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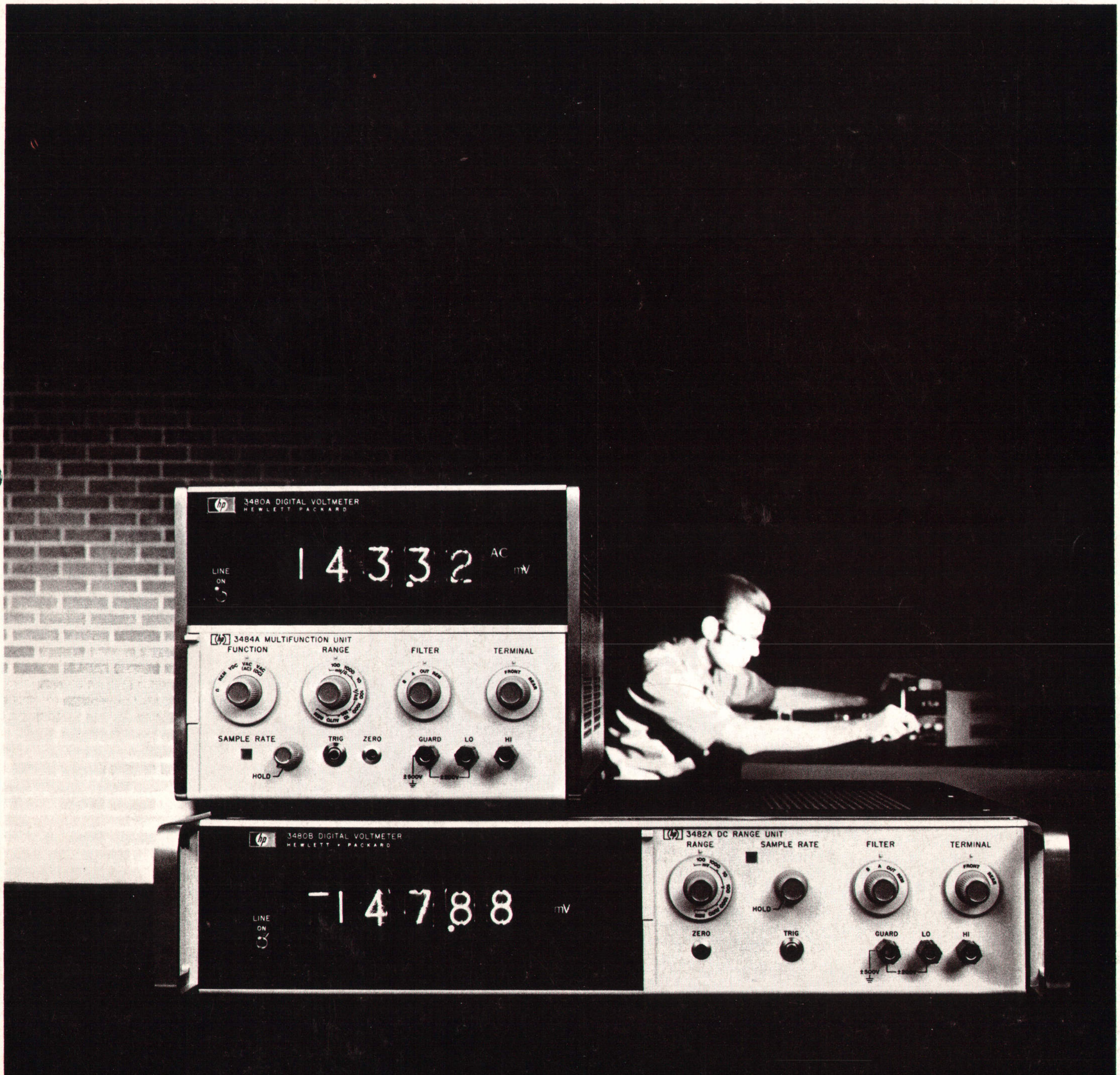

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A New High-Speed Multifunction DVM

Plug-ins provide true rms ac capability as well as dc and ohms. Reading speed is 1000 per second of ohms and dc.

By Craig Walter, H. Mac Juneau and Lee Thompson

THERE IS A NEED today for 'horizontal expansion' of the capability to measure dc and ac voltage, and resistance—more accuracy in general applications, with good repeatability. In addition, there is a need to reduce the difficulty of eliminating errors under conditions such as making a floating dc measurement in the presence of both common mode and normal mode error signals, or avoiding large errors when measuring distorted sinusoids or waveforms without zero axis symmetry.

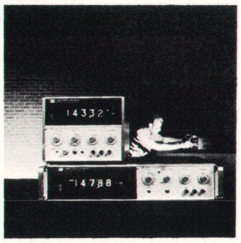
For bench users, the need is not to make an already difficult measurement with greater precision, but there is a need to make measurements of *adequate* resolution with more ease and reliability. The measurement problems of the bench user have often been ignored in favor of 'greater' or 'more' rather than 'better'. Recently some instruments have been compromised in favor of the 'system' aura—instrument optimization for system use at the expense of, rather than for, the bench user.

The system user can generally find a unique solution to his unique problem. Having found it, he can operate his system properly. He has the time and generally the capital to find unique solutions to his individual problems.

The bench user has a difficult problem each time he uses the instrument. A lash-up that provides optimum results for a measurement one day cannot be expected to yield the same results if the measurement problem changes. The bench user's measurement problems vary from day to day, and he seldom has time or money to invent solutions for each problem.

Nevertheless, the problems associated with instrument use in both applications are not totally unique to either. A great degree of commonality exists. Providing solutions for the common measurement errors that exist in bench applications *can* result in an instrument useful for systems use at little or small expense to the bench user.

Indeed, the primary distinction between the two application areas often is in the speed (and end use) of the measurement, not in the measurement itself. The instrument, in bench applications, is interfaced to a human; in system applications, to a machine. If the same measurement can be made with greater speed (and if, in addition, the data collected is easily transferred to a machine as well as a human), the instrument can also satisfy many system requirements. It should be possible, then, to provide an instrument that could properly be called a hybrid —optimized for bench and widely useful in systems.



Cover: *Both half-module and rack versions of the Hewlett-Packard Model 3480A/B are shown. Its reading speed is 1000 per second for ohms and dc to 1000 volts. True rms ac is an option. This article discusses dc processing and preconditioning as related to the Model 3480A/B. The ac conversion technique will be covered in detail in a future issue of the Hewlett-Packard Journal.*

In this Issue:

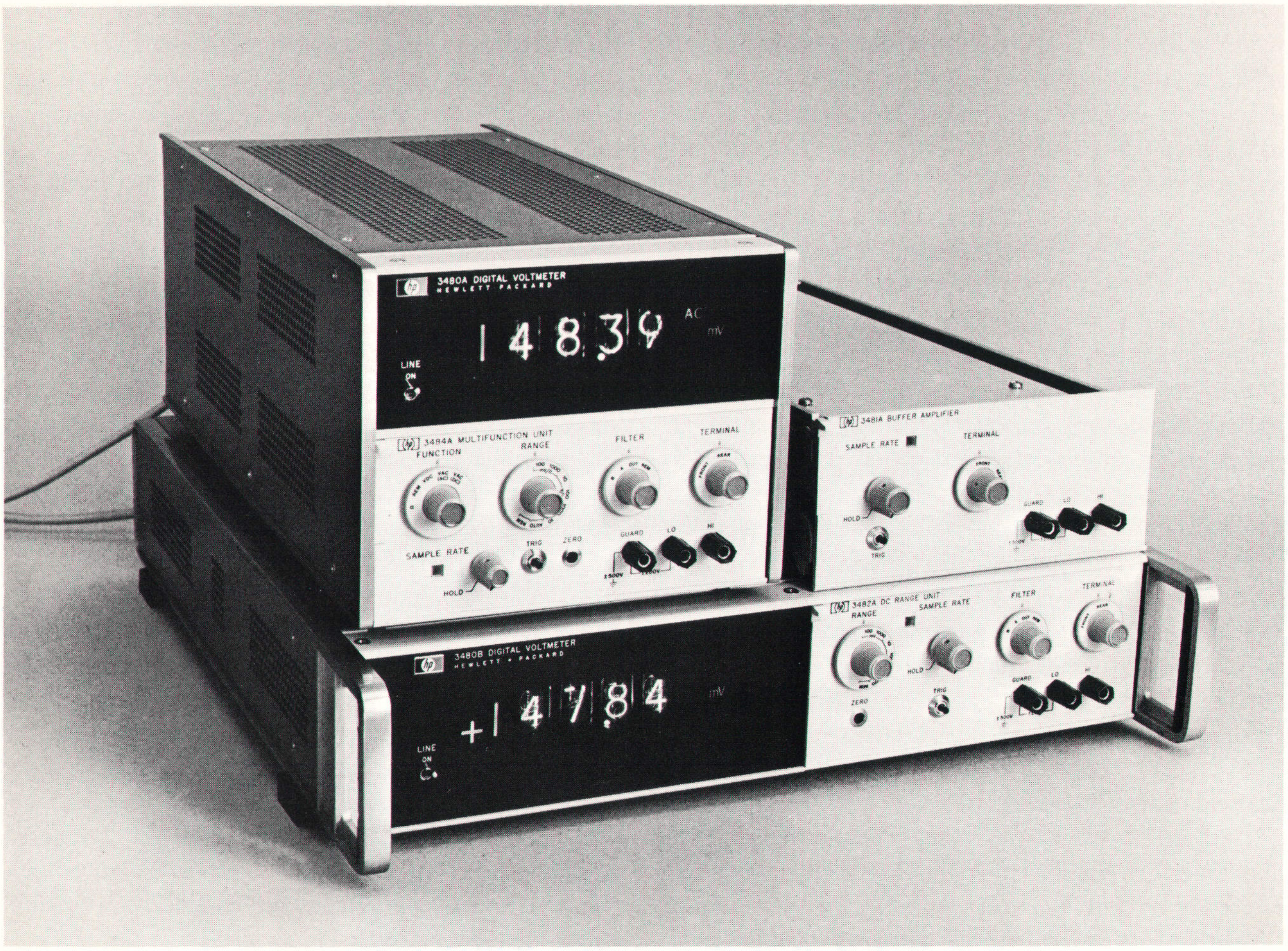


Fig. 1. *This new Hewlett-Packard Model 3480A/B is a high speed multi-function DVM capable of making 1000 readings per second up to 1000 volts dc, and ohms down to 100 ohms full scale. It comes in both half module and rack versions. Also shown here are the Models 3481A Buffer Amplifier (with one 10 V dc range), 3482A DC Range Unit and the 3484A Multifunction Unit.*

