If you want to build the unit with the highest possible precision and performance, this can be done by using the BQ or KQ versions of the AD588. You may be able to 'special order' these from Farnell, but be warned: the BQ version is considerably more expensive than the AQ version we have specified, and the KQ version is probably much more expensive as well.

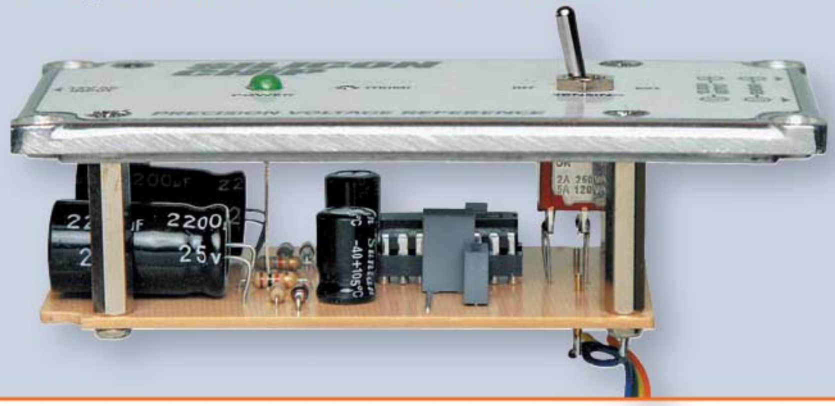
Construction

Apart from the output terminals, virtually all the components are mounted on a single PC board measuring 84mm × 53.5mm. The PC board is available from the *EPE PCB Service*, code 805. The board fits inside a diecast aluminium box (111mm × 60mm × 54mm), which provides both shielding and physical protection. The output and remote sensing terminals are all mounted on one end of the box, while the internal/external sensing switch (S1) is mounted directly on the lid, with short wire leads connecting it to the PC board – see photos.

The PC board itself is mounted on the back of the lid and is supported via four M3 × 25mm tapped metal spacers. Unlike switch S1, the power indicator LED (LED1) mounts directly on the board and protrudes through a hole in the lid.

The parts layout on the PC board and the external wiring are shown in Fig.3. Note that trimpot VR1 is optional, as mentioned earlier. Note also that IC1 should not be soldered directly into the board, but plugged into a *high-quality* 16-pin DIL socket.

Below: the PC board is 'hung' off the lid of the case on M3 × 25mm tapped metal spacers and secured using M3 × 6mm screws. Note the 'extension' leads attached to the switch terminals. Right: the view inside the case with the output terminals mounted and wired back to the board.



Begin the assembly by installing the single wire link on the board, then fit the five fixed resistors, followed by the three non-polarised MKT capacitors. The four electrolytic capacitors can go in next. Be sure to orient these as shown in the overlay diagram and note that the two 2200μF electrolytics are mounted on their side, with their leads bent at right-angles to go through their respective holes in the PC board.

Follow these parts with diodes D1 and D2 and Zener diodes ZD1 and ZD2. LED1 can also be installed. It mounts vertically with the bottom of its plastic body about 22mm above the board surface. Be sure to install all these parts with the correct orientation.

If you are going to use the optional trimpot VR1, fit it now. It must be installed with its top adjustment screw at lower left (this is to align it with the adjustment hole drilled in the lid).

The PC board assembly can now be completed by installing the DC power socket (CON1) and the socket for IC1. Orient the IC socket with its notched end towards the right, as shown in Fig.3. Leave IC1 out for the time being.

Preparing the case

Fig.4 shows the drilling details for the case. Note that the larger holes are best made by using a small pilot

Voltage standards: a brief history

From 1905 to 1972, the national standard of EMF or voltage used by the USA was the Weston Cell, a wet chemical primary cell or 'battery' developed in 1893 by Edward Weston, of Newark in New Jersey. Weston had improved on an earlier 'voltage standard' cell, which had been invented by English engineer Josiah Latimer Clark in 1873. Weston cells were adopted as the International Standard for EMF/voltage in 1911.

