SENSITIVE SAMPLING PLUG-INS ADD NEW CAPABILITIES

Human engineering and new circuit design provides 875 megacycle bandwidth and two millivolt sensitivity in a sampling system as easy to operate as a standard laboratory oscilloscope. Further, these sampling plug-ins facilitate direct digital readout of risetimes, etc. to a fraction of a nanosecond.

HISTORY

Extreme operating speed and versatility have propelled electronic instruments into almost every field of science and industry. The low inertia cathode-ray tube and a video amplifier are the heart of almost all conventional oscilloscopes. For widest bandwidth the cathode-ray tube used alone extends perhaps another decade beyond amplifier bandwidth limits. Oscilloscopes of this latter class may have 1000 megacycle-plus bandwidth, but for lack of amplification, generally have stiff beams in the range of 2 to 200 volts per centimeter. Present-day high-speed electronics employing, for example, tunnel diodes and fast transistors, demands the high sensitivity and bandwidth of the sampling oscilloscope. The oscilloscope extends the senses of the operator to a domain in time which is normally inaccessible to his senses. Thus, by sampling a 1000 megacycle signal event and then displaying it on a conventional oscilloscope screen at a very slow speed, the eye is then able to interpret the pattern and understand the nature of a signal event which would otherwise be inaccessible to the operator's mind.

THE STROBE PRINCIPLE

Suppose each time a drop of salt water leaves a partly open faucet it passes over a trigger wire and flashes a light. This strobe of light would then always catch the drop of water at the same point as it leaves the faucet. If an electrical delay were now inserted between the trigger signal and the light strobe, it would be possible to select a point in time when the drop of water were just impinging on a puddle of water below, and the drop of water would appear stationary just above the surface. If the operator then were to select slightly greater amounts

of delay, the "strobed" drop would appear to progress very slowly into the surface of the pond, allowing detailed analysis of a fast-changing event which would otherwise not be visible to the eye.

The sampling timebase plug-in receives its trigger signal from the input signal as it first enters the companion sampling vertical plug-in units. The delay control on the timebase can be set to wait as necessary until the desired signal reaches the end of the internal signal-delay line in the vertical plug-in and is ready for sampling. The timebase, further, electronically and automatically performs the function of scanning through the desired time interval one wishes to study. As the sampling-time delay is increased incrementally, the beam of the indicating oscilloscope is moved from left to right.

Rate of taking samples is controlled by the hold-off portion of the 3T77 to assure adequate time for processing each event, and is always at least 10 microseconds. After each sample is taken, a dot appears on the screen at the proper horizontal and vertical point corresponding to the instantaneous height of the signal when sampled and the time at which the sample is taken. This dot is displayed for as long as necessary until the next signal event is received, but always at least 10 microseconds. Figure 2 demonstrates the individual dots of the sampling process.

TWO SAMPLING PRINCIPLES

A system which can be described simply as "open loop" sampling is shown in Figure 3. The signal is sampled independently each time the sampling process takes place and each discreet sample is taken slightly displaced in time so that the final display of the height of each sample describes the waveshape of the high-speed event. Each measurement, independent of all others, must be made accurately and linearily in order to have a true display.*

Figure 4 shows the "closed loop" sampling system used for the vertical sampling plug-in. After each sample is taken in the system of Figure 4, the sampled voltage

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* The Tektronix type "N" sampling system is of this type.

level is stored in the memory and supplied back to the terminals of the sampling input bridge so that the next sampling event measures only the difference between the stored voltage and the new signal voltage. If the signal voltage has not changed between these two sampling intervals, there will be no signal presented through the error amplifier. However, if the voltage level changes a small percentage between samples, an error signal will enter the error amplifier and change the stored signal in the correct direction and magnitude to produce the new sample signal output level. Thus, the sampling process serves to test for error between the output signal from the previous sample and the new input signal, rather than to provide the entire output signal from each sample. The inherent linearity of this "closed loop," or "feedback," system is excellent, for the sampling system tends to reduce errors toward zero during each sampling event.**

INPUT IMPEDANCE

One of the basic choices affecting a sampling oscilloscope is that of input impedance. The choice depends upon an understanding of the four-diode sampling bridge of Figure 5. Terminal 1 is the point to which input signal voltage will be introduced. Terminals 2 and 3 are normally back-biased by sufficient voltage to entirely cut off current flow to the four diodes in the bridge. Terminal 4 is the input terminal to the error amplifier. It is driven by the output signal from the memory storage circuits to the voltage level resulting from the last sampling event. Terminals 2 and 3 are kept at constant voltage difference with respect to terminal 4. Thus, terminals 2 and 3 are also driven from the output signal from the memory storage circuits. The sampling process is completed by providing two strobe pulses of opposite phase to terminals 2 and 3 such that all four diodes of the signal input bridge are closed momentarily and terminal 4 tends to assume the voltage at terminal 1. The resulting voltage change at terminal 4

** The "closed loop" sampling system may further be defined as a "sampled-data feedback system, zero order." Sampled Data Control Systems, McGraw Hill, 1958, page 5 and chapters 2 and 3.

is then amplified by the error amplifier and operates on the memory circuit so as to drive the memory output to the newly measured signal level. Shortly after, the new output signal voltage is fed into terminals 2, 3 and 4 of the sampling bridge in preparation for the next successive sampling event. During the small part of one nanosecond when the four diodes are strobed into conduction, the

Italics

error amplifier input is drawn toward the new signal level. The efficiency of the transfer is directly related to the impedance at terminal 1. It is thus highly desirable to remove the impedance of the circuit under measurement from the impedance at terminal 1. For this reason, the 3S76 employs a terminated delay line in front of the four-terminal bridge to fix the terminal 1 impedance at 25 ohms and the "sampling efficiency" at 25 to 30%. This removes the possibility of (1) change in sampling efficiency resulting from change in test circuit impedance (attached to terminal 1); (2) d-c shift or complete loss of ground reference when inherent sampling bridge unbalances interact with different terminal 1 impedances (R,L,C); and (3) generation of unwanted vertical signal waveform by signal-voltage-produced changes in circuit impedances (caused by bridge unbalances as in 2). Thus, the delay line removes unpredictable deflections resulting from impedances associated with the signal source.