Bench Features

Many features of the new HP Model 3480A/B, Fig. 1, which may seem mundane by themselves, combine to make the instrument easy to use. The display is easily readable, function and range information and the instrument's functions are readily apparent. Autoranging is complete through all ranges and functions. The first reading after an autorange cycle will be correct. The sample rate is fully controllable, from a sample initiated by a front panel pushbutton to >25 readings per second; higher sample rates—to 1000 per second—can be initiated by external commands. Selectable filtering is provided for normal mode signals so that the user has a variety of choices between instrument settling time and interference rejection. The instrument is fully protected from damage from overvoltage, on any range, in any function. Overload recovery of the amplifiers is fast enough that a correct reading upon removal of the overload is guaranteed, even though the reading is started at the same time the overvoltage is removed.

Zeroing requirements are held to a minimum. The instrument has accuracy commensurate with its resolution—at moderate or extreme speeds. The ac converter uses a thermopile to provide true rms conversion to eliminate common ac measurement errors. And of great importance, the instrument has minimum effect on the device or circuit under test—all injected currents have been eliminated or reduced to an insignificant level.

Measurement Speed

Terminology usually undergoes transformation when applications are changed; hence, for system use, the DVM is more properly called an A/D (analog to digital) converter. There can be significant differences.

For bench applications, the sequence of readings per second should be quick compared with human reaction time. A good performance criterion is the time required for a single measurement, limited by the ability of the analog circuits to respond to sudden input changes and settle to the final value.

Most systems are without similar restrictions—data can be absorbed at much faster rates. Thus, high reading speed is a primary concern, provided, of course, that response and settling times within the instrument are commensurate with its reading rate.

Often speed is a major distinction. Because of the design compromises generally required to obtain high system speeds the system-designed analog to digital converter (A/D) is ordinarily less versatile than its bench counterpart. It is *task dedicated.* A DVM, although slower, has varied functional capability and more versatile signal preconditioning. Does the versatility necessary for bench use preclude the measurement speed deemed necessary for systems applications?

In many system applications, the Model 3480A represents a solution to this apparent paradox. For systems use it can be considered a comparatively slow A/D (its maximum sampling speed is 1000/s) with 15 bit resolution and much greater signal-conditioning capability than the typical A/D. As such, it may be the best candidate for certain system situations.

The digitizing technique used—successive approximation—provides moderate speed at low cost. It is inherently simple and quite reliable. Reed relays in the A/D converter are replaced with semiconductor switches. The instrument accommodates plug-ins to provide signal preconditioning (giving great measurement versatility), and the main frame contains the necessary power supplies and the A/D. The performance of either section is complemented, not compromised, by the other.

To avoid placing an undesirable burden on the bench user—added costs without benefit—the interfacing circuitry required to communicate with other instrumentation is not included within the basic instrument. These interfacing circuits are, instead, available as options.

The emphasis during development was to capitalize on the digitizing speed made available by the successive approximation technique without compromising bench performance or increasing the instrument's basic cost; to solve those problems common to all traditional measurements, not those related to instrument use in a single application—bench or system.

Measurement Errors

Errors associated with instrument use commonly fall within three groups. One group is caused by the measurement circuit's interaction with its surroundings. The most common sources are normal mode and common mode generators which, directly or by magnetic coupling, induce unwanted currents in the measuring loop; the sources can be magnetic fields from other instrumentation or voltages generated because of the flow of relatively large currents in the ground connections among instruments. A second error group is caused by interactions between the measuring instrument and the circuit or device under test. Common mode or normal mode sources exist *within* virtually all instrumentation, and may force 'injected currents' into the circuits being measured; this may occur between 'high' and 'low' or between the instrument's chassis and its other input terminals. These currents can create errors by flowing through unbalanced impedances in the input circuit or, more importantly, may actually upset or change the characteristics of the circuit under test. Third among error sources is those caused directly by the instrument. The most obvious are errors in amplification, attenuation, or conversion that somehow modify the information being sought so that the data presented as absolute may actually be in error.

Unfortunately, reducing the errors of one group does not guarantee reduction of the others. In fact, the opposite is often true. These sources of error, although classified separately, must be treated simultaneously to minimize the entire error matrix.

ERRORS CAUSED BY THE MEASUREMENT CIRCUIT AND/OR INTERACTION WITH THE DVM

CM and NM Sources—Outside the DVM

The most general measurement situation is shown in Fig. 2. A floating (above earth or chassis ground) measurement is to be made across a resistance bridge. Although the instrument ground and the source ground are on the same line, a voltage generator (the common mode source) will exist between them. The difference in the ground voltage is primarily due to induced currents and ground currents that flow between the two physically isolated grounding points. This current creates a voltage difference (the ground line or plane will always have some impedance) whose magnitude depends on the hookup and the environment into which it is placed.

The common mode generators (ac and dc) will not, by themselves, cause measurement errors if the instrument impedance from chassis to each of its input terminals is infinite. Unfortunately, this is not generally the

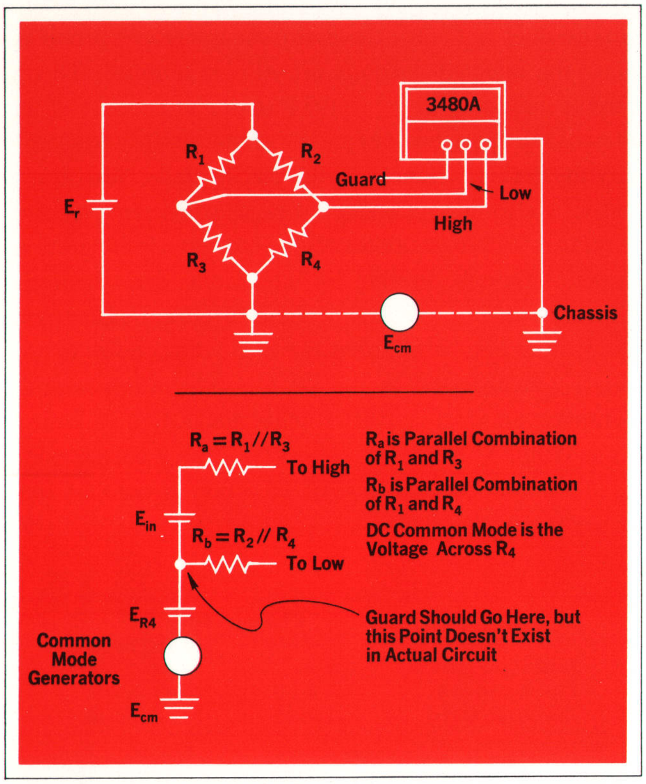


Fig. 2. *A general measurement situation where a floating measurement is made across a resistance bridge. Its Thévenin equivalent is shown.*

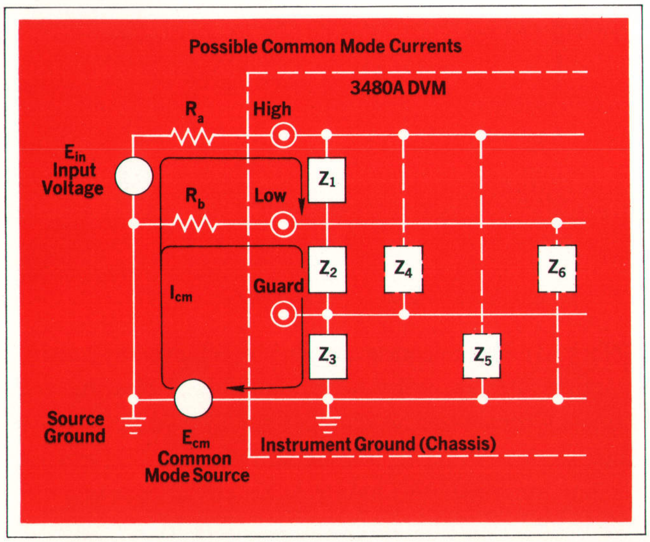


Fig. 3. *Possible common mode currents from external sources. Assume $Z_6 << Z_1$ and Z_5.*

case. Because impedance is finite between the instrument's high and low terminals and the point to which the common-mode generator is referenced (the instrument's chassis), Fig. 3, current will flow through each of the imbalance resistors. The resulting voltage drop across these imbalance R's will enhance or oppose E_{in}, creating normal mode errors—the common-mode signal has been converted to one in *series* with the primary measurement loop, that is, to a normal mode error signal. (The treatment of common mode errors, once the conversion to normal mode occurs is then identical to that for normal mode errors.) These signals create undesirable errors—either dc offsets or a time varying voltage which may cause the DVM's display to 'rack.'

