dominant factor contributing to the long-term stability of an instrument is the ability to hold a calibration adjustment. Environmental factors are of major importance here. The HP 3457A has entirely electronic calibration. Electronic correction cannot account for future changes to mechanical settings, so electronic calibration means that there are no mechanical adjustments in the circuits that can affect calibration integrity. The third factor in DMM long-term stability is the instrument voltage reference. In an instrument with electronic calibration like the HP 3457A's, the voltage reference is by far the dominant term. However, if this were not the case, the calibration adjustment stability could be of similar or greater significance.

The HP 3457A uses a pretested voltage reference assembly to guarantee the long-term stability characteristics of the instrument. Each reference assembly is monitored for a two-month period in a temperature stabilized environment. Individual reference drift rates are determined and compared against acceptable limits. Reference boards that drift beyond these limits are rejected. Much effort was placed on fine-tuning our ability to test and characterize reference assemblies in a production environment so that a reliably low-drift voltage reference could be achieved. Fig. 9 shows the results obtained. The mean long-term drift of the references for one year is characterized to be approximately 3.5 ppm. Also shown is the sample mean plus three standard deviations. This data shows an expected maximum drift of approximately 12 ppm in one year, a significant improvement. The earlier HP 3456A has taken advantage of these results also and an amended data sheet has been issued to reflect this enhancement. Reduced instrument drift translates directly to a lower cost of ownership. Costly system downtime resulting from frequent recalibration cycles can be reduced.

Frequency Counter Technique

The HP 3457A Multimeter can make floating frequency measurements on signals ranging from 10 Hz to 1.5 MHz at levels from 10 mV to 300V. The DMM automatically acquires the input signal, performs the necessary range selection, and measures the input frequency.

This process does not require any user intervention to set up a trigger level control. All signal conditioning is performed by the ac voltage front end and is designed to ensure that the proper internal levels are presented to frequency comparator U3 (Fig. 10).

As mentioned previously, the ADC has external digital hardware to support the measurement of run-down slope times in 0.5-μs increments. This same hardware is used in the frequency measurement mode to accumulate the actual measurement gate time. Since by definition, frequency is cycles or zero crossings (A) per unit of time (B), the job becomes one of measuring these parameters and computing the result (A/B). To do this, the DMM measures the number of zero crossings during the gate period.

Referring again to Fig. 10, one can see that the 8051 microcomputer has two 16-bit counters that are prescaled by 4-bit counters U5 and U6. The 8051 outputs a measurement gate of approximately 0.5 second (the actual length is unimportant). The frequency comparator generates a logic-level signal at the measured signal's zero-crossing rate, which is used to clock flip-flop U4 and the zero-crossing counter U6. U4 provides an enable signal to the time interval (U5) and zero-crossing (U6) counters as long as the 8051 measure gate signal is present. After the enable signal, both counters are read by the 8051, including the external prescalers, and the input frequency is computed as A/B hertz. The actual measurement gate is always guaranteed to be at least one period of the input frequency,