Weston's cell had a cadmium-mercury amalgam anode, a pure mercury cathode, a paste of mercurous sulphate as the depolariser and a saturated solution of cadmium sulphate as the electrolyte. It was built in an H-shaped glass container, with the anode at the bottom of one 'leg' and the cathode in the other leg. The electrical connections to the two electrodes were made by platinum wires fused through the glass at the bottom of the legs.

The Weston cell provided an accurate 1.0183V reference with a very low temperature coefficient – much lower than Clark's earlier cell. However, like the Clark cell, it could supply virtually no current and could only be used to provide a reference voltage for high-resistance measuring circuits like the classical 'potentiometer' (a kind of bridge which compared a known proportion of an unknown voltage against the reference voltage, so no current flowed when the two voltages were 'in balance').

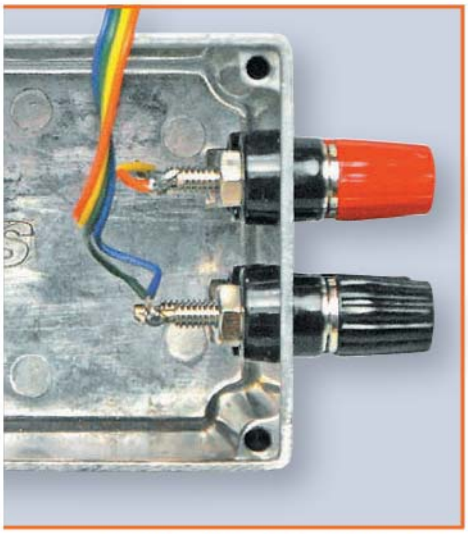
Weston cells were used as the US and International standards for EMF/voltage until 1972, when a new standard came into use: the Josephson Junction Voltage Standard (JJVS). This operates on a very different principle: the phenomenon of quantum-mechanical tunnelling currents which flow between two weakly coupled superconductors separated by a very thin insulating layer.

This is known as a Josephson junction, and the current is known as the Josephson current – named after British physicist Brian David Josephson, who had predicted the effect in 1962. An improved version of the JJVS was subsequently developed In the 1980s: the Josephson Array Voltage Standard or JAVS. By the way, because Josephson junctions and arrays depend on superconductivity for their operation, they must be operated in a liquid nitrogen environment at 77K (–196°C).

Essentially, a JAVS forms a frequency-to-voltage converter, whose conversion factor is exactly reproducible (the agreed figure is 0.4835979GHz/μV). Because frequency can be measured extremely accurately using caesium-beam and caesium fountain standards, the JAVS therefore provides a practical voltage standard of similar accuracy. In fact, the estimated accuracy of current JAVS 10.0V voltage standards is typically quoted as ±0.017ppm.

More information on the Weston Cell can be found in Weston's original US patent (No. 494,827), available on the US Patent Office website.

Further information on the Josephson effect, JJVS and JAVS standards can be found at: **http://en.wikipedia.org/wiki/Josephson_effect** and at: **http://www.nist.gov/eee1/**



drill to start with and then carefully reaming each hole out to its correct size.

Once you have drilled all the holes, mount the output terminals in place and tighten their mounting nuts firmly to prevent them from later coming loose. That done, solder a short length (say 75mm) of insulated hookup wire to the solder spigot at the rear of each terminal, ready to make the connections to the PC board.

Next, attach the front-panel label to the lid. This label can be made from a piece of plain or coloured thin card. The top diagram in Fig.4 can be used as a guide for marking out the required card hole positions. See the main title page for label lettering. It can then be covered with protective self-adhesive transparent film. Attach the label using a thin smear of silicone sealant, then cut out the holes using a sharp hobby knife.

Toggle switch S1 can now be mounted in position on the lid. Tighten its mounting nut firmly, then fit six 15mm lengths of tinned copper wire to its connection lugs (these leads later pass through their corresponding holes in the PC board). Loop the end of each wire through the hole in its switch lug before soldering, to make sure these joints can't come adrift when the outer ends of the wires are soldered to the board copper pads.