Because the instrument's 'high' terminal is generally a point or line rather than a plane, its impedance to chassis is generally quite high and common mode errors in this input lead can generally be ignored. If, however, the impedance from high to low ($>10^{10}\Omega$, <50 pF for each of the 3480's plug-ins) is not extremely high and a guard is either not available or used, significant errors can result—a 60 Hz common mode voltage of 10 V, an imbalance R of 1 kΩ, and an input capacity of 1000 pF combine to generate an error of 3.7 mV. Normal mode filtering can, of course, reduce the ac errors but not without a corresponding increase in measurement time (the response time of the filter must be added to the instrument's basic digitizing time).

The instrument impedance from low to chassis is usually much lower because of the instrument's physical construction; 'low' will generally be a plane—capacities of several thousand picofarads are not unusual. Guarding must then be used to reduce these errors. Connecting the guard, Fig. 4, will effectively bootstrap that portion of the impedance between low and chassis that is terminated on guard. It can be of little help, obviously, for that impedance not interrupted by guard.

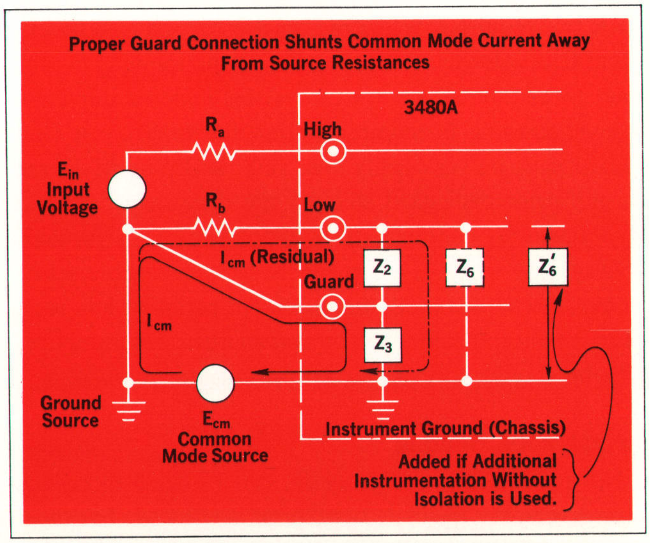


Fig. 4. *Proper guard connections will shunt most common mode current away from source resistances.*

The degradation in Z_6 that is so undesirable can easily occur when the instrument is interfaced to other equipment. If, for example, the data generated by the DVM is to be used to provide hard copy, a printer or other recording device will be electrically tied to the DVM's data output lines. If, too, the instrument is to be remotely programmed or externally commanded, the program source must be electrically connected to the DVM. As the DVM's data programming lines are referenced to the instrument's low terminal, a floating measurement will be impossible unless this added instrumentation can also be floated. Floating this instrumentation, unfortunately, will reduce Z_6 and cause deterioration of the system's CMR. Injected currents from low to chassis will also be significantly increased—unless the output or controlling circuitry is completely isolated from its chassis. If the output and control lines can be so referenced, and if isolation can be provided within the DVM, these system errors can be eliminated. The Model 3480A/B and its plug-ins have digital output and programming options for necessary electrical isolation without degrading other performance criteria (measurement speed, susceptibility to electrical interference). The isolated programming option also provides program storage.

The physical architecture of the Model 3480A/B has eliminated the necessity for costly 'box-within-a-box-construction' (all internal circuitry surrounded by guard)—yet CMR for the Model 3480A/B and any of its plug-ins is >80 dB at 60 Hz for a 1 kΩ imbalance. Physical spacing between the internal circuitry ('low') and chassis is as large as practicable. Where large spacings are impractical, individual shields are employed. 'Box-within-a-box' construction is necessary only when much higher levels of CMR are required. While reducing errors caused by external CM voltages, this type of construction may accentuate measurement errors caused by *injected* currents. Where guarding is required within the instrument (the transformer, power supply heat sink, and plug-in covers are the principal guard shields) the necessary care has been taken to eliminate time-varying voltages in their vicinity. The result is an extraordinarily favorable set of tradeoffs. The complete measurement problem has been taken into account. Errors from *all* sources, not just a few, have been reduced together in appropriate amounts.

Normal Mode Filtering

Normal mode filtering, again, can be used to reduce these errors, but measurement speed is reduced. The most obvious solution to this tradeoff is to use a digitizing technique that provides filtering—i.e., integration. Hence, the recent popularity of dual-slope DVM's. This compromise does not solve the entire measurement problem unless the injected currents are also minimized. Those currents may do nothing to the instrument because of its inherent rejection, but can and do create subtle and seemingly mysterious changes in the circuit under test. Integration is also only effective for noise whose frequencies are related to (and multiples of) the converter's integration period. Although filtering by integration can, theoretically, give superior results at these discrete frequencies, Fig. 5, little help is afforded the user whose noise is not *exactly* synchronized to the DVM's integration period. Moreover, an ideal converter using integration is limited to a maximum sample rate of 60 Hz (and a corresponding minimum aperture time of 16.6 ms) if the CM frequency is exactly 60 Hz.

	Frequency (Hz)		
	60 Hz	61 Hz	64 Hz
1/10 s Gate (100 ms)	Essentially 'infinite'	46 dB	27 dB
Filter A (200 ms)	30 dB	30 dB	30 dB
Filter B (1000 ms)	80 dB	80 dB	80 dB

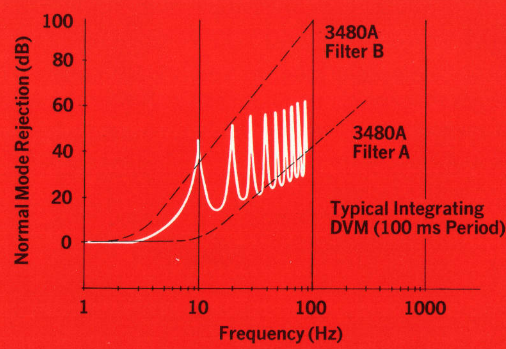


Fig. 5. *Normal mode rejection at discrete frequencies characteristic of a typical integrating DVM.*

Normal mode rejection can also be achieved by passive or active filtering or by a combination of filtering and frequency conversion. A chopper stabilized amplifier is a good example. Filtering may occur before, within or after this input amplifier. All have relative advantages and disadvantages—none is an ideal solution to the general measurement problem. The degree of filtering required for different applications will, of course, be different as will the measurement times desired. There will always be a speed/rejection tradeoff, stated or implied. Rather than restrict the user to a fixed compromise—the amount of filtering and the delays that are a necessary consequence—filtering in the plug-ins for the Model 3480A/B is selectable (see Specifications). The user can choose the compromise that best suits his needs.

Strong magnetic fields near the DVM can contribute both common mode and normal mode errors if care is not exercised in the design of the instrument. Here, filtering may be of no direct benefit, for the injected currents may be induced in the instrument's filter or in the circuitry following the filter or the integrator (if the DVM uses integration). A five gauss 60 Hz field (typically found near the primary power section of most instrumentation) can induce a peak-to-peak error as large as 30 μV if the circuitry within the field encloses an area of one square inch. Loops can be generated by the improper layout or design of either or both of the DVM's high and low leads. Shielding will be of little help if the field is large enough to cause saturation.

Reducing these errors within the Model 3480A/B and its plug-ins is accomplished in several ways. All the input wiring—high and low—form tightly twisted pairs to reduce the area that may enclose the field. Where twisted pairs are impractical, compensating loops have been added. Wirewound resistors, notorious for their ability to sense magnetic fields, even when 'non-inductively' wound, have been replaced in sensitive areas by precision metal film resistors.

CM and NM Sources Inside the DVM

Not all common mode currents (and the normal mode errors they create) come from the circuit being measured. Some common mode error sources are generated within the measuring instrument. These are caused by currents induced into the ground or guard shields by voltages referenced to chassis, or into chassis from sources referenced to low. These internal common mode sources are generally constant current sources and force 'injected currents' into the circuits being measured, Fig. 6. Direct measurement errors are the normal result, but by upsetting the circuit under test or by changing its characteristics during the measurement period, indirect errors often occur—these errors, because they occur only when the device under test is connected to the DVM, are often impossible to isolate and identify.

The most common source of these injected currents is the instrument's power transformer. The transformer, to reduce its capacity from low (secondary) to chassis (primary) is guarded. Capacity from chassis to low is interrupted by a guard shield between the two windings, Fig. 7. If the guarding is complete (C_1 quite small) the injected current flowing through low will be correspondingly small (if E_1 is 100 V at 60 Hz and $C_1 = 10$ pF, the result current—400 nA—will develop 400 μV across an R_b of 1 k, Fig. 6).