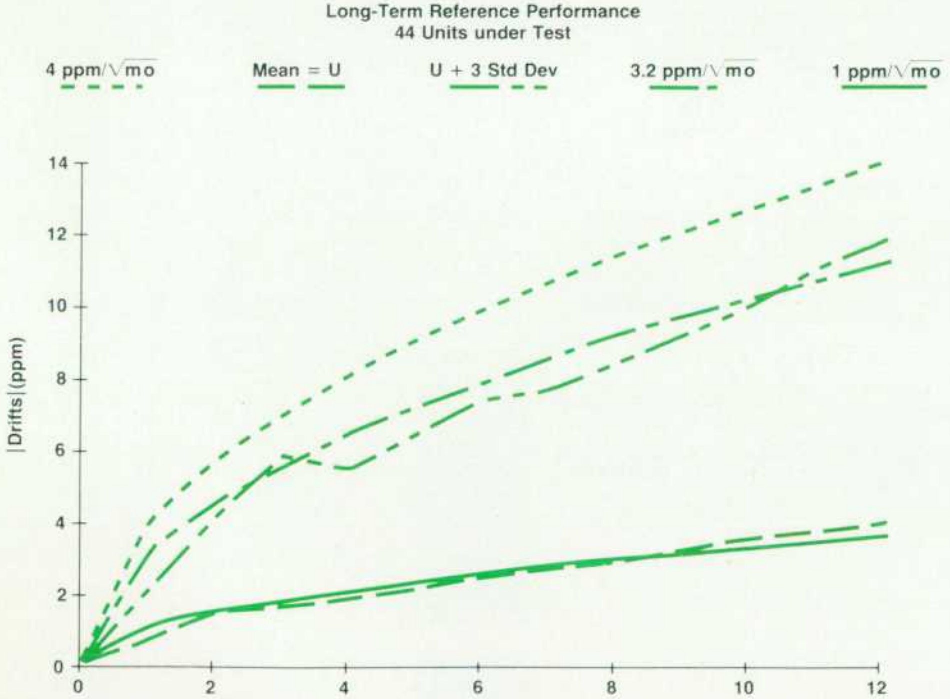

Fig. 9. *Characterized voltage reference drift mean and mean plus 3σ (σ = standard deviation). The 4 ppm/$\sqrt{month}$ represents the reference drift contribution included in the HP 3457A's specifications.*

thanks to the operation of U4. This technique yields a constant measurement resolution of 1 ppm independent of the input frequency two times per second. The frequency is then electronically gain-corrected to yield accurate results.

The benefits of this counter technique are:

- Floating frequency measurements 450V peak from earth ground
- Autoranged input leveling for easy measurements
- Selectable frequency measurements on ac voltage, ac + dc voltage, ac current, or ac + dc current functions
- Constant 1-ppm resolution at any frequency within range.

AC Section

The ac measurement functions of the HP 3457A are voltage, current, frequency, and period. They can be used in either an ac coupled mode or a dc coupled mode. For ac current measurements, the input signal is routed through the same set of shunt resistors used for dc current measurements and the ac voltage drop across those resistors is measured. The current ranges provided are 30 mA, 300 mA, and 3A rms. However, the high input current limit is 1A. Five voltage ranges are provided in decade steps from 30 mV rms to 300V rms full scale. The 30-mV full scale range allows good measurement accuracy of small signal inputs. The ability to measure the frequency of these small signals is another useful feature of the HP 3457A.

The circuitry of the ac section, Fig. 11, consists of two compensated attenuators, two $\times 10$ gain stages, an rms converter, a filter, and various control circuits. Many voltmeters make ac measurements at frequencies up to 100 kHz, but it was desired to have the HP 3457A operate to 1 MHz. To achieve this, compensated RC attenuators are used. At low frequencies the attenuators are resistive dividers, while at high frequencies they act as capacitive dividers. To equalize the high-frequency and low-frequency responses of such an attenuator, a manual adjustment of one of the capacitance elements is often used. In the HP 3457A, that adjustment is performed electronically with the use of the Autocal function. By adding a third capacitor to the attenuator and driving it with a scaled value of the input signal, the capacitive attenuator can be controlled so that a flat frequency response is produced. The signal fed back to the capacitor is controlled by a DAC (digital-to-analog converter) operated as a variable attenuator, as shown in Fig. 12.

The response of the RC attenuator to a pulse input is directly related to the accuracy of its compensation. Therefore, during Autocal, a pulse is internally generated and applied to the input of the ac board. Its time response is measured by the ADC and the change needed in the feedback signal is calculated. The feedback is adjusted and the pulse is remeasured. This process, shown in Fig. 12, is repeated until the desired response is achieved. With this technique the flatness of the attenuator can be set quite rapidly without the need for external equipment.

Range switching is accomplished with the use of FET switches on the input attenuators and following the first gain stage. An rms converter follows the second gain stage and a filter is included in the rms section to reduce the output ripple of the converter. The filter has two bandwidth settings controlled by the ACBAND function; this provides some flexibility in reading speed. Either setting can be used to 1 MHz, but if frequencies below 400 Hz are to be measured or maximum filtering is desired, a number between 1 and 399 is used in the ACBAND function, e.g., ACBAND 20. For higher frequencies or faster response, the user can set the ACBAND function to 400 or greater. The output of the second stage also drives a comparator whose output is used by the frequency counter.

