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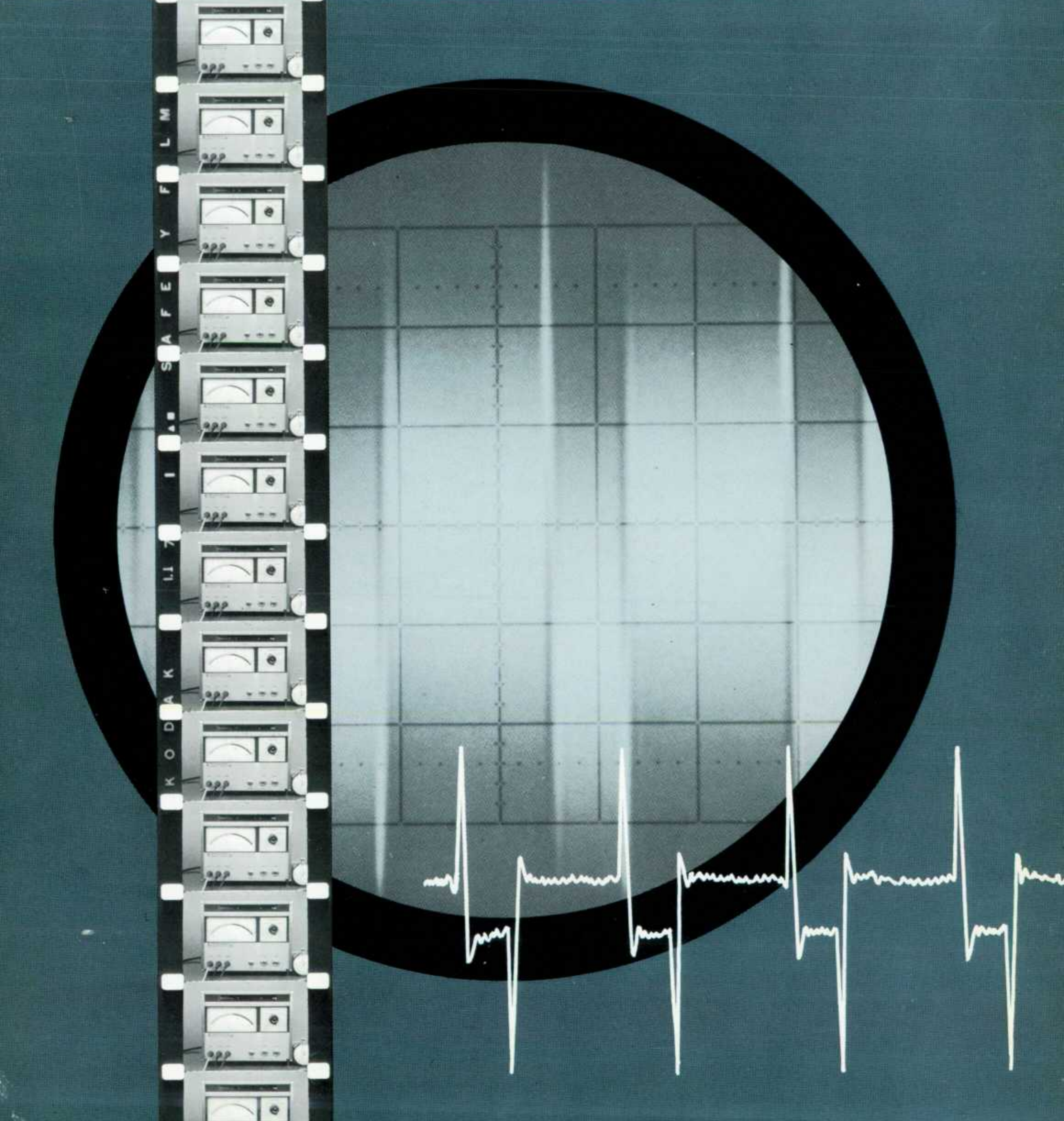


A NEW AUTOMATIC ANALOG VOLTOHMMETER READS IN A FRACTION OF A SECOND; SEE P. 2

RECORDING RECURRENT PULSES BURIED IN NOISE; SEE P. 6-8

A PRECISION ANALOG VOLTOHMMETER WITH AUTOMATIC RANGING

An automatic analog voltohmmeter simplifies dc voltage and resistance measurements and gives higher measurement accuracy and speed than is usually obtained.

AUTOMATIC range and polarity selection is a valued feature of most digital voltmeters that has long been recognized as a distinct advantage to the user. The "touch-and-read" convenience of automatic ranging speeds up measurements on production lines, in point-to-point troubleshooting, in data taking, or in any test procedure that involves potentials of widely ranging magnitudes and differing polarities.

The convenience of automatic range and polarity selection has now been coupled with the lower cost of a meter readout in a new analog-type instrument designed for both dc voltage and resistance measurements. The new automatic voltohmmeter selects the proper measurement range in less than 300 milliseconds after contact is made to the measured circuit or component. A lighted display above the meter shows the automatically-selected range, the units of measurement and, in the case of voltages, the polarity of the input. The instrument up-ranges immediately to a less sensitive range when the measured quantity exceeds 95% of full scale, and it down-ranges at 25% of full scale. Both range-changing and meter response are very fast, requiring no waiting on the part of the operator even for the longest-duration range change.