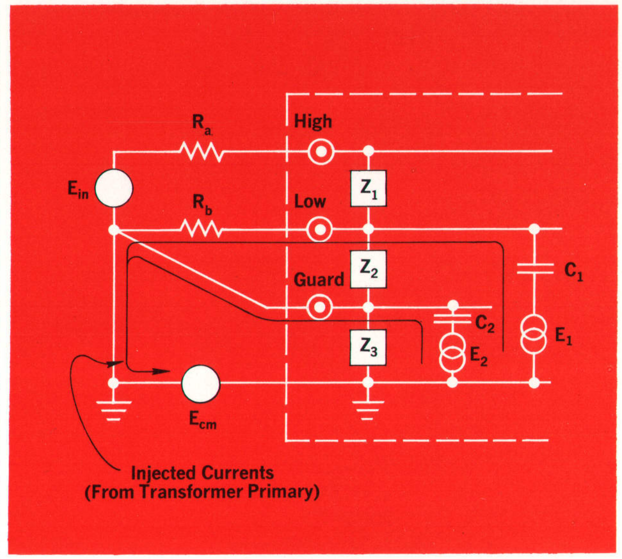


Fig. 6. *Internally generated common mode sources referenced to chassis.*

The injected current flowing through the guard terminal—caused by C_2—is of no consequence as it shunts the measurement circuit. If, however, the guard is connected to low, all the injected current will flow through the measurement circuit. This error can be hundreds or thousands of times larger than the one previously calculated ($C_2 \cong 1000$ pF). This error source can be reduced by placing an additional shield between the existing guard shield and the transformer primary winding.

Other sources of similar magnitudes exist between the transformer's secondary winding and its guard shield, Figs. 7 and 8. These inject current from low to guard. This injected current will only go through R_b if the guard is *properly* connected; if tied to low the current is shunted around the measurement circuit. So connecting the guard to maximize CMR will also maximize the effect of this particular injected current. Connecting it to minimize the injected current will correspondingly reduce the CMR. The need for this tradeoff can be eliminated if still another shield—between guard and low—is added to the transformer, Fig. 9.

The transformer construction in the Model 3480A/B incorporates all three shields to reduce all of these injected currents. Both the primary and secondary windings are completely enclosed in 'box' shields tied to their respective grounds. A guard shield between these two boxed windings is used as a guard to maximize CMR. In this manner injected currents are limited to a few nanoamps.

Shielding requirements for the transformer must also extend to all primary and secondary wiring—in fact to all time varying voltages within the DVM. The primary wir-

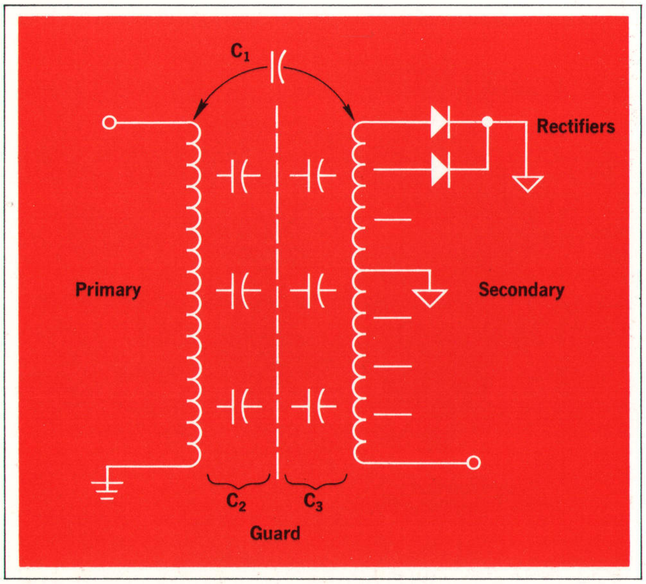


Fig. 7. *A typical guarded transformer and capacitances resulting.*

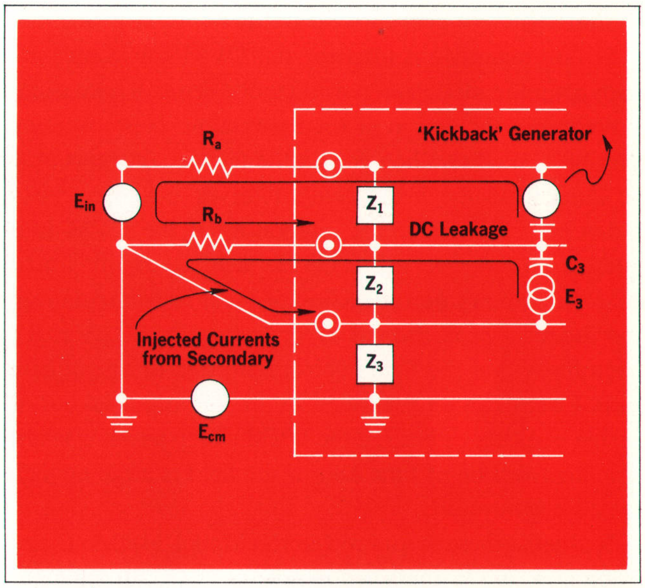


Fig. 8. *Internally generated common mode sources referenced to 'low.'*

ing is physically isolated and shielded from circuitry referenced to low. The secondary wiring and all the rectification and regulation circuitry used for the DVM's internal power supplies are also shielded and isolated from chassis (the instrument's frame).

Timing, gating, and external display circuitry must also be shielded (and guarded, if necessary) from the instrument chassis. Logic circuitry that generates internal timing and gating is located on a single printed-circuit card in the middle of the instrument—boards on either side shield it from chassis. The sample rate generator that initiates each sample is coupled to the plug-in by a steady state voltage, not one that is time varying. Time varying voltages on the 'mother board' are shielded and guarded from the chassis by another board below. This board, physically attached to the mother board, also provides the mechanical stiffening necessary to insert and extract the other plug-in cards from the mother board.

Gas discharge display tubes are also isolated. Because of the differences in the glow area of the various segments (glow tube cathodes), each has a different sustaining voltage. Because of the differences in the spatial arrangement of the segments, every unlit segment assumes a unique voltage—a voltage that will be dependent on the lighted segment. These voltage variations can be in excess of 40 V. When the display is changed, these voltages also change, and create large voltage transients that can generate large injected currents (the capacity between the Nixie segments and the instrument's chassis is relatively large because of the glow tube's large surface area). Isolation is achieved by depositing a metallic coating (tied to low) on the inside of the plastic window that is the front of the mainframe. This conformal coating, although it does provide significant attenuation of the broadband noise generated by these display tubes, is not sufficient to reduce the injected currents to the nanoamp levels desired. Therefore, buffering between the decoder drivers and the D/A logic has been added. The display is changed only once—at the completion of each reading. From a visual standpoint, buffering is not required because of the relatively small digitizing time of the A/D—the human eye could not detect the change in the voltage displayed during digitizing.

Shielding has also been added to the board on which the D/A converter and the comparator are located. Shielding is required here because the physical spacing between the components on the board and top cover is not sufficient to reduce the injected currents from these sources to acceptable levels. These components are deliberately near the top of the instrument to provide easy accessibility to calibration potentiometers. The heat sink on the regulator card must of necessity, be tied to guard (its capacity to the instrument top cover cannot otherwise be tolerated). Here again, all time varying circuitry referenced to low has been physically removed from the vicinity of this shield to reduce injected currents. Time varying lines between the mainframe and plug-in are either shielded (and guarded, as necessary) or have voltage levels reduced commensurate with the injection desired.

This method of guarding and shielding to minimize injected currents without the necessity of sacrificing CMR in actual use has also been used in the plug-ins, the iso-

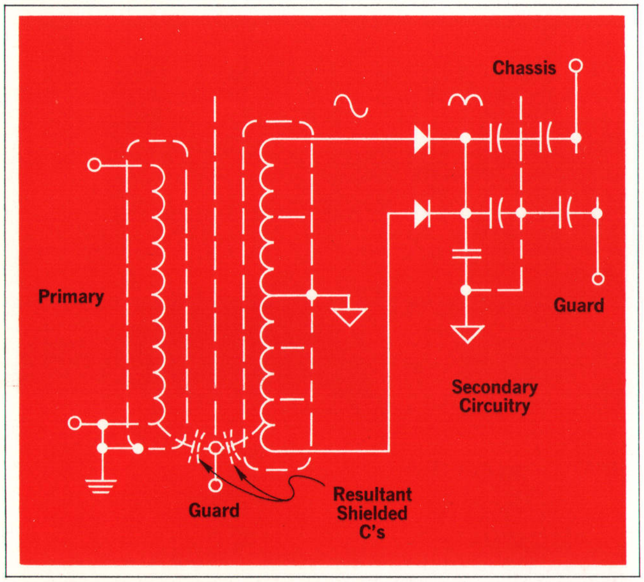


Fig. 9. *Manner in which the transformer in the Model 3480A is shielded and guarded.*

lated digital output option (for the mainframe), and the isolated programming option (for the plug-ins). The total injected current from all sources has been reduced to a few nanoamps—a level sufficient to eliminate any error when moderate unbalances are used, regardless of the guard connection.

Current injection from the instrument high terminal to low will also cause an obvious error. Leakage or injected currents are dc rather than time varying (currents used to bias the input amplifier or currents from improperly shielded power supply voltages). The total input error involves not only the instrument's input resistance but also this dc leakage current. An instrument with $10^{12}\Omega$ input resistance may have a leakage current of 1 nanoamp. If a source resistance of 1 MΩ is used, little loading error will result, but the offset caused by the leakage current will be 1 millivolt. The plug-ins for the Model 3480A/B have an initial offset current of <10 picoamps; its change with temperature (perhaps of more importance) is less than 1 picoamp/°C.

Input impedance (and offset current) of the instrument is also constant with time or sample rate. 'Kickback' currents that might adversely affect measurements from relatively high source impedances have been eliminated.

ERRORS CAUSED DIRECTLY BY THE DVM

DC Signal Preconditioning

Conditioning the signal voltage to the nominal value required by the A/D (10 V) within the accuracies desired ($\pm 0.005\%$) can be achieved easily. It is more difficult though, if characteristics other than accurate amplification or attenuation are also required. Some of the more obvious requirements are: moderate bandwidth (20 kHz @ $A = 40$ dB); wide dynamic range (0 V to ± 15 V at the instrument's input); extremely high input resistance ($>10^{10}\Omega$); very low offset voltage and current ($<1\ \mu$V, 1 pA at the amplifier input); and low sensitivity to power supplies, source and load impedances, temperature and humidity.