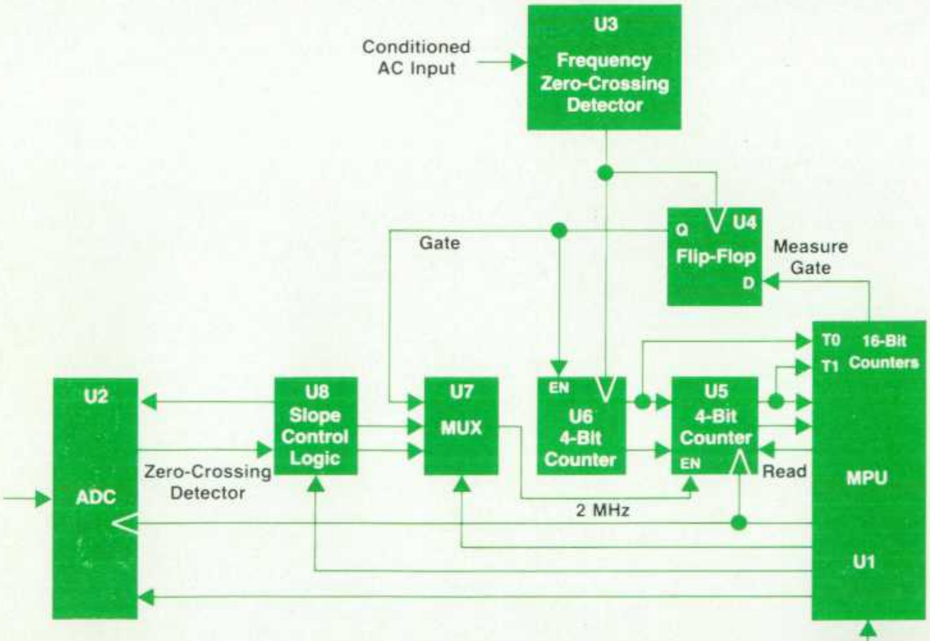

Fig. 10. *Simplified schematic diagram of the analog-to-digital converter and frequency counter in the HP 3457A DMM.*

Calibration RAM Protection

In recent years, software calibration algorithms have become common. By doing the instrument calibration in software, it is possible to eliminate all hand adjustments, and thereby highly automate the calibration process. Typically, such an algorithm requires the user to place some known signal at the inputs to the instrument. The instrument then uses this value to generate appropriate calibration constants. One drawback of this practice is that these constants must be stored in read/write memory. Should this memory be contaminated, the instrument would no longer make accurate measurements. Contamination may be the result of a processor run amok after an electrostatic discharge or some other transient condition that would not normally have serious repercussions.

A frequent solution to this problem is to provide some sort of mechanical device that prevents the processor from writing to calibration memory. This mechanical device might be a simple switch, or a key in a lock. In the case of a key, the calibration is further protected by limiting access to the key. The disadvantages of this approach are that calibration then requires operator intervention, and that the instrument remains vulnerable if the device is left in the wrong position.

The HP 3457A uses a special circuit that prevents the processor from writing to calibration memory unless it can ensure that the processor is executing in a well-behaved manner. This circuit detects that the calibration algorithm has been invoked and completed without error. Special checks are made on various processor status lines to ensure that the processor has not run amok. The instrument software also provides the security of a key by allowing the user to specify a password that must be entered before calibration is allowed. The HP 3457A allows an entire calibration to be done under the control of a computer, with no operator intervention.

The calibration RAM protection circuit checks several events to guarantee that writes to RAM should be allowed. The most fundamental portion of the algorithm is that a processor reset must occur, followed after exactly four milliseconds by a pulse from an output port. Although other things are monitored, these events contain the gist of the algorithm. The requirement that the processor be reset does two things. First, it guarantees that the processor is executing instructions normally. Second, it synchronizes the hardware with the software. The reason for requiring a short pulse exactly four milliseconds after the reset is to ensure that the software is requesting a calibration write enable. This sequence is virtually impossible to generate randomly.

The software procedure is as follows. First, the calibration constants are generated. Then, a reset is generated. The reset routine then determines if the reset was actually a calibration request. This is done by checking numerous strategic variables. If these checks all pass, the remainder of the four-millisecond wait is generated, followed by the pulse and the writes to calibration RAM.