Delay preceding the sampling bridge eliminates the hazard of intercoupling between two sampling bridges attached into the same circuitry, which might otherwise cause erroneous indications. Further, it permits the observation of "dead time" ahead of the leading edge of the triggering signal, in the fashion of the delay line in a conventional oscilloscope. The greater flexibility of observing pulse waveshapes by internal triggering greatly offsets any disadvantage of 50 ohm input impedance.

It is sometimes difficult to visualize the effects of a very small input capacitance, say 3 picofarads, on the operation of a high-speed circuit at 1000 megacycles. Let us multiply 3 picofarads by 10^6 and divide the frequency by 10^6. A 3 microfarad capacitor at 1000 cycles would indeed be a difficult load to apply to the stages of an audio-amplifier at the point of measurement, while expecting

the performance of the amplifier to remain unchanged.

Consider the common laboratory oscilloscope with 1 megohm, 25 picofarad input impedance and 30 megacycle basic bandwidth. The RC time-constant at the input terminal is 25 microseconds, corresponding to approximately 7 kilocycle bandwith at the upper 3 db point! It is necessary to reduce the input terminal RC time-constant if full bandwidth is to be realized. A 1000-ohm plate-load resistor, for example, would approach 6 megacycle upper bandwidth limit when connected directly to the terminals of a 25 picofarad, 30 megacycle instrument. Even if the external circuit were to contain insignificant stray capacitance to

Italics ground, it would still be necessary to have a circuit impedance of 200 ohms or less to reasonably utilize the bandwidth of the 30 megacycle oscilloscope.

Now, an input impedance of 3 picofarads at 1000 megacycles is -J53 ohms. However, at 500 megacycles, the reactance is -J106 ohms. Thus, it can be seen that 50 ohm resistive input impedance offers the advantage of constant input impedance over the passband in which the measurement is to be made. Resistive input impedance allows either current- or voltage-input waveforms to be monitored by the oscilloscope.

Most high-speed circuitry is designed at low impedance in order to reduce the effects of circuit and stray capacitance on signal waveform. Thus, 50 ohms is directly compatible with many circuits being studied.

TRIGGERING

The noise level of the type 3S76 is approximately 2 millivolts peak-to-peak. With the SMOOTH NORMAL switch in the SMOOTH position, the gain of the error amplifier is reduced by 4 times, and the noise level of the display is reduced to 1

Italics millivolt peak-to-peak. This high sensitivity in the display combined with the extreme bandwidth puts intense requirements on the trigger system to respond equally to a large-amplitude signal and a small signal of short duration. The most descriptive term for discussion of trigger circuit performance is the term "trigger slewing." Figure 6 shows the trigger slewing characteristic of the time-

is generated to initiate the strobe generator. As a result, sample number 2 corresponds to a later event in time on the input signal waveshape. After the sample has been taken, the error amplifier moves the output of the memory circuit to the new level corresponding to the second sample, and the sweep unit now moves to the right one dot after which time the spot is unblanked for display of the second sampling event. Blanking of the spot lasts from the start of the sampling event until the deflection amplifiers are steady at the voltages of the next dot. As the waveshape proceeds, successive dots are unblanked and presented for periods of time depending upon the time interval between input signals. After the selected number of dots have been displayed, the CRT team is blanked and returned from the right edge to the left edge of the screen and the process is repeated.

The repetition rate for display is set by two factors. First, it is simply the repetition rate of the signal divided by the number of the dots displayed, provided that the oscilloscope can reset quickly between signal events. Second, when significantly longer times are required for operation of the fast ramp on slower sweep speeds, the number of displays per second are sometimes limited entirely by the process time of the timebase. At 10 μsec per division, the maximum sample rate is approximately 3 kc. In any case, it can be seen that the greater the number of dots displayed, the longer the time required for each complete display. For this reason, it is useful to select 10 or 100 dots per centimeter in the display.

DELAY LINE EQUALIZATION

A particularily important part of a sampling oscilloscope is the delay line. A large, low-loss line is commonly employed to provide the utmost preservation of the input waveshape. Such a delay line tends to become bulky even when the shortest possible length is used. Attempts to reduce the volume of the delay line package causes loss of high frequencies from the input signal. Equalization is employed ahead of each sampling bridge to correct for internal delay line losses

in the sampling vertical plug-in. Care must also be exercised in the use of external signal cables to keep signal losses low.

OFFSET VOLTAGE

The front panel "OFFSET VOLTAGE" controls on the sampling vertical supplies ±1 volt dc "buck" or "boost," into either channel so that millivolt signals may be observed in the presence relatively large DC potentials. By monitoring the offset voltage required to offset the pulse from baseline to peak, the peak voltage of an input pulse may be measured without use of amplifier and CRT calibrations.

SNAP-OFF DIODE

The snap-off effect of a diode is highly important in nanosecond circuitry. While the HD5000 at the left of Figure 9 behaves as a normal diode at 50 mc, the right-hand diode has a peculiar quirk. During turn-on the current seems to grow slowly. After the peak forward voltage passes, the forward characteristic falls toward the origin at much lower impedance than during the initial turn-on. Then comes the quirk. Even after the voltage has reversed, current flows. In fact, for a time, more reverse current flows than the peak forward current. During this interval of reverse-current flow, the diode is being drained of the same current carriers which took so long to turn on at first. When they are finally swept out, reverse current suddenly ends, and a "snap-off" results. The inverse voltage snaps (with very fast risetime) to the negative peak voltage. Although our example is given for a 50 megacycle rate, it should be clear that a diode may also be pulsed through the "snap-off" area at any slower repetition rate.

