

Built-In Self-Test and Calibration for a Scanning Analog-to-Digital Converter

Onboard calibration capability enables the HP E1413 to calibrate all 64 input channels in under 15 minutes, many times faster than the manual calibration techniques previously required in similar systems.

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The HP E1413 is a 64-channel scanning analog-to-digital converter (ADC) with configurable signal conditioning plug-on (SCP) circuits. The HP E1413 combines signal conditioning, analog multiplexing, analog-to-digital conversion, and digital data processing in one integrated subsystem. Similar subsystems are made up of separate components, often combined by the end user. In such systems it is difficult for the designer of one component to provide end-to-end calibration and self-test since the designer has no control over the design of some components. Final integration is often left to a system integrator or to the end user, who must then add hardware and software engineering to make the system fully functional. Calibration of high-channel-count data acquisition systems of this sort may take many hours or even days, which drives up the cost of ownership.

With design control of all four major components, the HP E1413 design team was able to add considerable value by integrating these components and their interaction during calibration, self-test, and measurement operations. This is accomplished using additional calibration hardware and software that enable stimulus and measurement access to all major components of the measurement hardware.

Calibration and Self-Test Hardware

Three major hardware components were added to the HP E1413 to enable self calibration and test: onboard voltage and resistance reference sources, a calibration bus that connects sources to various points in the circuit, and multiplexers and relays to control measurement and source signal routing.

Fig. 1 shows a simplified diagram of the HP E1413 calibration hardware. The voltage and resistance source section provides a precision 7500-ohm resistor, a programmable voltage source, and a short circuit (zero voltage) reference. The calibration bus (CALBUS) connects the various sources either to the input of the signal conditioning plug-on boards or to an external multimeter via the front-panel connector. The 64 calibration relays serve two purposes: first, to allow calibration sources to enter the signal conditioning of a channel, and second, to isolate the HP E1413 input stages from the customer wiring when power is lost or when excessive input voltages are detected. The semiconductor multiplexers MUX B and MUX C allow the reference sources to be connected to the calibration bus or directly into the ADC input amplifier stage.

Different Types of Calibration

The objectives of the HP 1413's built-in calibration are to provide high measurement accuracy and to make calibration simple and fast for customers, including measurement systems with more than one HP E1413. The calibration tree in Fig. 2 shows that there are several types of calibration available for the HP E1413. The three main types are calibrations using an external standard multimeter, working calibrations including those done using the multimeter, and internal self-calibrations. Fig. 3 shows the HP E1413 components calibrated by these different calibration types.

Working calibrations and internal calibrations are depicted in Fig. 3 as nested boxes because these calibrations are related in a hierarchical manner. Subsets of these major calibrations are accessible to the customer because their speed and convenience make them individually useful (see "A Hierarchy of Calibration Commands," on page 28). For best results, internal self-calibrations and working calibrations should be performed in the HP E1413 working environment. This means the HP E1413 should be warmed to normal operating temperature with normal operating airflow from the VXibus cardcage. There can be significant temperature and airflow differences inside a VXibus mainframe between a standards laboratory environment and the working environment depending on ambient temperatures and how many cards are loaded into the VXibus mainframe. An external multimeter with its heated reference and internally controlled airflow can handle these environment changes better than an HP E1413.

As the first stage of calibration, the external transfer standard digital multimeter should be calibrated in a standards laboratory. This multimeter should be a 6½-digit (21-bit) or better multimeter (such as the HP E1410 or the HP 3458A digital multimeters). The external multimeter is then taken to the HP E1413 operating environment where it can be used to calibrate multiple 16-bit HP E1413s. This makes the standards laboratory's calibration easier, and an HP E1413 calibrated in its working environment will be more accurate in that environment. In some systems, the digital multimeter is dedicated to the test system and wired to the HP E1413 calibration bus connectors and is only removed when the multimeter requires recalibration.