In addition to the convenience provided by automatic range and polarity selection the new instrument, the -*hp*- Model 414A Autovoltmeter, was designed to have the quality and accuracy needed to place it in the category of precision instruments. Because of the individually-calibrated, taut-band meter that is used, measurement uncertainties are held to less than ±½% of reading ±½% of full scale, a specification that departs from traditional analog voltmeter specification practice. Although equal to a specification of ±1% at full scale, the "half-and-half" specification is more accurate for readings below full scale, as shown in Fig. 1.

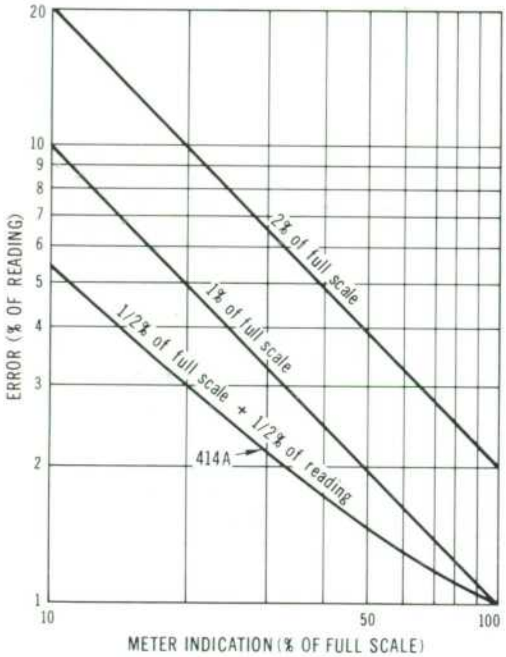


Fig. 1. *Accuracy of analog meters as a function of meter deflection. When meter deflection is less than 100% of full scale, -hp- Model 414A Autovoltmeter specification of ±½% of full scale ±½% of reading is more accurate than 1% of full scale specification. Improvement over 2% specification is correspondingly greater.*

The accuracy of resistance readings is ±1% of reading ±½% of full scale, an accuracy considerably higher than that normally expected of an analog voltohmmeter. Lead resistance has been eliminated as a source of measurement errors by use of a "4-terminal" probe arrangement (see Fig. 5). The ohmmeter mode uses linear meter scales which do not have scale compression, and consequent loss of accuracy and resolution, at either end of the scale as is the case in more conventional ohmmeters. The use of linear ohmmeter scales was made possible by a constant-current drive technique.

The new Autovoltmeter has 12 voltmeter ranges, with sensitivities from 5 mV full scale to 1500 volts full scale, and 12 ohmmeter ranges from 5 ohms to 1.5 megohms full scale. Higher values of resistance may be measured by a shunting resistor technique, described later. The minimum readable input voltage is 0.05 mV and the minimum resistance reading is 0.05 ohm. Since the voltmeter and ohmmeter functions use the same linear scales, the meter needs only two scales, one ranging from 0 to 5 and the other from 0 to 15.

Separate probes are provided for the ohmmeter and voltmeter functions. The input resistance of the instrument as a voltmeter is 100 megohms on all ranges except for the two most sensitive ranges (5- and 15-mV), in which case it is 10 megohms. The instrument's signal ground is isolated from the chassis, permitting measurements on voltage sources referenced up to 500 volts off ground. The injection of power-line ac from the Autovoltmeter back into the circuit under test, a frequently-overlooked characteristic of floated measuring instruments, is held to less than 4 mV rms by the use of a shielded power transformer.

Fig. 2. *New -hp- Model 414A Autovoltmeter switches to correct range in less than ⅓-second after contact is made. Illuminated display shows range and selected function (volts or ohms). Mirror-backed, taut-band meter has individually-calibrated scales for high accuracy. Separate probes on 4-ft. cables are provided for voltmeter and ohmmeter functions.*

AUTORANGING METERS

The combination of automatic range and polarity selection with a pointer-type meter has several operational advantages, in addition to the cost advantage already cited. With automatic ranging, no prior knowledge of the voltage at a point in a circuit is required. Time consuming trial and error procedures that approach the final reading from a less sensitive range are not necessary nor is there any waiting for the voltmeter to recover from an accidental overload.

The meter readout itself is advantageous in certain situations, such as those that depend on a sense of direction in the measurement. Adjustment of a circuit for a maximum or minimum indication is more easily performed while watching a moving pointer than it is with a numerical display. Likewise, adjustments within a certain tolerance are more easily made by bringing a pointer within indicated limits.

Circuit adjustments that require the monitoring of a voltage that spans several voltmeter ranges are speeded up by the self-acting characteristics of the Autovoltmeter. In examining the performance of transistor switching circuits, for example, the saturation and cut-off voltages may be read in quick succession as the circuit under test is triggered from one state to the other. This capability is further enhanced by the ability of the Autovoltmeter to be floated up to 500V above power line ground.