Each time a sample is taken in the vertical plug-in, a "snap-off" diode is switched from 60 ma d-c forward current to more than a hundred milliamperes reverse. When the diode suddenly open-circuits, this large current is permitted to drive the sampling bridges into conduction. A shorted stub line forms a reflection which turns the bridges off again, all in a fraction of a nanosecond.

THE DISPLAY

Either A or B trace may be inverted if desired and displayed separately or in "dual-trace" mode. The algebraic sum or difference can be selected in the "A + B" mode. In addition, the A trace may be displayed vertically against the output of the B trace in the horizontal direction. The resulting Lissajous display is useful in phase measurements between the two channels, for high-frequency core flux density versus magnetization, or in E-I measurements such as in Figure 9.

The speed with which the display is scanned can be controlled by several methods. For example, the manual scan control gives the operator smoothed direct control of the position of the spot in the horizontal direction and, simultaneously, the sample-delay scanning function. An external sweep voltage from a pen recorder or laboratory oscilloscope may be applied back to the external sweep input terminal of the timebase to control the scanning function. In similar fashion, the sweep output connector of the timebase may be connected to a companion laboratory oscilloscope to provide identical staircase sweeps.

PROBES

Several types of probes may be used. Two of these are oriented toward the "dispensable" mode of installation wherein the original circuit is wired to contain either current-sample or voltage-sample output points for the oscilloscope. The first of these, the current-sample probe, is illustrated at top center of Figure 10. Sensitivity of this probe is 5 millivolts per milliampere. The voltage type is shown on the left. When a voltage measurement is to be made, a series-resistance 10x or 100x pencil probe is plugged through the dispensable chassis adapter to the circuit under test. Total loading on the circuit under test is 0.6 picofarads before connection of the probe and 1.2 pf when the probe is actually in service. This low-capacitance loading helps preserve signal waveshape and permits accurate measurement even in moderately high impedance fast circuits.

It is sometimes advantageous to observe waveforms with 10-megohm input

impedance. The cathode-follower probe of Figure 11 is arranged to convert an input signal to the low impedance necessary for operation of the sampling vertical plug-in. Attenuation factor of the probe is 10x and plug-on attenuator heads permit attenuation factors to 1000x.

DIGITAL READOUT

Probably the most interesting application of the sampling process is shown in the digital oscilloscope of Figure 12. This type 567 oscilloscope produces automatic readout of voltage amplitude on either trace, time difference measurements between rise or fall of A or B or between traces, risetime measurements between selected amplitude points, and has the ability to average a number of traces to produce a final weighted answer. Perhaps for the first time, the time constant of an RC or L/R waveform can be automatically read out. The sampling system provides discreet output pulses throughout the signal waveform which are readily counted and converted to digital display.

DOT READOUT

Without the type 567 oscilloscope, it is still possible to enjoy a "modest" numerical technique. Each dot in a display represents a calibrated step in time. A simple count of the number of dots from 10 to 90% amplitude provides an excellent risetime measurement. By use of the type 564 memory oscilloscope (or a camera and type 561), a display can be recorded and then analyzed.

WAVEFORM STANDARDS

Figure 13 shows the pulse waveshape of a mercury-switch generator. The risetime of this particular display is approximately .44 nanosecond (0.4 nanosecond sampler and 0.18 nanosecond pulse generator risetime). This suggests an area of extreme difficulty, namely pulse waveshape standards and standard risetime generators. Oscilloscope manufacturers have been aware of this problem area for some time. However, there has not been certification capability at the National Bureau of Standards in time-domain measurements as contrasted by efforts

in the frequency domain. Many requests have been received for certification of risetime of a display instrument, traceable to the National Bureau of Standards. At present such certification must be met by the manufacturer. Future work can be expected in this area, but will depend primarily upon customer interest and the availability of funds for NBS studies, as well as a fuller understanding of the needs.

Acknowledgment

The author wishes to acknowledge the teamwork behind the design of these instruments. Particular credit is due development engineers C. Calvin Hongel and A. James Geddes.

Clifford H. Moulton

Figure 1. The sampling plug-ins and a general-purpose laboratory oscilloscope.

Figure 2. Coarse display uses 10 dots per centimeter and 10x magnifier to show each sampling dot.

Figure 3. "Open loop" sampling system.

Figure 4. Simplified "closed loop" or "feedback" sampling system.

Figure 5. Simplified sampling bridge.

Figure 6. Timebase trigger-slewing curve shows extremely fast impulse response, plus good sensitivity.

Figure 7. 10 microwatt 250 megacycle display, 20 mv/cm and 2 ns/cm.

Figure 8. Functional block diagram of plug-in system, excluding the second signal channel and dual-trace circuits.