All but the requirement for bandwidth are associated with the design of any low level dc amplifier. The actual operating characteristics desired are fast recovery from overload ($>50\ \mu$s) and a slew rate and settling time fast enough to make useful the A/D digitizing time. These requirements imply a bandwidth in excess of 20 kHz. To satisfy the bandwidth requirement only is simple. But to satisfy both the requirement for dc preconditioning and for bandwidth requires greater sophistication.

Chopper amplifiers (which up-convert the signal to some low carrier frequency, amplify, then down-convert) will not normally satisfy the bandwidth requirement. Such amplifiers are normally used only to amplify dc and low-frequency voltages near dc. To amplify the higher frequencies, an ac-coupled amplifier can be paralleled, but this is, of course, more complicated and more costly. Up-conversion to a much higher frequency carrier (megahertz), as in a parametric amplifier, accommodates the frequency range requirement, but adequate amplifier accuracy and dc stability (variation of the offset voltage and current at the amplifier input with time and temperature) are difficult to achieve.

A direct-coupled amplifier of unusual design was the final choice for the instrument, satisfying performance requirements at reasonable cost.

A matched pair of field-effect transistors is used for the differential input stage, Fig. 10. The FET offers both the high input resistance and the small leakage current required. Bipolar devices, though not necessarily limited by their lower input resistance (although lower than the FET, it is boosted by the amplifier's loop gain) have considerably more leakage current. The FETs are operated in a balanced common drain configuration to achieve minimum sensitivities of offset voltage and gain to variations in power supply and device parameters. High CMR, >80 dB, is not readily obtainable in a common source configuration because of the inherent mismatch of the two discrete devices.

To reduce parameter variations caused by temperature fluctuations, the FET environment is temperature controlled at a temperature higher than the maximum ex-

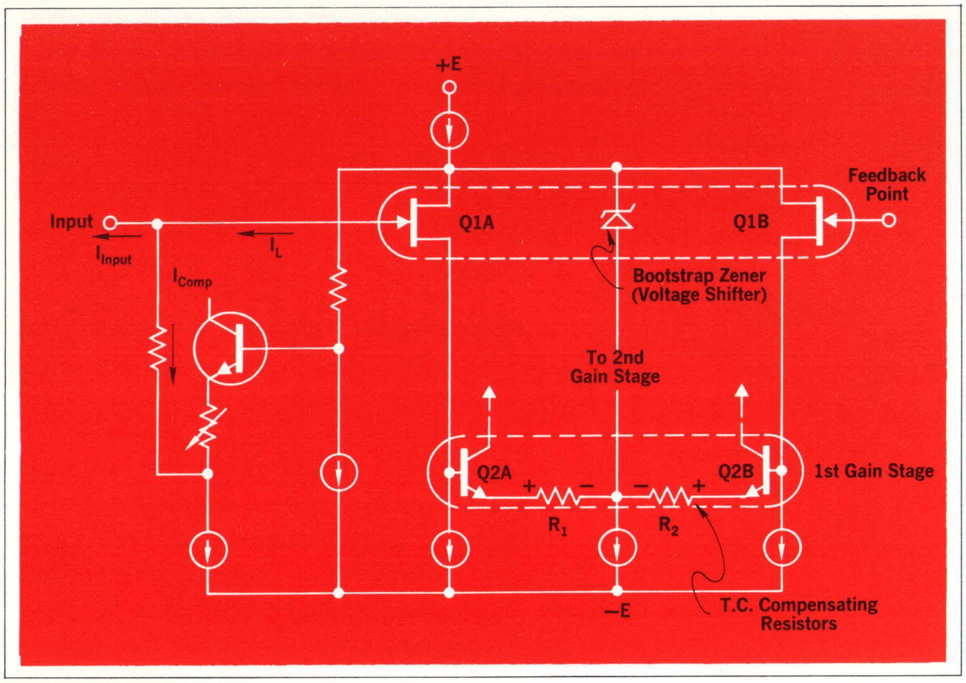


Fig. 10. *Input stage of the Model 3482A and Model 3484A dc preconditioning amplifier.*

pected ambient. An integrated circuit is used as an 'oven' to maintain the FET at constant temperature. The monolithic IC has within it all the circuitry normally associated with an oven and its control circuitry—heaters, temperature sensors, and amplification. The FET dice, mounted atop the IC, assume the temperature of the larger chip. Although the temperature control does operate open loop (the sensing devices are within the IC, not the FETs), the resultant thermal gain (ΔV_{GS} without temperature control/ΔV_{GS} with temperature control) can be quite high ($A_T \geq 100$). A high thermal gain, however, does not guarantee a reduced offset voltage temperature coefficient. The thermal gains of the two devices must be matched because of their large initial TC ($\sim 600\ \mu V/°C$), i.e., if the two devices are ideally matched initially but $A_T = 100$ for one side and 1000 for the other, the net TC will be 5.4 $\mu V/°C$, not zero. Compensation must be used to reduce the effects of open loop control.

The device is constructed with obvious symmetry about the two FET dice, Fig. 11. Thermal gradients across the face of the IC have been reduced by an anodized aluminum heat sink (0.001″ × 0.030″) between the IC and the FET chips. The epoxy used for mounting the FETs and the IC is thermally conductive although electrically resistive. The aluminum bonding wires (1.5 mil diameter) used for connecting the FETs are thermally bootstrapped. Such bootstrapping is required to minimize the effect of the heat conduction through the bonding wires—>60% of the heat lost. If heat is lost unevenly, the gradients that result are severe enough to seriously degrade both the absolute value of thermal gain achieved and the resulting match in thermal gain between devices.

The FETs are operated at 80°C, a temperature high enough above ambient to allow regulation when the instrument is operated at elevated temperatures. Compensation reduces the offset current initially to <10 pA and attains a composite TC of <1 pA/°C. To keep the resulting offset current independent of input voltage level, the compensation circuitry is bootstrapped.

Even though the temperature of the FET is controlled, the offset voltage temperature coefficient of the FET, combined with the rest of the amplifier, may still be greater than desired. To reduce this to $< \pm 1\ \mu V/°C$ the entire amplifier is temperature compensated. The amplifier's temperature is varied and its TC calculated. Resistive compensation is added, that is the amplifier's TC is changed and the amplifier is rerun until the desired TC is achieved. Compensation is achieved by varying the V_{BE} match of the first bipolar gain stage. Its TC match will change by approximately 1 $\mu V/°C$ for each 300 μV mismatch in its base-emitter voltage.[1] Resistors are added in series with the emitters of these transistors to get the required mismatch. As the stage is driven by a current source, the voltage drops across the emitter resistors act as small batteries to mismatch ΔV_{BE}.

To take full advantage of the DVM's reading speed, field effect transistors are used for dc range switching.

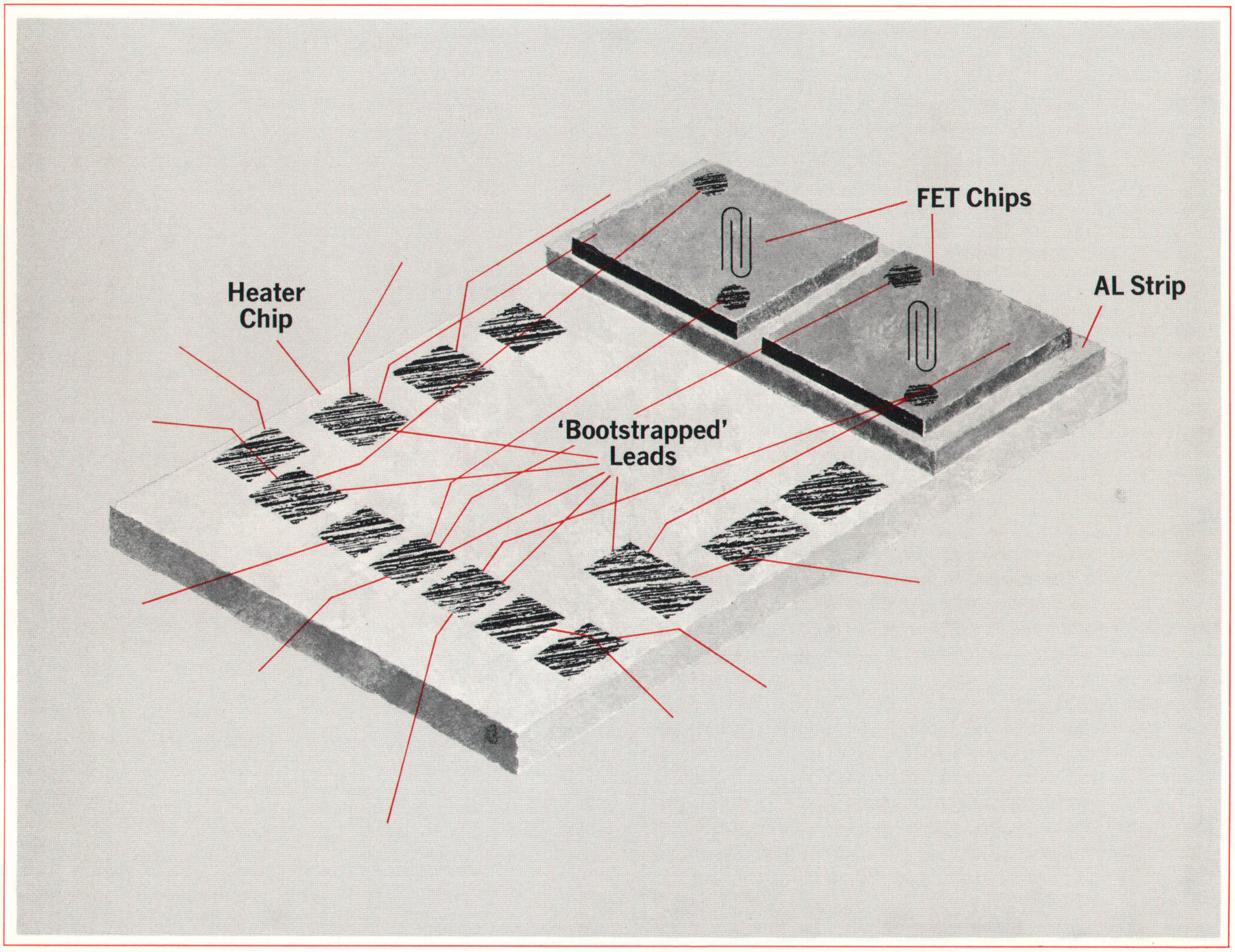


Fig. 11. *Construction of the FETs on a chip with temperature compensation. Heaters are on the same chip.*