The next step is to attach an M3 × 25mm tapped metal spacer to each corner of the PC board. Secure these using four M3 × 6mm pan-head machine screws, then install the leads between the output terminals and their corresponding PC board pads – see Fig.3.

IC1 can now be plugged into its socket. Be sure to orient it correctly and make sure that all its pins go into the socket – ie, not down the outside of the socket or folded under the IC itself. The PC board can then be attached to the lid.

Note that the extension wires fitted to switch S1 must all pass through their matching holes in the PC board, while LED1 must pass through its corresponding hole (C) in the lid. Secure the board to the lid using four countersink-head M3 × 6mm screws, then solder the six switch leads to their board pads.

The unit can now be completed by fastening the lid/PC board assembly to the box using the screws supplied.

Using it

There are no adjustments to be made to the Precision Voltage Reference if you don't have access to a very high precision voltage source to calibrate it. As stated previously, without calibration, it will operate with better than ±3mV precision, as provided by the AD588AQ chip itself.

In that case, it's merely a matter of switching S1 to the internal sensing position and applying power (12V AC) to CON1. LED1 should light immediately to show that the unit is operating and 10.000V ±3mV will

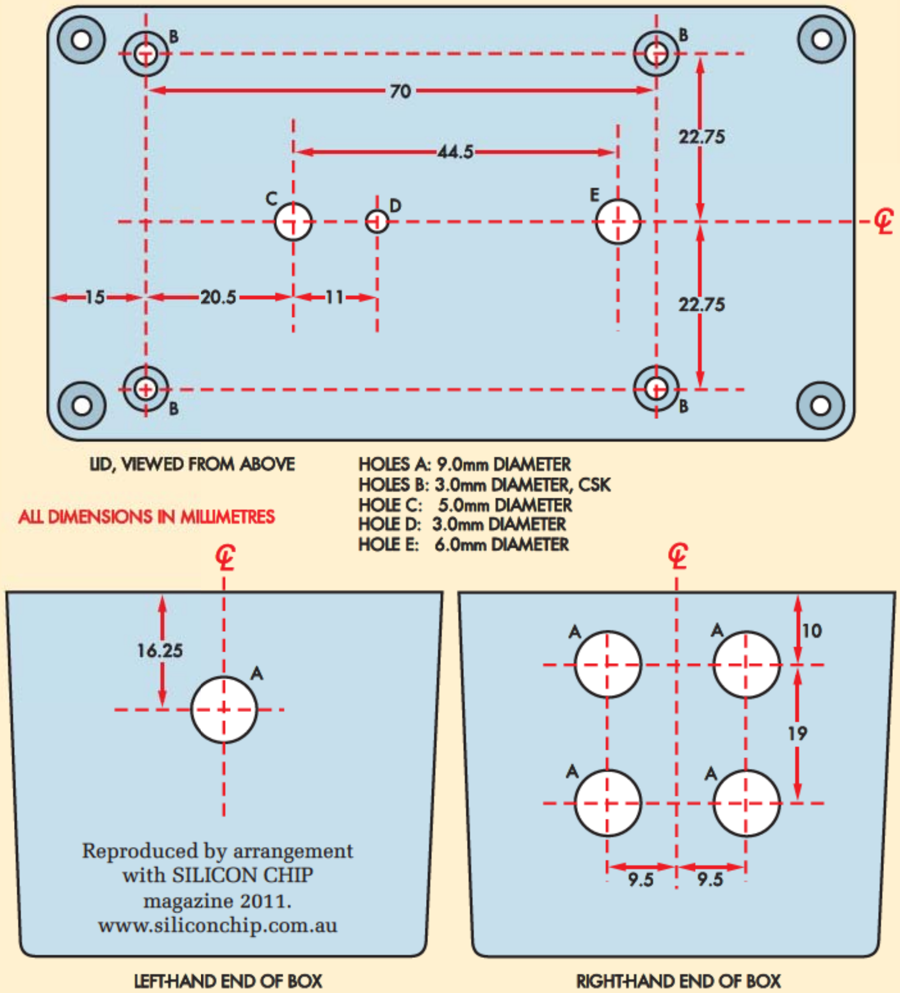


Fig.4: the drilling details for the case. Use a pilot drill to start the larger holes, then step up to the correct size using a larger drill and a tapered reamer.