When there is a requirement for circuit adjustments that bring the indication to zero, both automatic ranging and polarity selection simplify the task. Gross overcorrections do not result in an overloaded meter. Overshoot in the adjustment merely changes the polarity indicator—the meter itself never pegs below zero.

FIXED RANGES

A HOLD switch is provided which, when engaged, disables the autoranging so that any particular range may be used over the full extent of meter deflection (automatic polarity indication continues to function, however). The range can be changed by a front-panel push-button that steps the ranging circuits one by one in a more sensitive direction each time the button is pressed (or to the highest range if the instrument is already on the lowest range).

The instrument protects itself from large overvoltages in the HOLD mode by switching immediately to the highest voltage range (1500V) in the event that the input voltage exceeds 140% of the range being held. It is thus impossible to overload or damage the Autovoltmeter with the voltages normally encountered in laboratory or production-line work. The self-protective upranging is neither required nor provided, of course, for the ohmmeter function.

Fig. 3. *Speed of response of new Autovoltmeter is shown by film strips photographed at 16 frames per second. In strip at left, input voltage is changed from +14 volts to −15.4 volts following first frame at top of strip. Range change, which requires uprange to 1500V and back down to 50V range, is completed by 3rd frame (polarity change requires no switching other than front panel polarity indicator). Meter pointer stabilizes on new reading by 10th frame. Strip at right shows response speed of meter without range change. Following 2nd frame, voltage is switched from +14V to +29.5V. Meter settles on new value by 9th frame, less than one-half second following voltage change.*

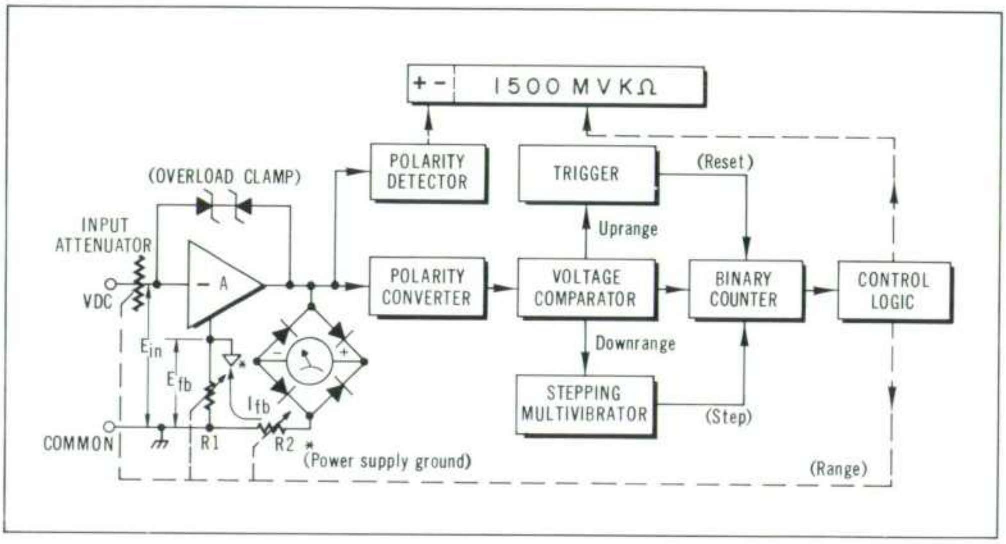


Fig. 4. *Block diagram of –hp– Model 414A Autovoltmeter operating in voltmeter mode. Feedback amplifier nulls input voltage E_{in} with voltage E_{fb} across resistor R1. Range changing is effected by switching value of resistor R1, in addition to two-state input attenuator. R2 is also switched to maintain same full scale voltage for amplitude comparators regardless of range.*

The HOLD mode is also useful for measurements on noisy signals because additional input capacitance is switched in when the instrument is placed in the HOLD mode. The added capacitance provides filtering which attenuates 60-c/s signals by more than 30 dB (the 3-dB point is at 1.6 c/s). The instrument in the HOLD mode is thus insensitive to 60-c/s sinusoids of peak values up to 7 times the full scale deflection of the range in use, superimposed on the dc.

The capacitance is removed in the AUTO mode to permit the fast response required for autoranging. Nevertheless, superimposed 60-c/s ac of peak values up to 20% of the dc being measured is tolerated in the AUTO mode without creating any interference with the autoranging sense circuitry.

AUTORANGING OHMMETER

As an ohmmeter, the Autovoltmeter supplies an internally-generated constant current to the unknown resistance and the meter circuit reads the resulting voltage drop. The current is only 1 microampere on the 5 k-ohm and higher ranges, and it is 1 milliampere on the ranges below 5 k ohm. In contrast with other ohmmeters that supply 10 or more mA under short-circuit conditions, the Autovoltmeter current never exceeds 1 mA, thereby assuring that sensitive devices are not harmed by the ohmmeter.