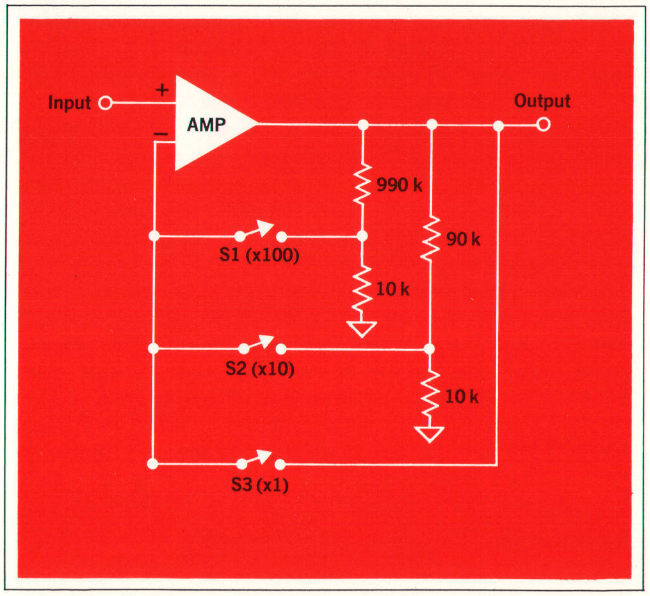


Fig. 12. *DC amplifier gain switching.*

Input voltages from 10 to 1000 V are divided down to 10 V by reed relays. Ranging is then by FETs. The FET 'on' resistance, although several hundred ohms, is in series with the amplifier's input impedance ($>10^9\Omega$) and thus creates little error. The leakage current from the inverting side of the amplifier (and from the 'off' switches) flows through the 'on' switch and, on the two lower ranges, 10 kΩ, Fig. 12. Even though this leakage current can be as large as 1 nA, it is relatively constant because of the controlled environment of the FET used as the amplifier input stage. The offset it creates can be removed initially by zeroing. Any changes with temperature are accounted for by the compensation technique previously described.

What is the HP Model 3480A?

The Model 3480A/B is a 4-digit digital voltmeter (with 50% overrange), an A/D converter with moderate speed which, when combined with one of its plug-ins, can provide multifunction measurement capability without many of the limitations created by traditional measurement errors.

The 3480A/B mainframe (the 'A' is a half module; the 'B', a full rack module) uses plug-ins—Models 3481A, 3482A or 3484A. The Model 3484A, with all options, has five dc and true rms ac voltage ranges, and six ohms ranges. The Model 3482A has the same dc capability as the Model 3484A (it cannot, however, be expanded to provide ac and ohms). The Model 3481A has only a single dc voltage range. All plug-ins fit either mainframe configuration.

Successive approximation is used for A/D conversion. Because of the design of the analog processing portions of the instrument (within the plug-in) and the means employed for data or programming transfer, reading and recording speeds up to 1000 per second are possible without performance degradation.

A true rms ac converter (an option within the 3484A) enables accurate voltage measurements to be made of waveforms with frequency components from dc to 10 MHz. The converter eliminates significant errors (when other conversion techniques are used) caused by small amounts of harmonic distortion present in most sinusoidal signals. Accurate measurement of non-sinusoidal phenomena is also possible —the full scale crest factor is 7:1. Because the converter can be dc coupled, it also measures the rms value of a combined ac and dc signal. A dual-thermopile makes the conversion and is 30 times more sensitive than a single thermocouple. This sensitivity permits accurate measurements on the 100 millivolt range.

DC input errors between the high and low input terminals are virtually eliminated by the combination of a constant input resistance of $>10^{10}$ ohms and a leakage current of <10 pA. A three position input filter can be used to reduce or eliminate measurement errors caused by normal-mode noise. Errors caused by common-mode noise can be reduced by using the guard. Injected currents flowing from the low and guard terminals to chassis have been significantly reduced to minimize the effect the instrument has on the device or circuit under test.

System options include isolated or non-isolated BCD outputs and isolated programming inputs. Everything (except terminal selection) on the DVM is programmable. A two range, three terminal, dc ratio option is also available. The variety of possible configurations available and the innate operating features allow the user to easily adapt the instrument to his specific needs while simultaneously reducing measurement errors.

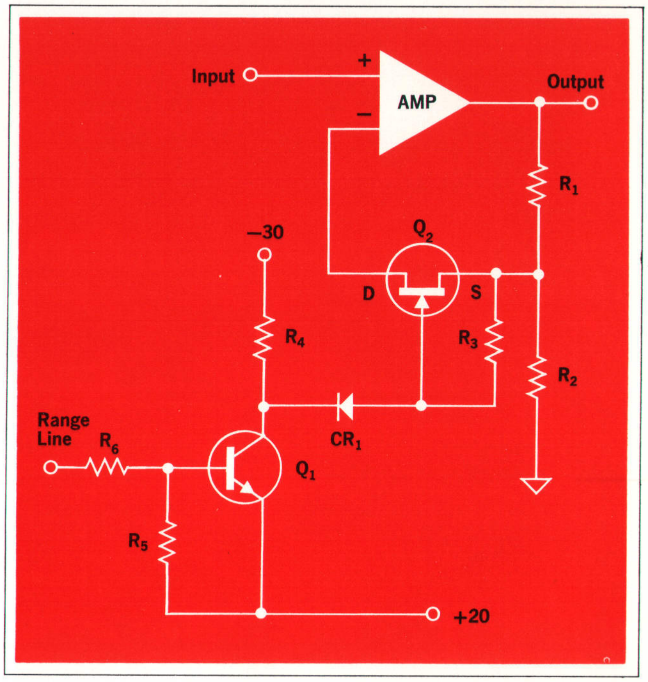


Fig. 13. *FET range switch.*

Q1 and its associated components drive Q2 'on' or 'off', Fig. 13. When the range line is open (high), Q1 is off and the gate is biased to the negative supply through R4 and CR1. Grounding the range line reverses biases CR1—Q2 turns on and is zero biased through R3.

Acknowledgments

Paul Baird and Ken Jessen contributed significantly to the project's definition. George Latham was responsible for the 3480A/B's electrical design, Dave Luttropp for its mechanical design. Jim Arnold's suggestions greatly increased the instrument's serviceability. John Hettrick bore the primary responsibility for coordination of the production transfer, Gregg Boxleitner the responsibility for production and electrical design of the 3481A. Karl Waltz and Barry Taylor were jointly responsible for the 3482A, Mike Aken for the 3484A. Jerry Blanz was responsible for the mechanical design of the plug-ins. Approbation must also be given to Larry Lopp and Jerry Harmon who contributed to the SFET's development and to Larry Linn who made many significant contributions. Too numerous to name but nonetheless indispensable are the many other people involved in layout and manufacturing.

References

1 A. H. Hoffait and R. D. Thornton, "Limitations of Transistor DC Amplifiers," Proceedings of the IEEE, February 1964.

Electrical Isolation: Coupling from Low to Chassis

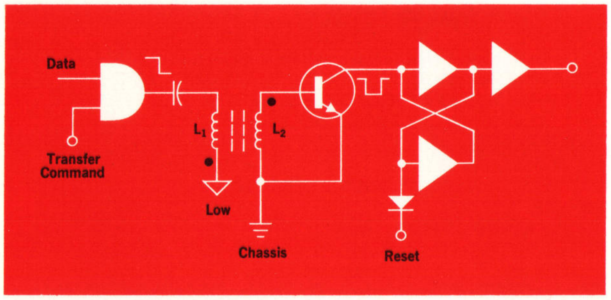
Transformer coupling is used to transfer the information used for programming or digital output—from circuitry referenced to low, to or from circuitry referenced to chassis. This solution offers both speed and reliability—neither achievable with reed relays. It has one inherent disadvantage, however. The successive approximation technique, unlike integration, presents the data in a parallel, rather than serial format. The information to be transferred is in its final form. Data transfer, then, requires a separate transformer for each bit—32 for data, 15 for programming.

Integrating or digitizing techniques that use voltage to frequency converters need provide transfer only for their clock pulses (a single line). Decoding is then done in the 'out guard,' or chassis section of the instrument. Programming isolation is inherent in the reed relays typically used, so additional transfer is not necessary.