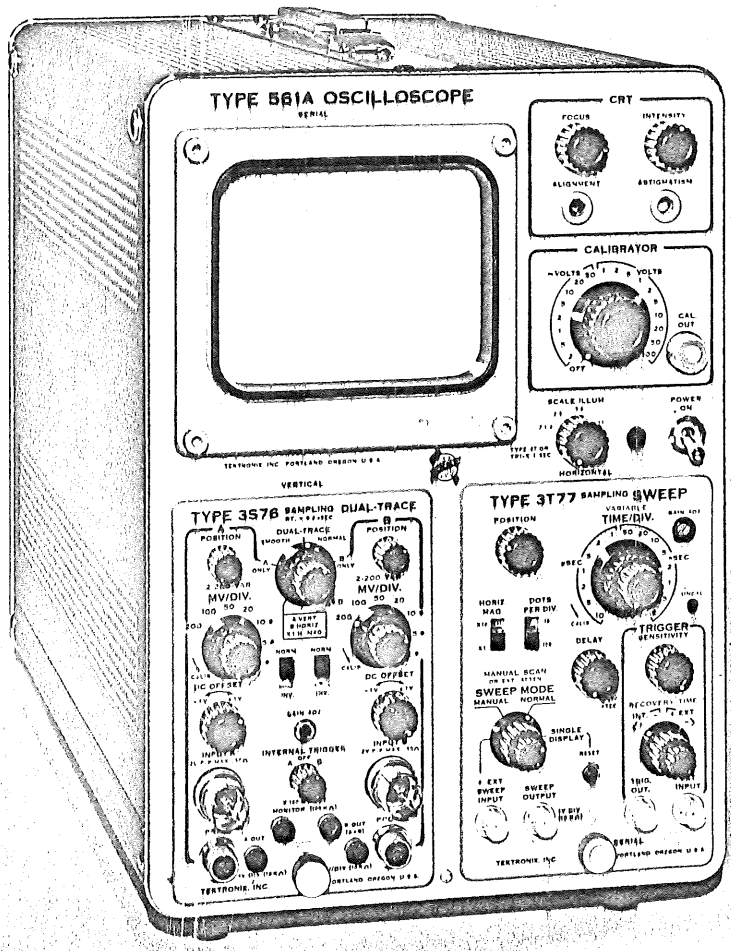
Figure 9. The E-I characteristics of two diodes at 50 megacycles utilizes the "A Vertical, B Horizontal" display. At left is an HD5000 fast diode, and at right is a snap-off diode, both at 40 ma/cm vertical and 1 volt/cm horizontal. See text.

Figure 10. These two "dispensable" probe adapters can become an original part in fast circuit design. 10X, 500 ohm resistive probe is shown below.

Figure 11. The cathode-follower probe retains full bandwidth but has high input impedance.

Figure 12. Accurate digital readout of fractional nanosecond rise, delay, or fall times and time differences are possible using sampling plug-ins.

Figure 13.



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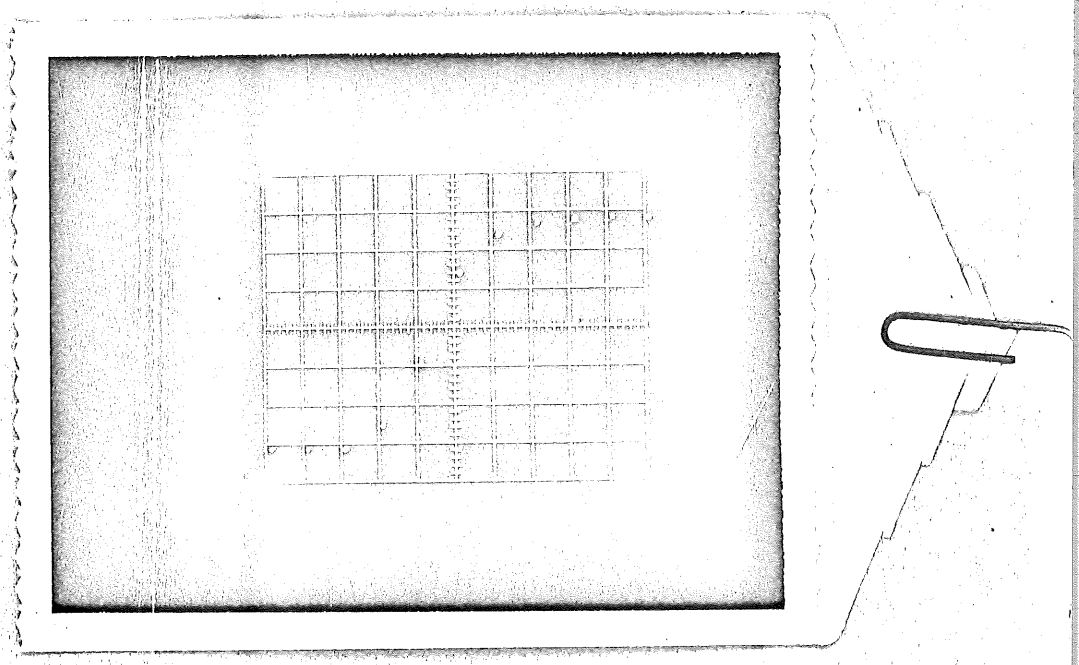