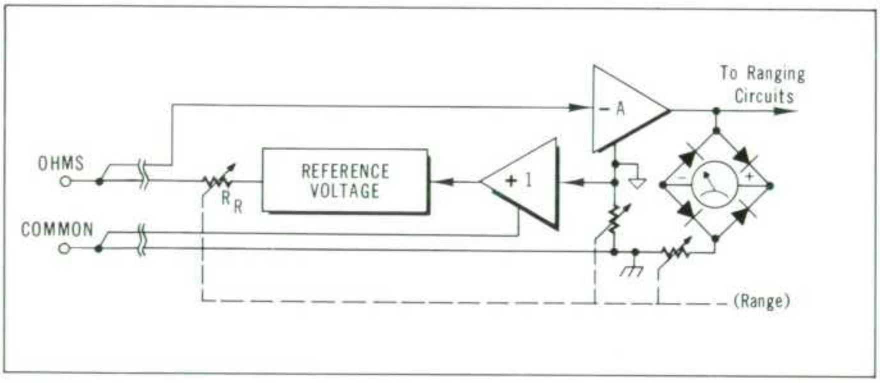


Fig. 5. *Block diagram of Autovoltmeter input circuits when switched to ohmmeter mode. Plus-1 amplifier bootstraps Reference Voltage Supply to maintain constant voltage drop across series resistor R_R. Ohmmeter cables are arranged for "4-terminal" resistance measurement.*

Either current may be selected by placing the Autovoltmeter in the HOLD mode and stepping the ranging circuits to the appropriate range. This technique is useful for checking semiconductor junction resistances, for instance, at two different operating points. To do this, the Autovoltmeter is placed in the AUTO mode before the component is connected, so that it switches automatically to the highest range. The instrument is then placed in the HOLD mode, the component is connected, and the DOWNRANGE button is pressed repeatedly until the meter reads on-scale, usually on the 100k range. Only 1 μA is thus supplied to the tested component. The reading is recorded and the button is pressed again until the meter reads on scale once more, usually on the 100-Ω range. Now the current is 1 mA. The second junction resistance operating point is thus measured and can be recorded.

Tests of very high values of resistance, such as leakage resistance, can be made with the new voltmeter by paralleling a lower value resistance with the unknown. The scale indication of a 1-megohm resistor, for example, is changed by half a scale division when a 100-megohm resistance is connected in parallel with it. (A half scale division

Fig. 6. *New autoranging dc voltohmmeter automatically changes measurement range whenever meter indication exceed 95% of full scale or drops below 25% of full scale. Autoranging speeds measurements in applications such as with dc resistance bridge shown here in which new instrument serves as null detector. Voltmeter switches ranges as required while bridge is brought to balance, thus avoiding overloading or pegging below zero.*

on the 1.5 megohm range corresponds to a change of 10 kilohms in the resistance being measured.) Lower value resistances provide correspondingly greater changes in pointer deflection. This measuring capability, which effectively extends the ohms measuring range, is an example of the advantages offered by the resolution of the linear resistance scales.

CIRCUIT OPERATION

A block diagram of the new instrument operating in the voltmeter mode is shown in Fig. 4. Voltage inputs are coupled to the meter circuit by the chopper-stabilized DC Amplifier. Sensitivity is determined by the overall transconductance of the amplifier, as controlled by resistor R1 in the main feedback network, and by the input voltage attenuator. The input attenuator is inserted automatically on the 15-V and higher ranges to reduce the input by 60 dB but it is bypassed on the lower ranges. The feedback network is switched to control the gain in 10-dB steps from 0 to 50 dB which, in combination with the input attenuator, achieves the 0 to 110 dB measurement range.

The measurement range is set by a logic system which senses the states of four flip-flops in the binary counter and which operates reed switches in the attenuator, feedback, and display circuits accordingly. Range changing decisions are performed by two voltage comparator circuits. When the meter reads below 25% of full scale, the down-range comparator allows the free-running multivibrator to step the binary counter at a 40-c/s rate. Each time that the binary counter is stepped, the logic system switches the attenuators to the next range in the more sensitive direction. Downranging continues until the meter reads far enough upscale or until the most sensitive range is reached.

If a voltage exceeding 95% of full scale is applied to the input, the uprange comparator fires a trigger circuit that resets the counter for the highest range. If at this time the meter deflection is less than 25% of full scale, the multivibrator steps the counter to successively more sensitive ranges until the meter reads upscale far enough to stop the down ranging.

The polarity converter passes positive voltages but inverts negative voltages. The amplitude comparators therefore always work with positive

(Continued on Page 6)

SPECIFICATIONS
-hp- MODEL 414A
AUTOVOLTMETER

DC VOLTMETER

VOLTAGE RANGE: ±5 mV to ±1500 V full scale in 12 ranges (manual or auto-ranging).

ACCURACY: ±0.5% of reading ±0.5% of full scale.

INPUT RESISTANCE: 100 megohms on 50-mV range and above; 10 megohms on 5- and 15-mV ranges.