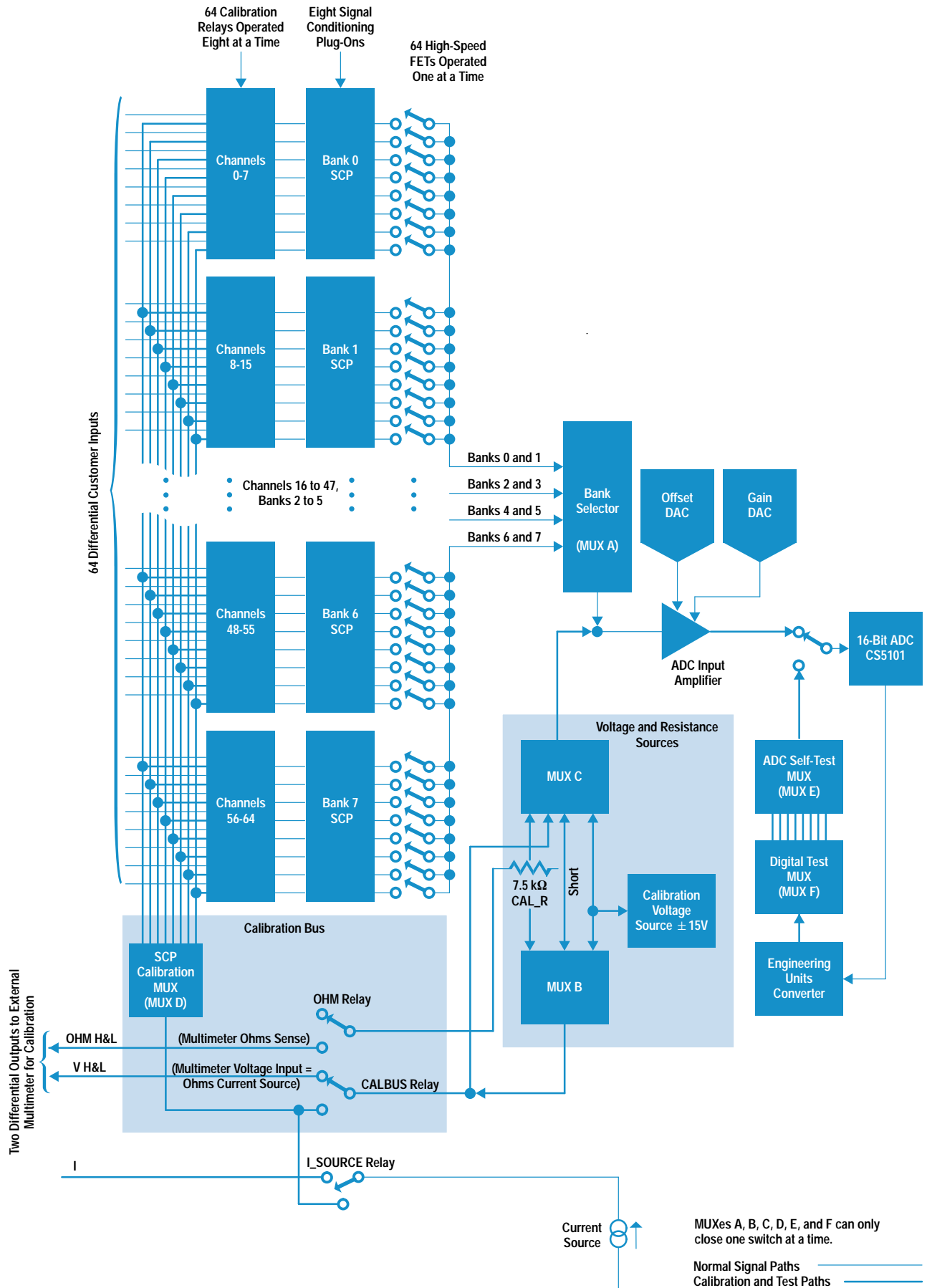


Fig. 1. A block diagram of the HP E1413 circuits used for calibration and test.