Since the software tests are done immediately after reset, and the hardware requires the reset to enable calibration RAM writes, we have guaranteed that the software tests are all done and passed before calibration RAM is enabled. Herein lies the key to the technique. We have guaranteed that the software tests have been executed and passed instead of merely moving the point of vulnerability to just after the tests have been completed. The hardware is necessary to ensure that these checks are executed and passed. It is then the responsibility of the software to see that sufficiently robust checks are included. If the hardware were not present, the possibility of a randomly executing processor entering the code right after the software checks and writing to calibration RAM exists. But the hardware scheme prevents this by tying the reset event, which initiates the software checks, to the enabling of the calibration RAM.

To ensure the integrity of the calibration memory, we subjected the instrument to large magnetic fields and 15-kV static discharges, and ran tests in which the processor was intentionally traumatized thousands of times. In all of these tests, the calibration protection circuit prevented any loss of calibration constants.

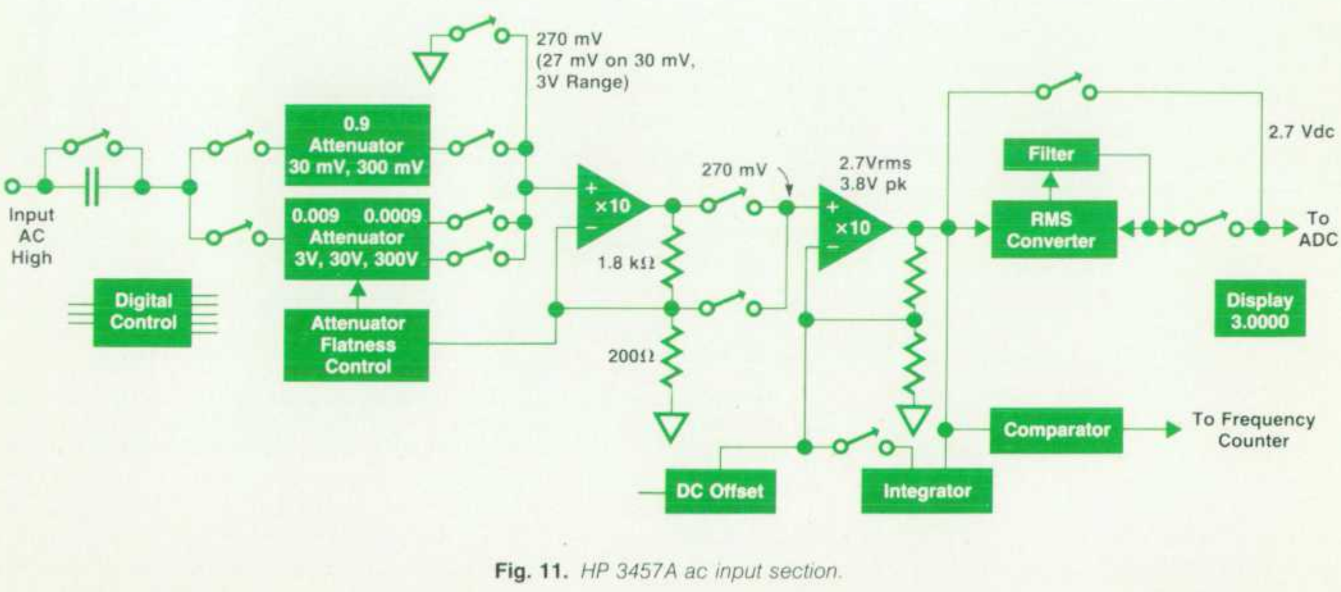

Fig. 11. *HP 3457A ac input section.*

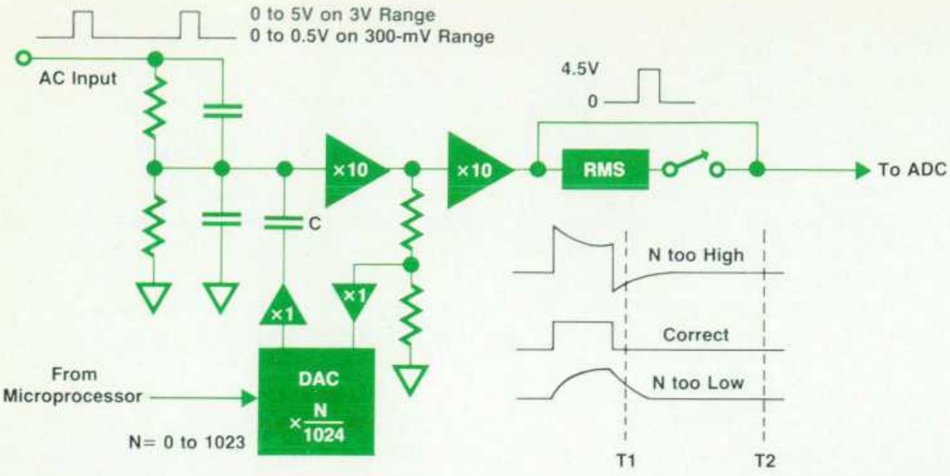

Fig. 12. *Attenuator compensation adjustment technique. When the feedback is correctly adjusted, the voltage readings at T1 and T2 will be equal.*

Command Language

The HP 3457A has many different measurement modes and makes a wide variety of measurements. One of the challenges in the design of the HP 3457A was to provide the user with a convenient technique to access this functionality.

An ideal language lets the user communicate to the instrument the measurement requirements in the terms in which the user perceives the measurement. The instrument must translate these parameters into those required by the hardware. Another important aspect of an instrumentation language is the ability to apply the same language to configure other instruments. By designing a language that describes the measurement parameters instead of the instrument parameters, this is also realized.

The HP 3457A language is made up of about 100 mnemonic instructions. Of these instructions, only about a dozen are required to meet most measurement needs. Each instruction can have several parameters. For convenience, defaults are available for each parameter except in rare circumstances where the value is extremely critical, e.g., calibration.

An example of a measurement-oriented instruction is the function command. A typical function command might be ACV 17,0.001. This indicates that an ac voltage measurement should be made on a range capable of accepting at least 17 volts, and that the measurement should be made to a resolution of at least 0.001%. Notice that this instruction could be used to configure any instrument capable of making this measurement since no part of the instruction is specific to the HP 3457A. Future HP multimeter products will use this same language, which is called HP-ML (HP Multimeter Language).