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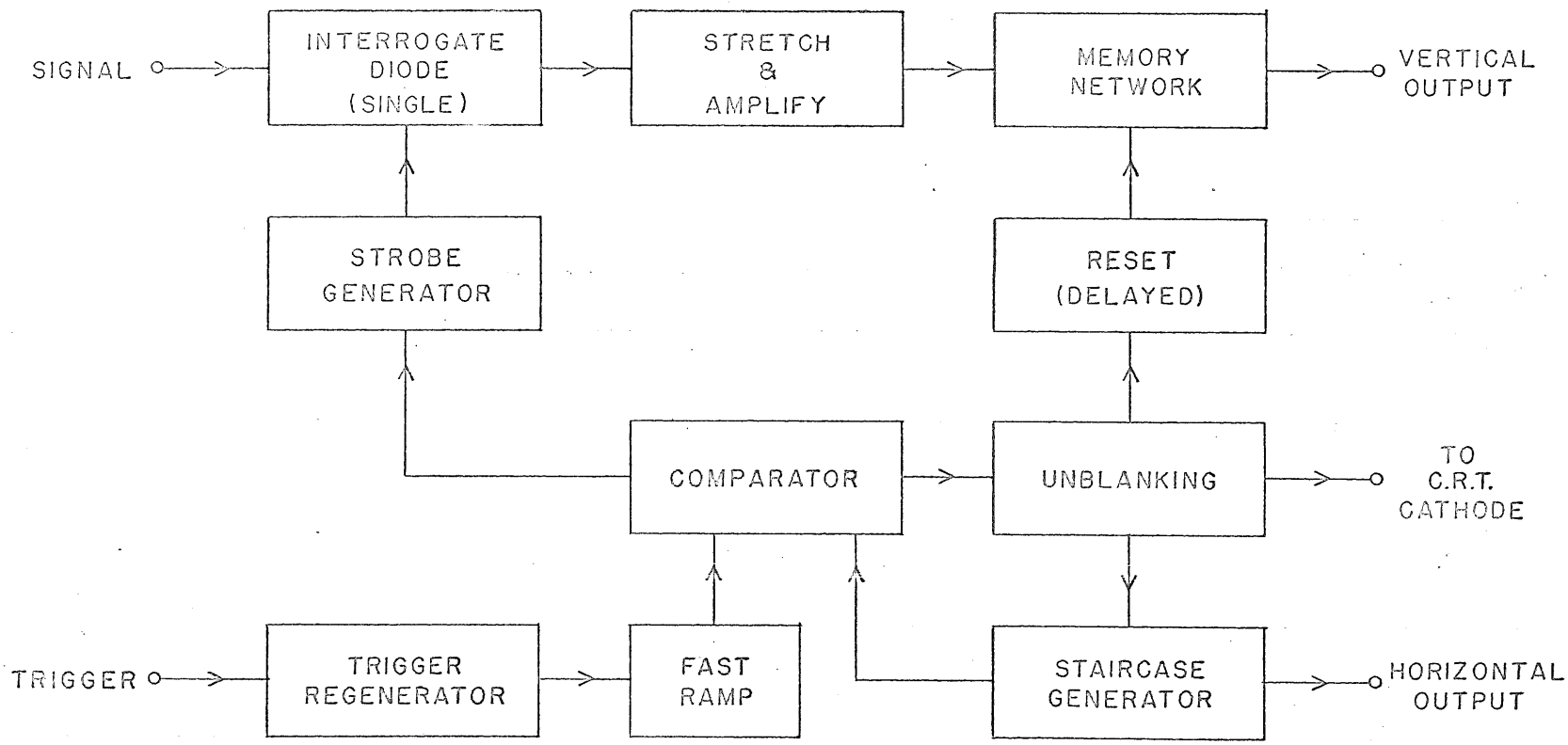

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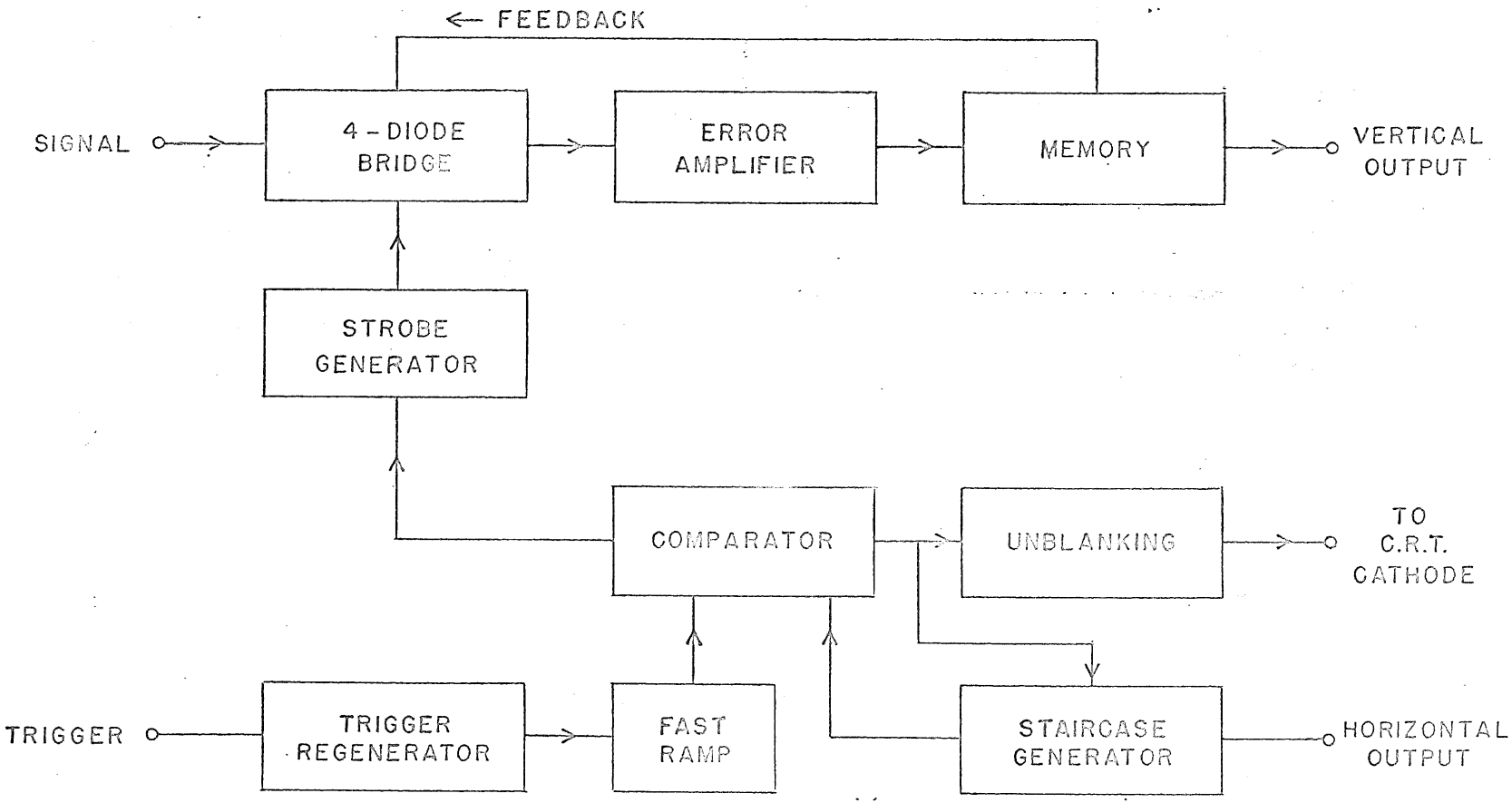