SUPERIMPOSED AC REJECTION: In manual mode, insensitive to 60 c/s signal with peak value less than 7 times full scale dc level of range in use. In auto mode, insensitive to 60 c/s signal with peak value less than 20% of dc being measured.

OHMMETER

RESISTANCE RANGE: 5 ohms to 1.5 megohms in 12 ranges (manual or auto-ranging).

ACCURACY: ±1% of reading ±0.5% of full scale.

SOURCE CURRENT: 1 mA up to 5 k ohms; above 5 k ohms, 1 μA.

GENERAL

AUTOMATIC RANGE SELECTION: Automatically selects correct voltage or resistance range in less than 300 milliseconds.

MANUAL RANGE SELECTION: Downranges one range each time Downrange button is pressed. Starts over at 1500 volts from 5-mV range.

POLARITY SELECTION: Automatic in either Manual or Auto mode.

METER: Individually calibrated taut-band meter with mirror scale. Linear scales, 0 to 5 and 0 to 15.

ISOLATION RESISTANCE: At least 100 megohms shunted by 0.1 μF between common terminal and case (power line ground).

FLOATING INPUT: May be operated up to 500 Vdc above ground.

POWER: 115 or 230 volts ±10%, 50 to 1000 c/s. Approx. 18 watts.

SIZE: 7¾ in. (196.9 mm) wide by 6⅛ in. (155.6 mm) high by 11 in. (279.4 mm) deep.

WEIGHT: Net: 10¼ lbs. (4,6 kg). Shipping: 13 lbs. (6,4 kg).

PRICE: $650.00.

Prices f.o.b. factory
Data subject to change without notice.

AUTOVOLTMETER DESIGN LEADERS

Donald F. Schulz

James F. Kistler

Jim Kistler joined the engineering staff of the Hewlett-Packard Loveland Division in 1963 following attainment of both a BSEE and MSEE degree at the Massachusetts Institute of Technology. While at MIT, Jim worked in the development of electronic test instruments during the work periods of the cooperative work-study academic program. At -hp-, his primary responsibility has been the Model 414A Autovoltmeter. He is presently engaged in advanced digital instrumentation development.

Between high school and college, Jim had a regular tour of duty with the U.S. Air Force.

Don Schulz joined Hewlett-Packard, Palo Alto, as a development engineer in 1956. He has been responsible for the development of a number of the Hewlett-Packard first-generation transistorized instruments, including the 721A, 722A, and 723A Power Supplies, the 403A Voltmeter, and the 466A Amplifier. He was also group leader concerned with the development of the 310A Wave Analyzer, the 2460A Operational Amplifier, the 3440A and 3460A Digital Voltmeters, and the 410C Multifunction Electronic Voltmeter. He presently is Engineering Manager of the Digital and Precision Measurement section in the -hp- Loveland Division Engineering Laboratories.

Don obtained BSEE and MSEE degrees from the University of Wisconsin, just prior to joining -hp-, and did further graduate study at Stanford University. He also spent 3 years in the U.S. Navy as an electronics technician.

A SIMPLE METHOD FOR RECORDING FAST AND LOW-LEVEL WAVEFORMS

A recently-developed oscilloscope plug-in unit makes fast, convenient records of displayed signals and greatly reduces accompanying noise.

THE sampling technique is usually thought of as a technique for displaying repetitive waveforms which are too high in frequency for conventional oscilloscopes. This technique may, however, also be used to slow fast waveforms so that they can be permanently recorded on a paper-strip-chart recorder, thereby giving advantages in cost and convenience.

The sampling technique is used in a recently-developed recorder plug-in which operates with the wide-band *-hp-* 175A Oscilloscope. The recorder plug-in is a combination display scanner, sampler, and strip-chart recorder in a single unit. Its purpose is to permanently record on paper the waveform seen on the oscilloscope cathode-ray tube. Even though the displayed signal be far in excess of the 35-c/s or so capability of the strip-chart recorder, the recording can be made so long as the waveform is repetitive. Records can be made of waveforms up to 30 Mc/s in a third of a minute at about 1/20 the cost of photographic records.

Fig. 1. -hp- Model 1784A Recorder Plug-In (lower left of panel) used with Model 175A 50-Mc/s Oscilloscope.

NOISE-FREE RECORDING

In addition to the ease and low cost of its recordings, the recorder plug-in permits making many measurements that heretofore were very difficult if not impossible. Since, for example, the 30-Mc/s bandwidth of the recording system prevails only for repetitive and non-varying signals, the recorder has only a 35-c/s bandwidth for signals not in synchronism with the oscilloscope sweep. This factor permits recording low-level signals clearly *even in the presence of severe noise*.

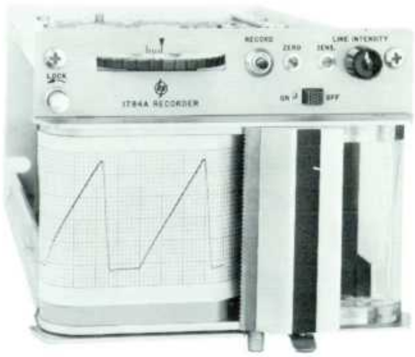


Fig. 2. -hp- Model 1784A Recorder Plug-In. Instrument makes permanent records of recurrent waveforms displayed on scope crt in a few seconds at a cost of about 1½ cents each.