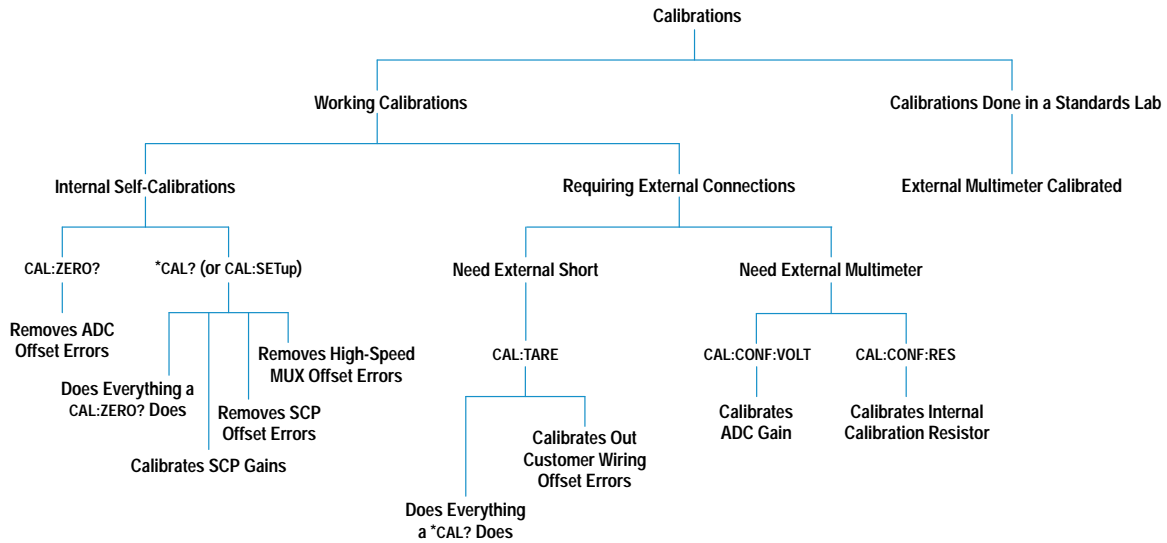


Fig. 2. HP E1413 calibration tree.

External HP E1413 Working Calibrations

External working calibration of the HP 1413 requires a multimeter to establish ADC gain calibration and the exact value of the precision resistor in the HP E1413. The ADC gain calibration forces the gain of the HP E1413 ADC to match the gain of the external multimeter on each of the five measurement ranges of the HP E1413. This calibration takes less than

five minutes using an external controller sending a sequence of setup and measure commands for each measurement range.

In the following discussion it is assumed that the multimeter is an HP 3458A DMM or other HP bench-type multimeter. Other types of multimeters may require different connections.

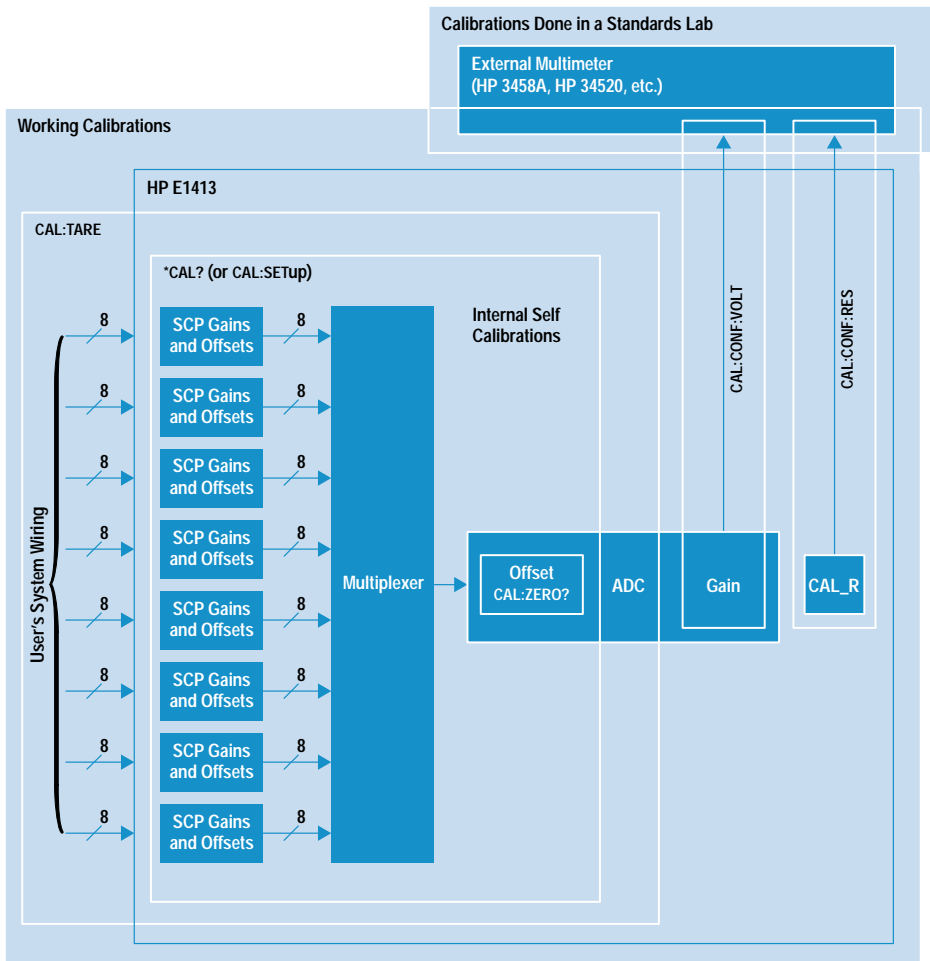


Fig. 3. Areas of the HP E1413 affected by the different calibration types.

A Hierarchy of Calibration Commands

Calibration of the HP E1413 ADC module can be performed using only one external instrument, a digital multimeter. As implied in Fig. 2 in the accompanying article there is a hierarchy of calibration types in the HP E1413 that can be invoked by the calibration commands.