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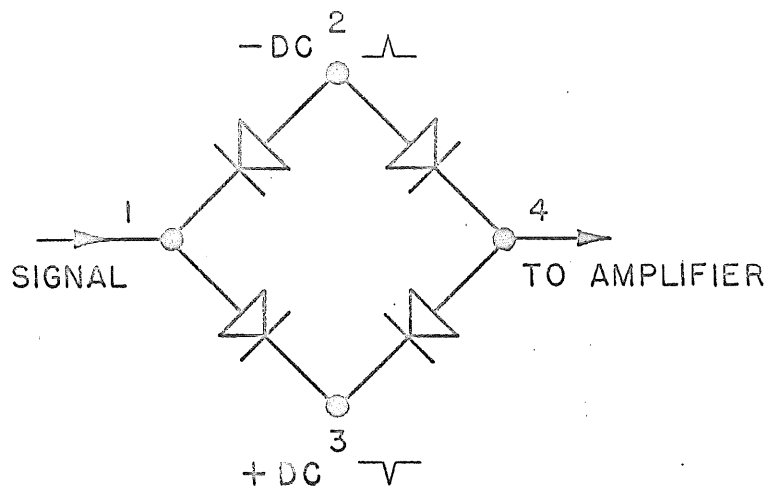
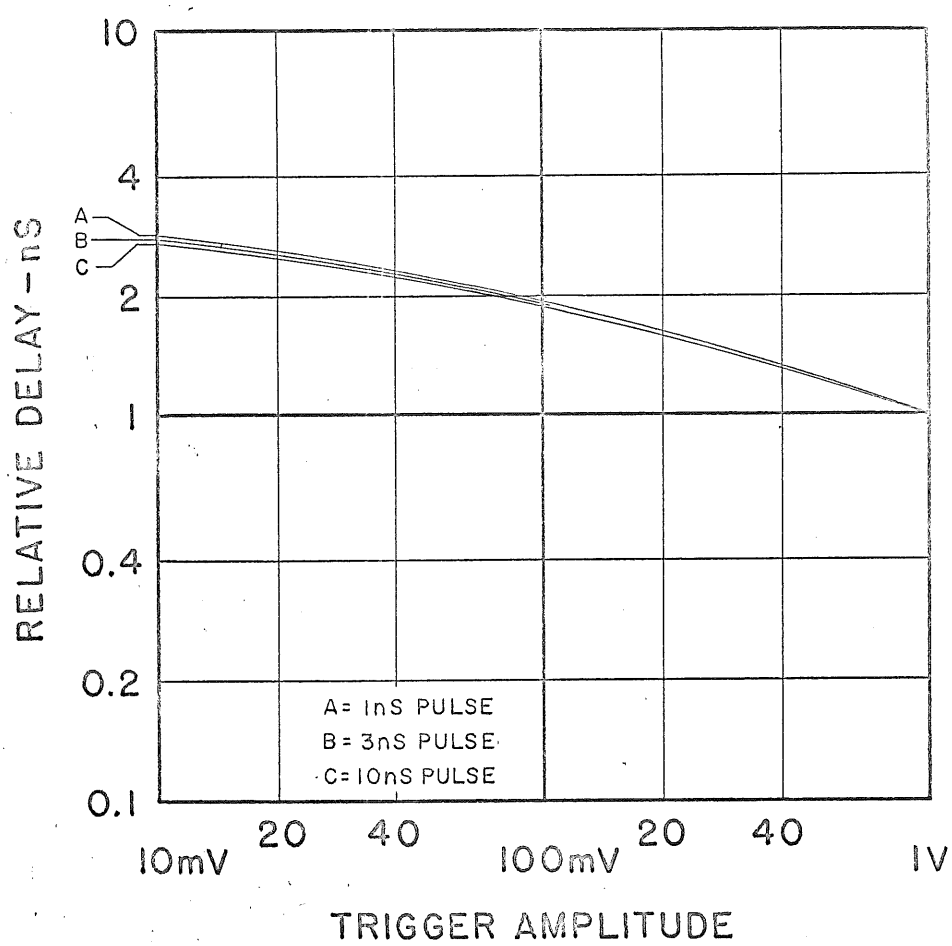


Figure 5. Simplified sampling bridge.