Reading Storage

A feature of the HP 3457A is its ability to store over 1000 readings internally. This can provide significant speed advantages in systems because many measurements can be made and the overhead of reading from the instrument need only be encountered once. This capability is also important when the measurements need to be made faster than they can be sent to a controller. The results can be extracted from memory either by reading from the instrument, in which case the reading memory behaves like a buffer between the instrument and the computer, or by explicitly specifying a group of readings to be recalled.

Readings can be placed in memory and read out in any one of four different formats: 16-bit integer, 32-bit integer, 32-bit real (IEEE 754), or ASCII (the number is converted to an ASCII string). Since the output format is independent of the storage format, it is possible to optimize the timing for a particular measurement. For instance, in a situation where computer time is of concern, the instrument can be configured to store readings in the same format that will be output to the computer. When the computer is ready, the formatted readings can be sent out at high speed. When the reading rate is the critical factor, the instrument should be configured to store readings in the format most convenient to the voltmeter, thus optimizing the reading rate.

When the readings are recalled from memory they can be converted to the format most convenient to the computer.

Mechanical Design

Product design plays a key role in the manufacturing cost of an instrument. To minimize factory cost, a major HP 3457A objective was to minimize part count, part cost, and assembly labor. Other objectives were to keep the mechanical design one phase ahead of the electrical design, to strive for simplicity and to use existing technologies.

It was decided early in the project to use an existing plastic package. This package was originally designed for the HP 3421A Data Acquisition/Control Unit and has since been adapted to the HP 3488A Switch Control Unit. Because this package is plastic, shielding and internal temperature rise were concerns, more so than with traditional metal packages. In addition, environmental requirements such as shock, vibration, and drop tests, as well as safety issues had to be carefully considered. It was desirable for manufacturing to build only one configuration. This required that the customer have access to line voltage selector switches and be able to install the optional multiplexer card options.

To achieve these objectives and requirements, the initial layout was closely evaluated using cardboard mockups and design reviews. As the design evolved it became obvious that hardware such as screws and fasteners could easily be eliminated by using snap-together parts. These included the shield around the isolated analog section, the card guide for the optional plug-in multiplexer cards, standoffs for the