Such a reduced-noise recording is shown in Fig. 5. By comparing the crt display in Fig. 5(a) with the recording in Fig. 5(b), the ability of the plug-in to reject noise is clearly demonstrated.

AUTOVOLTMETER

(Continued from Page 5)

voltages regardless of input polarity. The diodes in the meter circuit act as switches to cause the meter to read upscale with either input polarity while the polarity detector serves only to switch on the proper indicator.

When the instrument is switched to HOLD, the stepping multivibrator is disabled. Trigger pulses for stepping the counter are then generated by the front-panel push-button. At the same time, the triggering level of the uprange comparator is raised so that a voltage of 140% of full scale is required to generate the uprange signal.

The amplifier consists of two sections: the low-drift chopper amplifier section, which uses a photoconductor chopper, and a wideband direct-coupled section. Amplifier and component drifts are of such low order that no front-panel zero-set control is needed or provided. A capacitor bypasses high-frequency signal components around the chopper amplifier, thus enabling the fast transient response required for fast automatic ranging.

Overload recovery times are made very short with respect to ranging time by including breakdown diodes in a second feedback path. Under overload conditions, the breakdown voltage of one or the other of the diodes (depending on signal polarity) is exceeded, effectively limiting the potential rise at the amplifier input.

OHMMETER CIRCUITS

In the ohmmeter mode, the input circuits are switched to read the voltage at the ohmmeter probe, as shown in Fig. 5. The current to the unknown resistor is supplied by the reference voltage through series resistor R_R. The reference is boot-strapped by the +1 Amplifier, however, so that the current through the unknown resistor is constant. The voltage drop across the unknown resistor is thus a linear function of the unknown resistance, and linear meter scales may be used.

The ohmmeter ranges are selected by changing the gain of the amplifier, as in the voltmeter mode, and by changing series resistor R_R. Series resistor R_R can have either of two ohmic values. On the 5-ohm to 1.5 k-ohm ranges, the resistor is such as to supply 1 mA to the unknown. On the 5 k-ohm and higher ranges, a resistor 1000 times larger is switched in, thus allowing only 1 μA to flow.

The constant current for the unknown resistor is carried through both

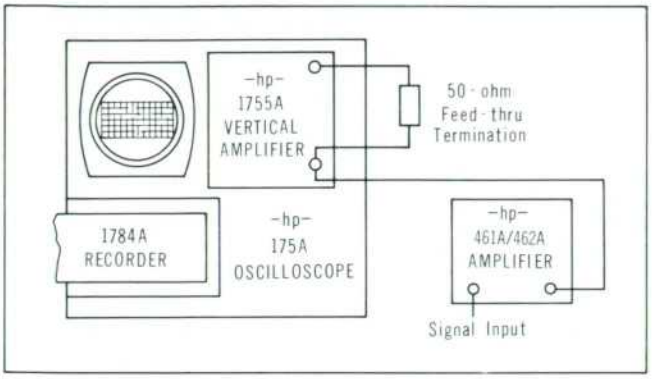


Fig. 3. *Instrumentation setup for recording pulses as small as a few microvolts. Model 461A or 462A Amplifier each provide up to 40 dB gain at bandwidths well beyond scope range.*

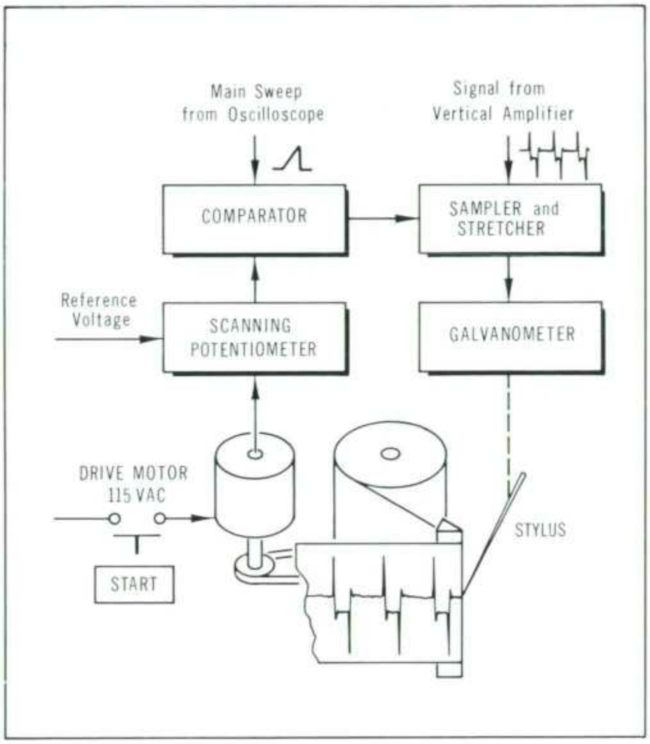
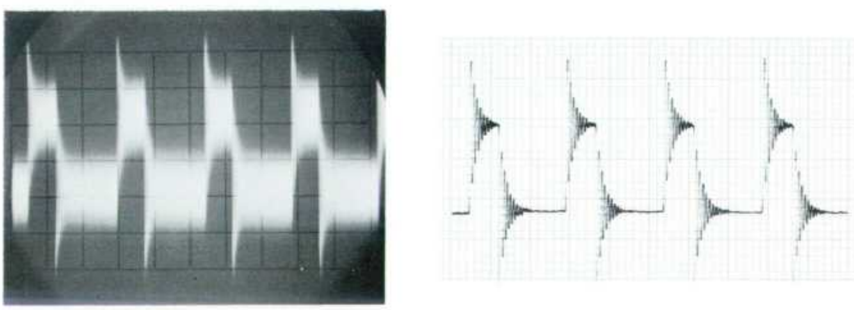