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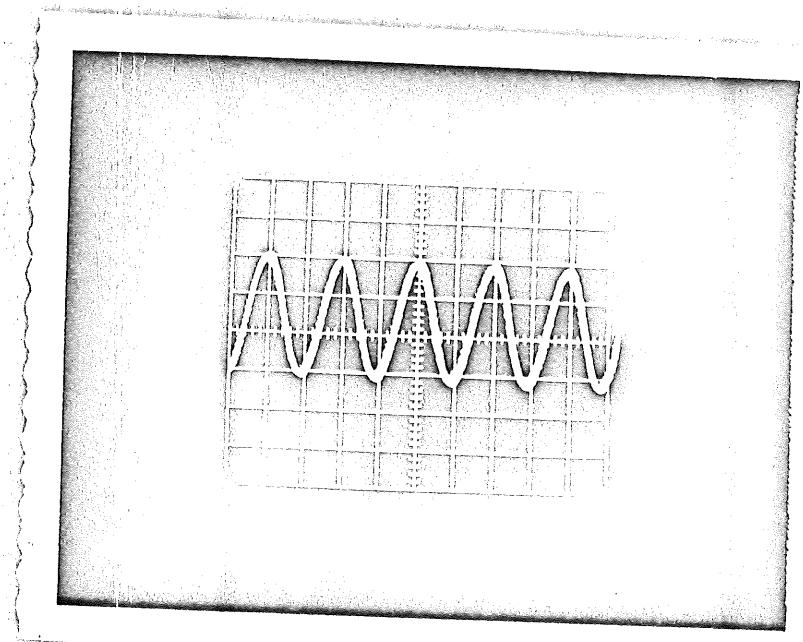
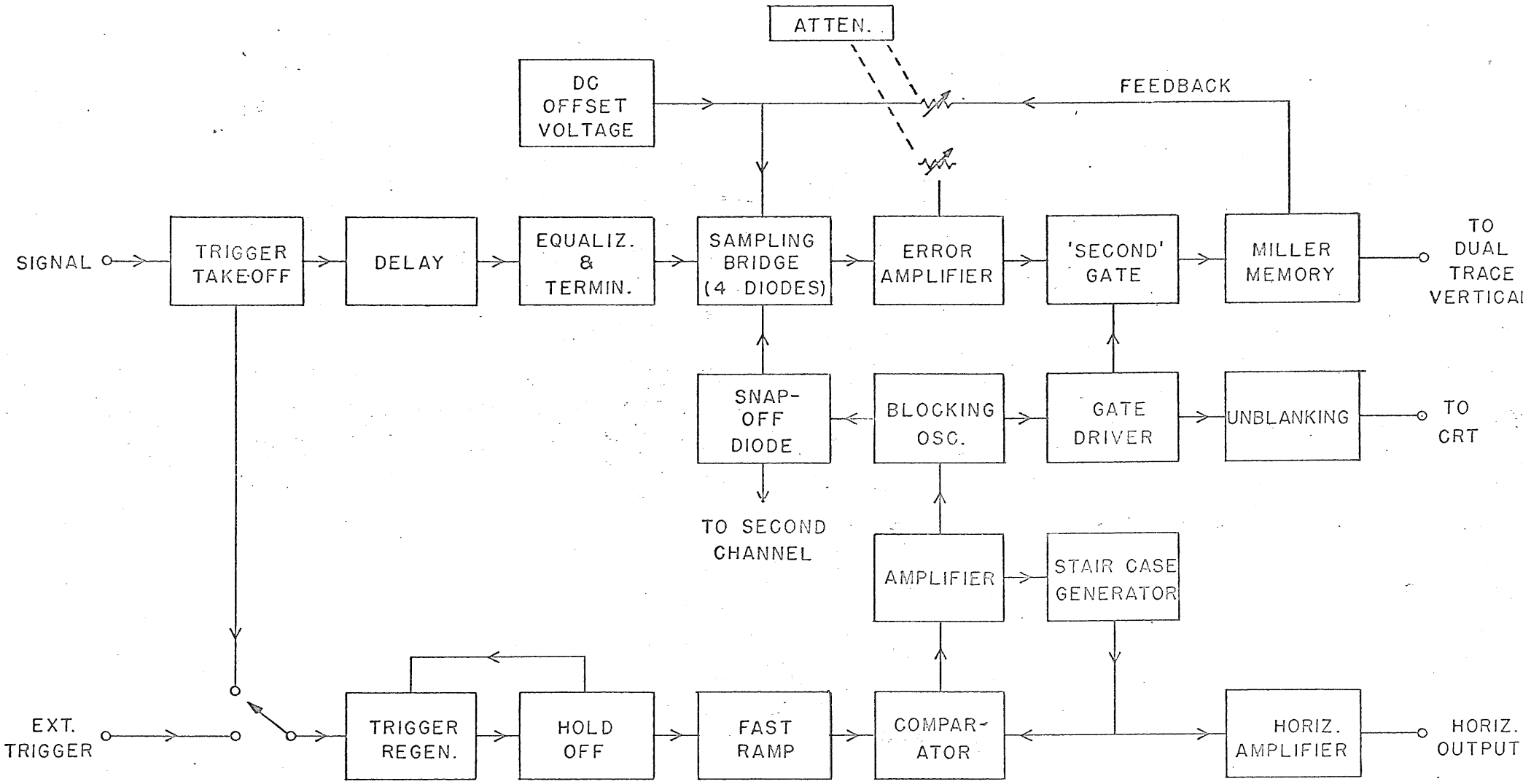


Figure 7. 0.1 milliwatt 250 megacycle display, 20 mv/cm and 2 ns/cm.