At the highest level are calibration commands that evaluate the HP E1413 transfer-standard components. These commands, which include CALibrate:CONFigure:VOLTage and CALibrate:CONFigure:RESistance, allow an external digital multimeter to make measurements to establish the value of key parameters in the HP E1413 circuitry. These key parameters are the ADC input amplifier gain on each of five ranges and the value of the precision resistor in the HP E1413. All other HP E1413 calibrations are based on these six parameters.

Below these calibrations are the working calibrations, which include CAL:TARE, *CAL?, and CAL:ZERO?. These calibrations affect smaller and smaller parts of the HP E1413 and are shown in Fig. 2 as being entirely contained within the previous type of calibration. The innermost (smallest span) calibration is CALibrate:ZERO?. CAL:ZERO? is used only to correct the ADC for drift in voltage offset, which usually results from temperature change. This command is very fast (less than five seconds) and can be executed frequently to compensate for any changes in the temperature or flow rate of the air cooling the HP E1413.

The *CAL? command is used to correct for any voltage offset caused by the SCPs or the 64-channel multiplexer, and for any gain errors in the SCPs. For example, if channel 1 of a SCP has a nominal gain of eight but an actual gain of 7.998, the *CAL? command will correct for the difference by adjusting the ADC input amplifier gain upward by a factor of 1.00025 whenever channel 1 is being measured. Every channel containing an input SCP is calibrated this way during the execution of the *CAL? command. Since up to 64 channels are calibrated, the *CAL? command can be time-consuming, usually requiring 5 minutes or more to complete. The onboard current source and any current or voltage sources on the SCPs are also calibrated during *CAL?. Fig. 3 in the accompanying article shows that CAL:ZERO? is also performed by *CAL?.

The outermost layer of calibration is CAL:TARE which adjusts all measurement channels for any voltage induced by customer wiring. To understand the tare calibration, consider an analogy from weight measurement. A customer wishing to buy rice by weight places the rice into a plastic container on the scale. The customer does not wish to pay for the weight of the plastic container in addition to the rice. So the container is first weighed alone (this is the tare weight), then its weight is subtracted from the total weight of the container and rice. In some measurement systems, the wiring between the HP E1413 and the transducer may cause some small voltage to be added to the actual transducer output voltage. Any measurement of transducer voltage will include this small additional voltage caused by the wiring. Therefore, the wiring is short circuited at the transducer, and the tare voltage is measured for each channel. This value is used during *CAL? to adjust calibration so that the tare voltage is subtracted from all future measurements on that channel. Again, as Fig. 3 shows, *CAL? and CAL:ZERO? calibrations are performed by CAL:TARE.

At the start of the calibration the HP E1413 is commanded to put out a voltage from its voltage source to the external calibration connector (connection path = calibration source to MUX B to the CALBUS relay to V H&L to the multimeter voltage input).†

Next, the HP 3458A multimeter reads the voltage and passes the reading back to the HP E1413. The HP E1413 calibration firmware now connects the source to the ADC (connection path = calibration source to MUX C to the ADC input amplifier to the ADC) and adjusts the input amplifier's gain to match the value of the reading from the external voltmeter. The gain of the HP E1413 ADC can only be calibrated in this

manner, so the stability of this gain is important to measurement accuracy.

The precision resistor is also measured by an HP 3458A multimeter using a very similar setup and measure sequence (connection path = multimeter ohms current source (voltage input) to V H&L to the CALBUS relay to MUX B to CAL_R and multimeter ohms sense input to OHM H&L to the OHM relay to CAL_R). The resistance measurement made by the external multimeter is passed to the HP E1413 and stored for use during internal self-calibration.

For best accuracy before an important data run, the ADC gain and the precision resistor can be recalibrated in less than five minutes if the external voltmeter is left connected (connection path = HP 3458A voltage input/ohms current source to V H&L and HP 3458A ohms sense input to OHM H&L). Multiple HP E1413s can be permanently wired in parallel, but only one HP E1413 can be doing these calibrations at a time. If an HP E1413 is not doing these calibrations, it will disconnect itself from the external multimeter by opening the OHM and CALBUS relays.

Internal HP E1413 Calibrations

The first internal calibration removes the offset errors in the ADC input amplifier with the command CAL:ZERO?. This calibration, which is used to remove any offset error caused by a temperature change in the ADC input amplifier, is entirely self-contained and requires no external equipment. It is performed by the onboard microprocessor by connecting the ADC input to a reference short and adjusting the ADC offset DACs to obtain a zero reading on each of the five ADC voltage ranges. This is similar to a multimeter's autozero function except that it is not done automatically, but on command. The CAL:ZERO? calibration takes less than five seconds to run and should be executed frequently (every five minutes if possible).