The costs involved in implementing a multiple transformer scheme at first appear prohibitive. But to convert first from the parallel format to serial, transfer, and then reconvert is also costly. Serial transfer also requires clocking to maintain cogency. At the speeds deemed necessary for data transfer, the injected currents caused were considered excessive. The use of light isolators, although attractive, is still somewhat expensive.

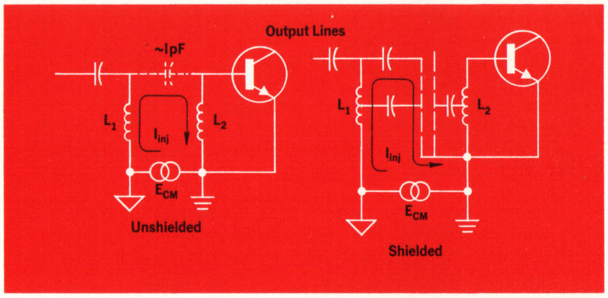
To reduce costs, the transformers used are simply pairs of molded RF chokes. DC isolation is achieved by mounting the chokes and their respective circuits on interfacing PC boards—one referenced to low and one to chassis. Power for the isolated or chassis side is provided by a separate winding on the transformer and by a separate regulator—both isolated from the instrument's ground (low).

The basic coupling circuit is shown below.



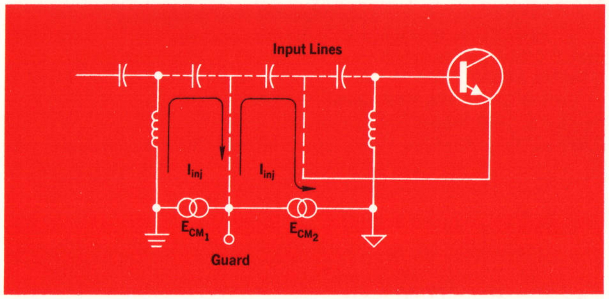
L_1 and L_2 (100 μH and 220 μH, respectively) provide a current step-up of approximately 2:1—low to chassis. A high current, low-voltage pulse, on transfer, is forced into the transistor's base causing saturation and a resultant change in state of the latch used to provide storage. Programming transfer is accomplished in an identical manner—the grounds are simply reversed. The coefficient of coupling, M, is 0.3 to 0.5.

It is imperative that the programming and digital output circuitry remain insensitive to externally changing voltage; otherwise, false triggering or programming, or a change in the output data could invalidate the measurement being made. As the low and earth grounds can vary by as much as 700 V (the maximum voltage that can be tolerated from low to guard is 200 V; 500 V from guard to chassis), and as these common mode voltages may be switched at rapid rates (when used with a scanner switching large high, low, and guard voltages), the shielding and the guarding it implies are necessary.



A small capacity (<1 pF) exists between each of the two coils used for transfer. In the example shown, a large and relatively fast common mode voltage (caused by switching) may inject enough current into the base of the transistor to cause the latch to change state. This injected current—caused by the external circuitry, not by the DVM—can be eliminated if a shield, tied to chassis, is used to interrupt the capacity between coils. If information is to be transferred in the opposite direction, the shield must be tied to low. Unless these shields are properly terminated, current injection will be enhanced and noise sensitivity reduced.

These shields, although providing the reduced sensitivities desired, greatly decrease CMR. An additional shield, tied to guard, is added to obtain a net reduction in capacity. A compromise between CMR and noise sensitivity is required, however, as common mode voltages may also exist between guard and low or guard and chassis. As the largest voltage change allowed is between low and chassis, only shielding (no guarding) is incorporated on output lines; the resulting decrease in CMR is tolerable (the instrument's system specification, regardless of option or plug-in, is 80 dB at 60 Hz with a 1 k imbalance in either input lead). Guarding of the input lines is tolerable because of the reduced voltage allowed between low and guard.



A multilayer flex circuit is used to implement the shielding and guarding between the coils. The shields are constructed in a manner that eliminates any eddy currents that could be induced in a solid sheet that would result in unacceptable coupling losses.

Double shields at different potentials are offset to reduce capacitance.

PARTIAL SPECIFICATIONS

HP Model 3480A/B (With 3481A Buffer Amplifier)

RANGE

FULL RANGE DISPLAY: ±10.000 V.
OVERRANGE: 50%

PERFORMANCE

ACCURACY:
90 days (25°C, <95% R.H.):
±(0.01% of reading +0.01% of range)
TEMPERATURE COEFFICIENT:
0°C to 55°C: ±(0.001% of reading +0.0003% of range) per °C
MEASURING SPEED:
Reading Period: 950 μs.
Reading Rate: Variable from 1 to 25 per s plus manual with front panel controls; 0 to 1000 per s with external trigger.
RESPONSE TIME: 1 ms. Reads to within 1 count of final reading when triggered coincident with step input voltage.

INPUT CHARACTERISTICS

INPUT RESISTANCE: $>10^{10}$ Ω.
COMMON MODE REJECTION: >80 dB, dc to 60 Hz with 1 kΩ in either lead.

HP Model 3480A/B (With 3482A DC Range Unit)

RANGES

FULL RANGE DISPLAY: ±100.00 mV.
±1000.0 mV.
±10.000 V
±100.0 V
±1000.0 V
OVERRANGE: 50% on all ranges. ±1200 V max input.
RANGE SELECTION: Manual, automatic or remote.
AUTOMATIC RANGING: Upranges at 140% of range; downranges at 10% of range.

PERFORMANCE

MEASURING SPEED:
Reading Period: 950 μs.
Reading Rate (without range change): Variable from 1 to 25 per s plus manual with front panel controls; 0 to 1000 per s with external trigger.
Autorange Time:
Filter Out: 4 ms per range change.
Filter A: 200 ms per range change.
Filter B: 1 s per range change.
Response Time (without range change):
Filter Out: 1 ms. Reads to within 1 count of final reading when triggered coincident with step input voltage.
Filter A: 200 ms to within 1 count of final reading.
Filter B: 1 s to within 1 count of final reading.

INPUT CHARACTERISTICS

INPUT RESISTANCE:
100 mV, 1000 mV, 10 V ranges: $>10^{10}$ Ω.
100 V, 1000 V ranges: 10MΩ ±0.1%.
EFFECTIVE COMMON MODE REJECTION (ECMR): ECMR is the ratio of the peak common-mode voltage to the resultant error in reading with kΩ unbalance in either lead.
DC: >80 dB.
AC: (50–60 Hz):
Filter Out: >80 dB.
Filter A: >110 dB.
Filter B: >160 dB.
NORMAL MODE REJECTION (NMR): NMR is the ratio of the peak normal mode signal to the resultant error in reading.
Filter Out: 0 dB.
Filter A: <30 dB at 60 Hz and above.
Filter B: <80 dB at 60 Hz and above.
FILTER SELECTION:
Manual or Remote.

HP Model 3480A/B (With 3484A Multifunction Unit) DC VOLTAGE

RANGES

FULL RANGE DISPLAY: ±100.00 mV.
±1000.0 mV.
±10.000 V.
±100.0 V.
±1000.0 V.
OVERRANGE: 50% on all ranges. ±1200 V max input.
RANGE SELECTION: Manual, automatic or remote.
AUTOMATIC RANGING: Upranges at 140% of range; downranges at 10% of range.

PERFORMANCE

MEASURING SPEED:
Reading Period: 950 μs.
Reading Rate (without range change): Variable from 1 to 25 per s plus manual with front panel controls; 0 to 1000 per s with external trigger.
Autorange Time:
Filter Out: 4 ms per range change.
Filter A: 200 ms per range change.
Filter B: 1 s per range change.
Response Time: (without range change):
Filter Out: 1 ms to within 1 count of final reading when triggered coincident with step input voltage.
Filter A: 200 ms to within 1 count of final reading.
Filter B: 1 s to within 1 count of final reading.

INPUT CHARACTERISTICS

INPUT RESISTANCE:
100 mV, 1000 mV, 10 V ranges: $>10^{10}$ Ω.
100 V, 1000 V ranges: 10 MΩ ±0.1%.
EFFECTIVE COMMON MODE REJECTION (ECMR): ECMR is the ratio of the peak common-mode voltage to the resultant error in reading with 1 kΩ unbalance in either lead.
DC: >80 dB.
AC (50–60 Hz):
Filter Out: >80 dB.
Filter A: >110 dB.
Filter B: >160 dB.
NORMAL MODE REJECTION (NMR): NMR is the ratio of the peak normal mode signal to the resultant error in reading.
Filter Out: 0 dB.
Filter A: >30 dB at 50 Hz and above.
Filter B: >80 dB at 50 Hz and above.
FILTER SELECTION:
Manual or Remote.

OHMS, Option 042

RANGES

FULL RANGE DISPLAY: 100.00 Ω
1000.0 Ω
10.000 kΩ
100.00 kΩ
1000.0 kΩ
10.000 MΩ
OVERRANGE: 50% on all ranges.
RANGE SELECTION: Manual, automatic or remote.
AUTOMATIC RANGING: Upranges at 140% of range; downranges at 10% of range.

PERFORMANCE

ACCURACY:
90 days (25°C ±5°C, <95% R.H.):
1000 Ω thru 1000 kΩ ranges: ±(0.01% of reading +0.01% of range).
100 Ω range: ±(0.02% of reading ±0.05% of range).
10 MΩ range: ±(0.1% of reading +0.01% of range).
MEASURING SPEED:
Reading Period: 950 μs.
Reading Rate (without range change): Variable from 1 to 25 per s plus manual with front panel controls; 0 to 1000 per s with external trigger.