Fig. 4. *Basic arrangement of Model 1784A Recorder. Scanning potentiometer provides voltage proportional to position of chart paper. This voltage is compared with the main sweep voltage from scope. When these coincide, a sampling cycle is initiated in sampler. A single short sample 7 nsec in duration is then taken and stored in stretcher until next sample is taken during following sweep. The galvanometer moves heated stylus to a point on chart corresponding to average dc level of signal during sampling time. Galvanometer acts as integrator to smooth samples into continuous waveforms and greatly reduce noise (Figs. 6 and 7).*

The input signal is a 2-mV pulse with 2 mV of superimposed noise — a signal-to-noise ratio of 0 dB. Although the pulse is visible on the crt, the detail is obscured by noise. In the recording, however, the noise is eliminated and the waveform is clean. It is obvious that wide-band performance can be achieved even with S/N ratios worse than 0 dB and that wide-band analyses can be made of signals much smaller than a millivolt. This is demonstrated next.

The recording in Fig. 5 was made without external amplification at an oscilloscope sensitivity of 1 mV/cm. The overall sensitivity of this measuring system can, however, be substantially increased using an external amplifier (Fig. 3). The oscillogram and record of Fig. 6 show the ability of the system of Fig. 3 to resolve low-level signals at an overall sensitivity of 50 μV/cm. On the crt the input signal is combined with about 200 μV of noise and produces an almost unrecognizable trace which, by comparison, is still clear on the recorder. The 461A/462A Amplifier used in this setup provides 40 dB of gain over bandwidths greater than 100 Mc/s.

Fig. 7 is an impressive indication of how much sensitivity and noise clean-up is possible with this measuring setup. Here the oscilloscope and the external amplifier achieve an overall sensitivity of 5 μV/cm! The original signal consists of a 6-μV pulse in the presence of 50 μV of noise, a S/N ratio of —18 dB. Although the crt gives only a faint impression that a signal is even present, the recording is a clearly-visible signal with a S/N ratio of +12 dB. Effective noise referred to the system



(a) (b)

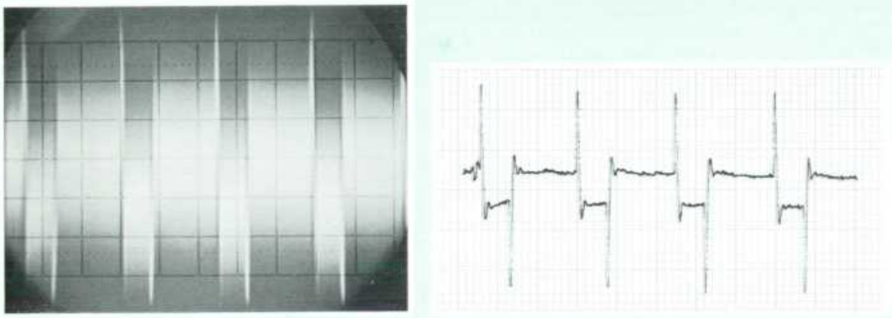
Fig. 5. *(a) Oscillogram comparing display of noisy signal with Recorder record (b) in which noise is eliminated. Sweep speed is 2 μsec/cm; scope sensitivity is 1 mv/cm. Pulse is 2 mV with 2 mV of noise.*

the "ohms" and "common" probe cables on conductors that are separate from those that carry the voltage measurement back to the instrument. The voltmeter circuits thus read the IR drop in the unknown resistance directly, and the resistance of the current-carrying wires is removed as a factor in the measurement.