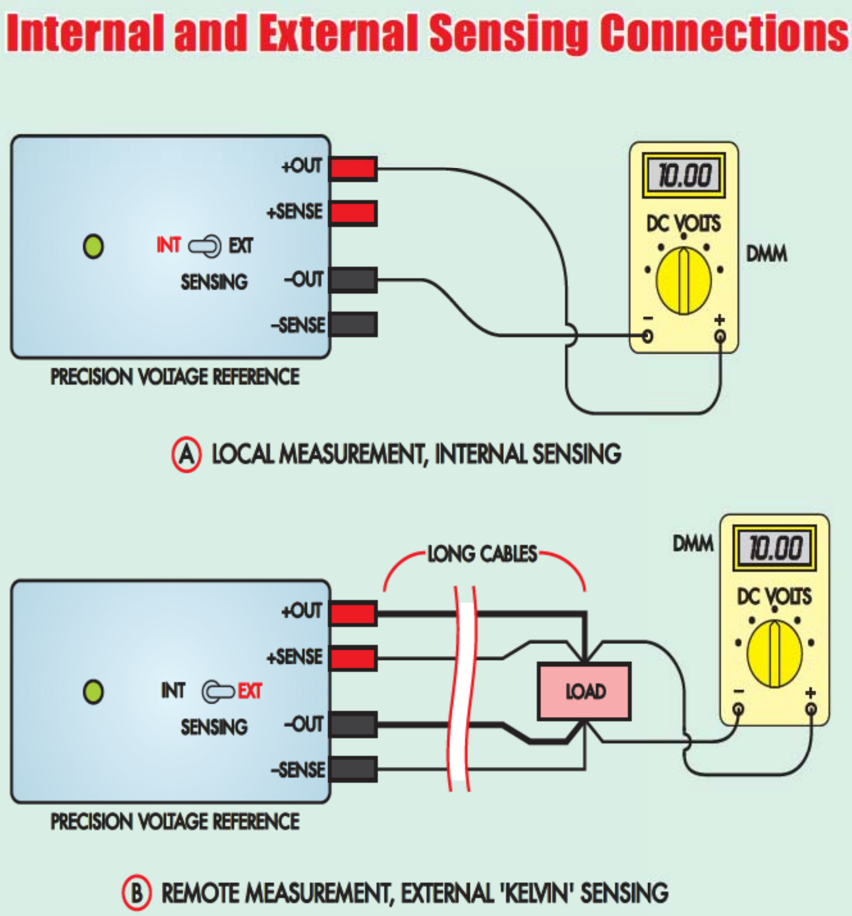


Fig.5: how to connect the Precision DC Voltage Reference for both local (A) and remote (B) measurements (the latter compensates for cable losses).

now be available at the upper output terminals, ready for checking your DMM or whatever.

This 'internal sensing' configuration is the one to use for most simple jobs like DMM calibration, with the DMM input leads connecting directly to the Precision Voltage Reference's upper output terminals.

Cable compensation

The only occasions when it's preferable to use external sensing or 'Kelvin connections' will be when you are supplying the unit's voltage to a load at the end of a cable and the load is drawing sufficient current to introduce a significant voltage drop due to the cable resistance.

In such situations, you'll need to extend the output sensing terminals of the Precision Voltage Reference to the load end of the cable via a second pair of leads, as shown in Fig.5. Then S1 is switched to the 'external sensing' position, so that the AD588 senses the output voltage right at the load end of the cable rather than at its own end. As a result, it will maintain the load voltage at the correct 10.000V, compensating for the cable drop.

All of the foregoing also applies if you build the unit with trimpot VR1 and/or use an AD588BQ/KQ for higher precision. The only complication in these latter situations is that you'll need to compare the output of the Precision DC Voltage Reference with a higher precision source and adjust VR1 to trim its output as close as possible to 10.0000V before you can put it to use. *EPE*