Response Time (full scale step input):

100 Ω thru 100 kΩ ranges (no filtering): 1 ms. Reads to within 1 count of final reading.

100 kΩ range (Filter A): 200 ms to within 1 count of final reading.

10 MΩ range (Filter A): 2 s to within 1 count of final reading.

Note: Due to noise generated in the unknown resistance, filtering may be required for quiet readings with inputs >100 kΩ. Response times with filtering are proportional less than those shown for inputs below full scale.

INPUT CHARACTERISTICS

VOLTAGE ACROSS UNKNOWN: 1 V at full scale on all ranges.

True rms ac Voltage Option 043

RANGES

FULL RANGE DISPLAY: 100.00 mV.
1000.00 mV.
10.000 V.
100.00 V.
1000.0 V.

OVERRANGE: 50% on all ranges. 1500 V peak max input.

RANGE SELECTION: Manual, automatic or remote.

AUTOMATIC RANGING: Upranges at 140% of range; downranges at 10% of range.

PERFORMANCE

MEASURING SPEED:

Reading Period: 950 μs.

Reading Rate (without range change): Variable from 1 to 25 per s plus manual with front panel controls; 0 to 1000 per s with external trigger.

Response Time (full scale step input, without range change):

AC Coupled: 1 s to within 5 counts of final reading.

DC Coupled: 15 s to within 5 counts of final reading.

INPUT CHARACTERISTICS

INPUT RESISTANCE: 2 MΩ ±1%.

CREST FACTOR: 7:1 at full scale. 70:1 at 10% of full scale.

GENERAL SPECIFICATIONS

Mainframes, Plug-ins and Options

DC Ratio 3480A/B Option 002

DISPLAYED RATIO: Display in all functions is proportional to the ratio of the input voltage to the external 10 V dc reference voltage applied to rear-panel Ratio terminals.

ACCURACY (with respect to external reference voltage):

10 V or 100 V ±5% external reference: Same as basic instrument accuracy specifications.

10 V, 100 V +5% to +35% or 10 V, 100 V −5% to −13%:

Add ±0.02% of reading to basic instrument accuracy specifications.

INPUT CHARACTERISTICS (ratio reference terminals):

INPUT VOLTAGE: +10 V or +100 V (referenced to Low side of measurement).

INPUT RESISTANCE:

10 V Ratio Range: 100 kΩ ±1.5%.

100 V Ratio Range: 100 kΩ ±0.5%.

RATIO MEASUREMENT SELECTION: Manual or Remote.

RATIO RANGE SELECTION: Manual.

REMOTE CONTROL

Remote controls are selected by application of a 'Low' state (logical '0') to the remote lines through a rear-panel connector.

REMOTE CONTROL LINES

ENCODE (external trigger): Initiates a measurement period. Actuated by application of 'Low' state for >50 μs. Line must be in 'High' state >50 μs before applying 'Low' state. Minimum time between ENCODE commands: 1 ms.

INHIBIT (Interface Hold): Disables front-panel Sample Rate control.

RATIO SELECT (Non-isolated Remote Control only): Selects Ratio Measurement (if mainframe has the Ratio option).

FILTER SELECT (3482A, 3483A only): Selects Filter A or Filter B; one line per filter.

RANGE SELECT (3482A, 3484A only): Selects measurement range; one line per range.

FUNCTION SELECT (3484A only): Selects measurement function; one line per function.

PROGRAM (3482A Option 021, 3484A Option 041 only):

Accepts program commands when 'Low' state is applied for >50 μs. Prevents changes in previously selected program when 'High' state is applied for >50 μs. Does not affect operation of ENCODE line. A minimum of 1 ms must be allowed between PROGRAM and ENCODE commands.

FLAG (Print Command): Line remains 'High' during reading period. Line changes to 'Low' to indicate completion of reading period and remains 'Low' until start of next reading period.

PROGRAM FLAG (3482A Option 021, 3484A Option 041 only): Line remains 'Low' until Program is executed. Line then goes 'High' upon execution, then 'Low' after programming is completed (~1 ms).

NON-ISOLATED REMOTE CONTROL

Non-isolated Remote Control is standard on the 3481A, 3482A and 3484A.

ISOLATED REMOTE CONTROL (3482A Option 021, 3483A Option 041)

3482A Option 021, 3484A Option 041 will operate only with 3480A/B mainframes equipped with Isolated Digital Output (Option 004). Isolated Remote Control for the 3481A is provided in the mainframe Isolated Digital Output option.

DIGITAL OUTPUT OPTIONS

The Digital Output Options provide measurement data outputs in digital form for printer and systems applications. In addition, input lines are included to remotely control triggering of the 3480A/B.

NON-ISOLATED DIGITAL OUTPUT, 3480A/B Option 003

Non-isolated Digital Output is available both as a factory-installed option (3480A/B Option 003) and a field installable accessory (HP 11147A).

GENERAL

POWER: 115 V or 230 V ±10%, 50 Hz to 400 Hz, 60 W max (including plug-in, options, normal environmental conditions).

INPUT TERMINALS: High, Low and Guard terminals on both front and rear panels of 3481A, 3482A and 3484A. Front/Rear selector switch on front-panel of plug-in. High and Low Ratio Reference Input terminals on 3480A/B rear panel. Low Ratio and Low Input terminals are electrically common.

WEIGHT:

3480A Basic Instrument: 11 lbs, 12 oz (5,25 kg)
Including Options: 12 lbs, 8 oz, (5,7 kg)
Shipping: 17 lbs, (7,75 kg)

3480B Basic Instrument: 12 lbs, 12 oz (5,71 kg)
Including Options: 13 lbs, 8 oz, (6,15 kg)
Shipping: 18 lbs, (8,1 kg)

3481A Net Weight: 2 lbs, 11 oz (1,2 kg)
Shipping: 5 lbs, (2,3 kg)

3482A Basic Instrument: 4 lbs, (1,8 kg)
Including Options: 4 lbs, 4 oz, (1,9 kg)
Shipping: 7 lbs, (3,15 kg)

3484A Basic Instrument: 4 lbs, 6 oz (1,97 kg)
Including All Options: 6 lbs, 2 oz, (2,76 kg)
Shipping: 8 lbs, (3,6 kg).

ACCESSORIES AVAILABLE:

HP 11148A Plug-in Extender Cable for servicing all plug-ins..$ 45

HP 11149A Remote Control Cable for all plug-ins............$ 25

The following accessories add optional capabilities not included with the basic instrument. Optional capabilities which are not listed as accessories can be ordered only at the time of initial purchase. The Isolated Remote Accessory, HP 11151A, can be used only when the 3480A/B has the Isolated Digital Output Option 004, which is not available as an accessory.

HP 11147A Non-isolated Digital Output for 3480A/B..........$200

HP 11151A Isolated Remote Control for 3482A
3484A (requires 3480A/B Option 004).....................$200

HP 11152A Ohms Converter for 3484A........................$200

HP 11153A AC Converter for 3484A..........................$800

PRICES:

HP 3480A ½ Module Main Frame..........................**$800**

HP 3480B Full Rack Width Main Frame.....................**$900**

Main Frame Options:

Option 002 DC Ratio...................................**$200**

Option 003 Digital Output..............................**$200**

Option 004 Isolated Digital Output.......................**$375**

HP 3481A Buffer Amplifier (includes Single Range DC Voltage and Non-isolated Remote Control).......................**$350**

HP 3482A DC Range Unit (includes 5 Range DC Voltage and Non-isolated Remote Control)............................**$700**

Option 021 Isolated Remote Control (requires Main Frame with Option 004, HP 11149A Remote Cable furnished).....**$200**

HP 3484A Multifunction Unit (includes 5 Range DC Voltage and Non-isolated Remote Control)...........................**$900**

Option 041 Isolated Remote Control (requires Main Frame with Option 004, HP 11149A Remote Cable furnished).....**$200**

Option 042 Ohms Converter..............................**$200**

Option 043 True RMS AC Converter.......................**$800**

MANUFACTURING DIVISION: LOVELAND DIVISION
Loveland, Colorado 80537

H. Mac Juneau

Mac received his BSEE from Swarthmore College in 1961 and his MSEE and Ph.D. from the University of Minnesota in 1965 and 1967 respectively. After graduation Mac came to Hewlett-Packard and worked on ac converters for DVM's, a job which has kept him occupied for three years.

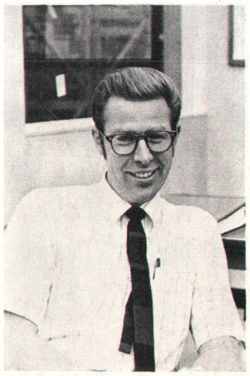
Outside working hours, Mac spends his time woodcarving and welding.

Lee Thompson

Lee Thompson received his BSEE degree from the University of Texas at Austin in 1966. He joined HP's Loveland Division that same year as a product designer. Lee did the product design and some circuit design on the rms converter in the HP 3450A before becoming involved with the true rms converter in the HP 3484A, where he has worked primarily on the amplifier design.

Lee received his MSEE degree from Colorado State University in 1968 as a participant in the HP Honors Cooperative Program. He is a member of Tau Beta Pi.

Craig Walter



Craig earned a BSME from Stanford University in 1961, then continued at graduate school while working part time for Hewlett-Packard. After receiving his MSEE in 1963, Craig joined the HP Loveland Division. In 1968 he assumed responsibility for the four-digit DVM program.

Craig's interests include sailing, bridge and woodworking. He is also an ardent sports enthusiast.

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