ACKNOWLEDGMENT

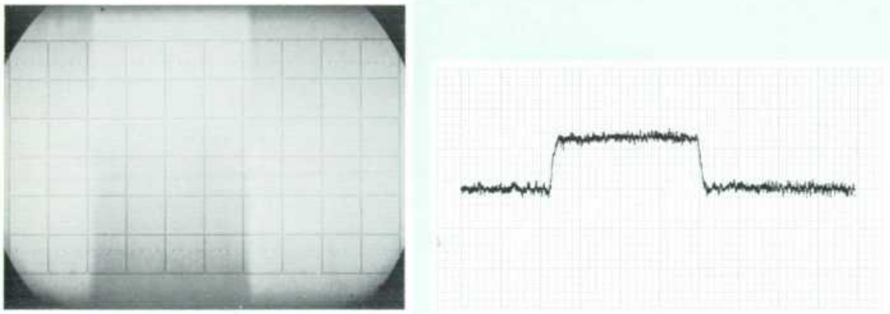
The design and development of the -hp- Model 414A Autovoltmeter was carried out at the Hewlett-Packard Loveland Division under the project leadership of Donald F. Schulz. Product development was the responsibility of Jerry Blanz and circuit design and development was performed by the undersigned. Many helpful suggestions were provided by Paul G. Baird.

—*James F. Kistler*



(a) (b)

Fig. 6. *(a) Oscillogram of signal with considerably more noise than Fig. 5 compared with record (b). No noise is yet apparent in record. Scope sensitivity is 50 µV/cm. Sweep speed is 2 µsec/cm.*



(a) (b)

Fig. 7. *(a) Oscillogram in which signal is almost completely masked by noise compared with resulting Recorder record (b). Overall sensitivity is 5 µV/cm. Signal is a 6-µV pulse with 50 µV of noise. Noise improvement is about 30 dB. Sweep speed is 200 nsec/cm.*

input is only 1½ µV over a bandwidth of about 15 Mc/s.

REPETITION RATE

Because of the nature of the technique, the observed noise on the recording will correspondingly increase as signal repetition rate decreases. At a repetition rate of 1 kc/s, for example, the observed noise will be closer to 5 µV. Since observed noise is directly dependent upon the frequency response of the recording system, a recorder with lower frequency response and a longer scanning time may be used with even more favorable results when the signal repetition rate is low. In place of the 1784A Recorder Plug-in, for example, the 1782A Display Scanner Plug-in may be used in the 175A Oscilloscope. When this plug-in is used with a Moseley X-Y Recorder, over a 10 times improvement in S/N ratio can be obtained in the final recording. Also, the -hp- 465A Amplifier may be used in place of the 461A/462A to provide the same 5-µV/division sensitivity over a lesser bandwidth.

ACKNOWLEDGMENT

The recorder plug-in was made possible by the efforts of Dr. Arthur Miller and engineers at the Sanborn Division of -hp- who developed a new galvanometer drive with an extremely low external magnetic field. The low external field permits the recorder to be operated in close proximity to the oscilloscope crt.

— *John N. Deans*
Applications engineer
Oscilloscope Division

SPECIFICATIONS

-hp- MODEL 1784A RECORDER

(In 175A Oscilloscope)

BANDWIDTH: DC to greater than 30 Mc/s when installed with a plug-in having 40 Mc/s or greater bandwidth.

RECORDING CYCLE TIME: Approximately 20 seconds.

ACCURACY OF RECORDING: Recording duplicates CRT display with better than 3% accuracy.

WRITING RATE: Waveforms with slopes of at least 50:1 can be recorded with a continuous line.

REPETITION RATE: Signal rep rates of 60 cps or greater and sweep speeds faster than 2 ms/cm are required. (Usable below these limits, but with progressively greater distortion in the form of small steps on the plot.)

PRICE: Model 1784A, $775.00.

Prices f.o.b. factory.
Data subject to change without notice.

RECORDER PLUG-IN DESIGN LEADERS

Donald Braidwood

Alan D. Henshaw

Keith McMahan

Don Braidwood joined Hewlett-Packard in November, 1963, and began working on the 1784A Oscilloscope Recorder. Prior to that time, he had been engaged for several years in the development of geophysical measuring and recording instrumentation.

He holds a Bachelor's degree in Electrical Engineering from Georgia Tech, and an M.S.E.E. degree from the University of Missouri, where he was also a part-time Instructor in the Electrical Engineering Department.

Don served for two years in the U. S. Army with a missile electronics group and has also had summer employment with the U. S. Naval Ordnance Test Station.

Al Henshaw joined Hewlett-Packard in 1960 as a tool engineer. He transferred to the Colorado Springs Division in 1963 as mechanical designer on the 1784A.

Prior to joining –hp–, he worked in England and Canada as mechanical designer on gas turbines, jet engines and telecommunication manufacturing facilities.

Al earned a degree from Royal Tech. College in Glasgow, Scotland.

Keith McMahan came to Hewlett-Packard at Colorado Springs in 1964 and was assigned initially as product designer on the 1784A recorder project.

Following graduation from Rensselaer Polytechnic Institute in 1955 with a B.M.E. degree, Keith served 2 years as an officer in the U. S. Navy. The succeeding three years were spent doing research on digital tape recorder systems and attending New York University, where he obtained his M.S. degree in 1960. He was elected to membership in Pi Tau Sigma and Tau Beta Pi while attending R.P.I.

Prior to joining –hp–, Keith worked more than three years as project engineer on the data acquisition and analysis portion of a passive reconnaissance system for the U. S. Air Force.