The second internal calibration is invoked with the SCPI *CAL? command and is a complete internal self-calibration that removes errors between the customer inputs and the ADC chip. These errors include SCP gain errors and any offset caused by the SCPs or the 64-channel multiplexer. This internal calibration also adjusts the value of voltage or current supplied by the SCPs to external transducers. The 7500-ohm internal calibration resistor is used to convert the HP E1413's internal current source and the SCP current sources to a voltage that is measured and calibrated by the internal ADC.

The *CAL? function measures and corrects HP E1413 offset and errors on a channel by channel basis. For offset calibration, the SCP inputs are connected one at a time to the same internal short used during a tare calibration (described below) (connection path = one bank of calibration relays to MUX D to CALBUS relay to MUX B to short). Next, the ADC output is forced to the value of the voltage difference between the internal short and the customer supplied short stored during the tare calibration by adjusting the value of the ADC offset DAC.

For gain calibrations, a measured input voltage is applied to each channel of the SCPs (connection path = calibration source to MUX C to ADC input, then calibration source to

† Refer to Fig. 1 for the components given in these calibration connections.

MUX B to CALBUS relay to MUX D to a bank of calibration relays to the associated SCP and finally to the ADC input amplifier). The output voltage of the ADC input amplifier is now adjusted to make it match the gain of the SCP channel. The *CAL? should be done immediately before an important test and any time there has been a significant temperature change. The driver allows multiple HP E1413's to be calibrated with the *CAL? command at the same time. When the HP E1413 contains SCPs with slow filters, no external voltage should be applied to the input terminals during *CAL?.

A tare calibration measures and corrects for the customer's and HP E1413's offset errors on a channel by channel basis. The offset errors this calibration removes come from the SCPs, the ADC input amplifier, and the ADC. There are 64 offset calibration constants that represent the voltage difference between an internal short (connection path = one bank of calibration relays to MUX D to CALBUS relay to MUX B to short) and the customer-supplied short (connection path = customer input to a calibration relay to an SCP to an FET switch to MUX A to the ADC input). This is the normal connection path when an HP E1413 is connected to measure customer transducers. When measuring the customer short, the measurement period is set to reject power line noise. Tare calibration requires from 5 to over 30 minutes depending on the SCPs that are installed, since the SCP filters must settle for external measurements. Each time CAL:TARE is executed, a full set of *CAL? constants must be generated. The SCPI driver allows multiple HP E1413's to be tare calibrated at the same time because of the length of time required. Tare calibration is usually a one-time calibration that is done the first time customer wiring is attached. However, it should be performed whenever the customer wiring offset changes.

Analog Self-Test

Analog self-test uses the same hardware as calibration. Three sections are associated with analog self-tests. The first section is centered around a digital multiplexer (MUX F in Fig. 1).

Eight tests are used to ensure that the control signals from the onboard microprocessor are correctly getting to the ADC, relay drivers, and multiplexer drivers. The second section is centered around the analog multiplexer in the ADC (MUX E in Fig. 1). For this section, 24 tests are used to ensure that the analog portion of the ADC is working. The third and final section uses the calibration hardware to connect to the calibration paths and make sure the offsets and gains are within the three-sigma limits of the hardware. The third section also tests the SCPs. There are about 14 tests in this section, some of which are run on each channel. The actual number of tests and which tests are run depends on the type of SCPs installed. This section of self-test is the most time-consuming because some of the tests have to be run on each of the 64 channels. As with the calibrations, if SCPs with slow filters are installed the self-test will take longer to let the voltages settle before taking measurements. If only HP E1413 Option 11 SCPs (with no filters) are installed, the self-test will take less than six minutes. If eight HP E1413 Option 12 SCPs (with 10-Hz filters) are installed, the self-test can take over 30 minutes. The self-test should be run only after the HP E1413 has been allowed to warm up in its operating environment. An HP E1413 may fail self-test during the first five minutes after power-up because test measurements may drift out of limits as the circuitry warms up.

Conclusion

By adding a modest amount of circuitry and firmware to the HP E1413, the speed, simplicity, and accuracy of calibration were improved. The circuitry includes relays and analog multiplexers to route calibration signals to different sections of the instrument. The only external instrument required for calibration is a digital multimeter, and most calibration functions are performed in an entirely self-contained manner. The same circuitry used for calibration is also used for self-test. During self-test various sections of the instrument are evaluated and diagnostic functions report failures to a very fine degree.