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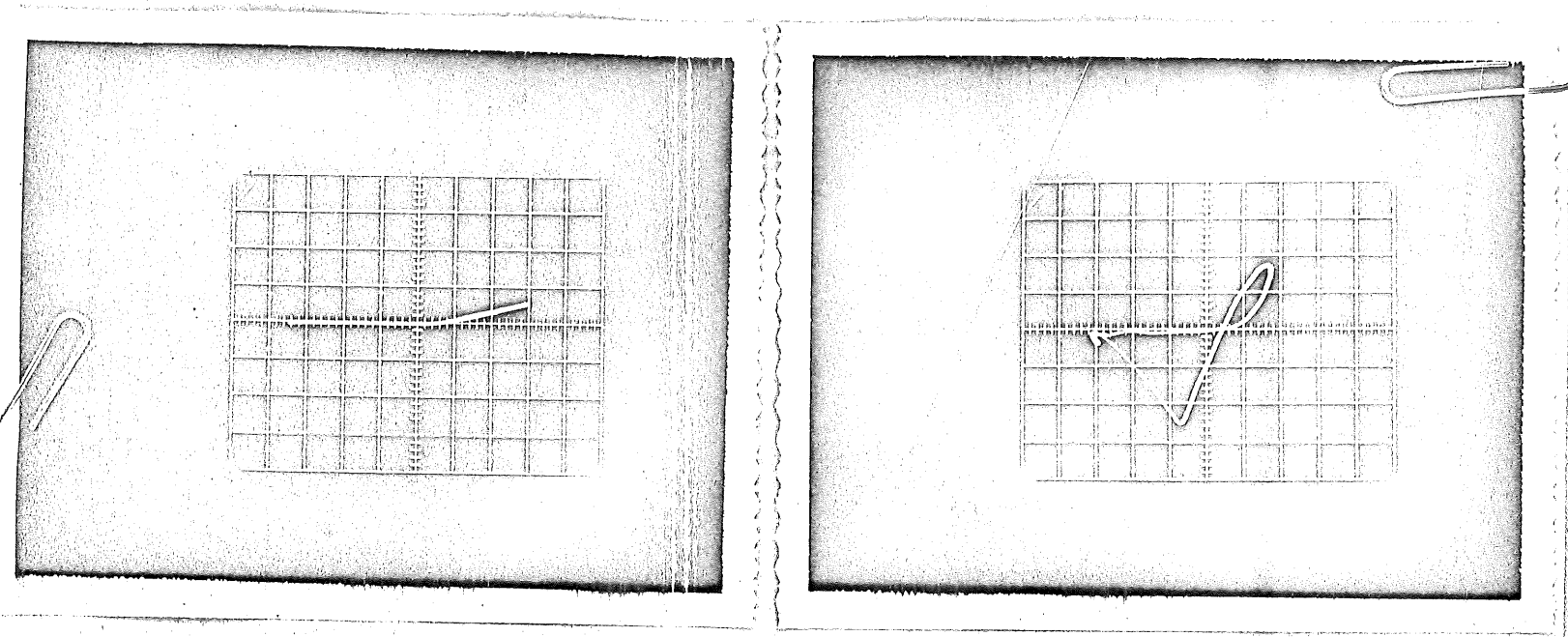

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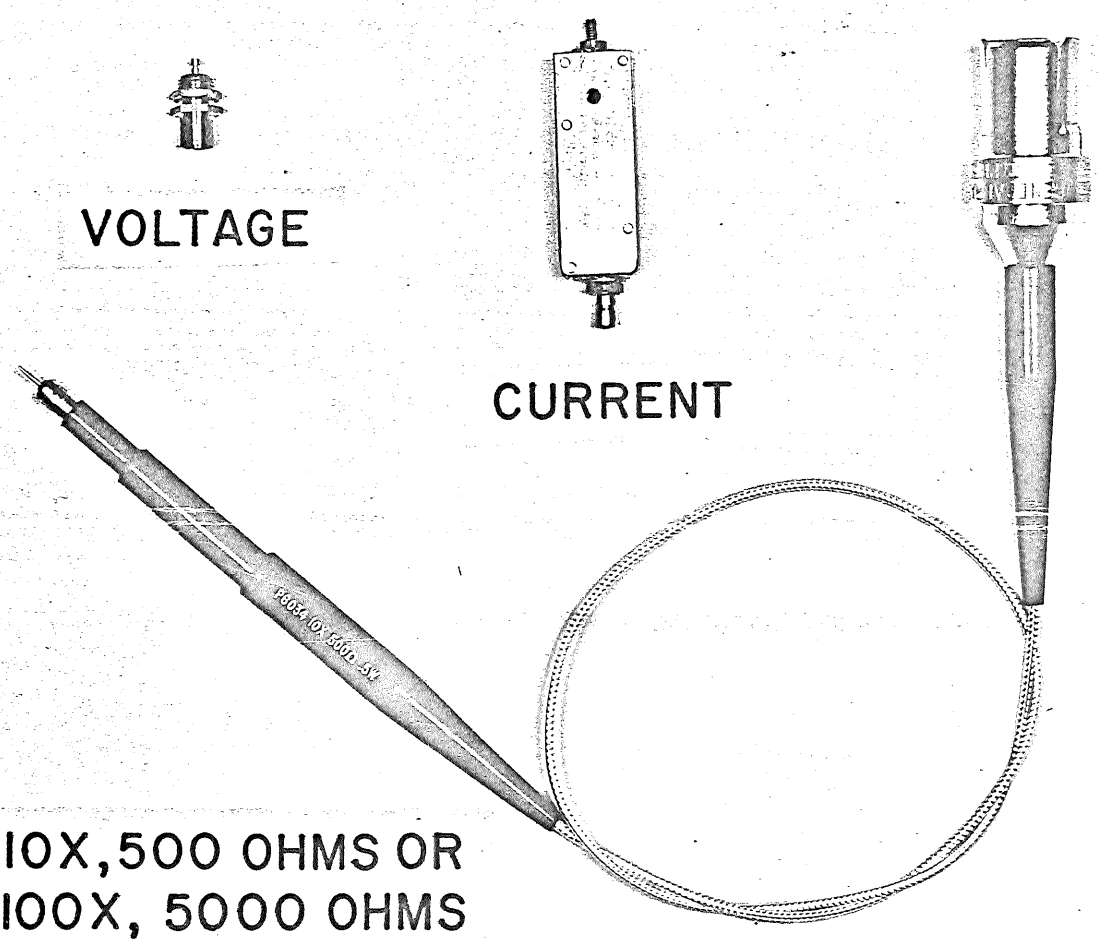

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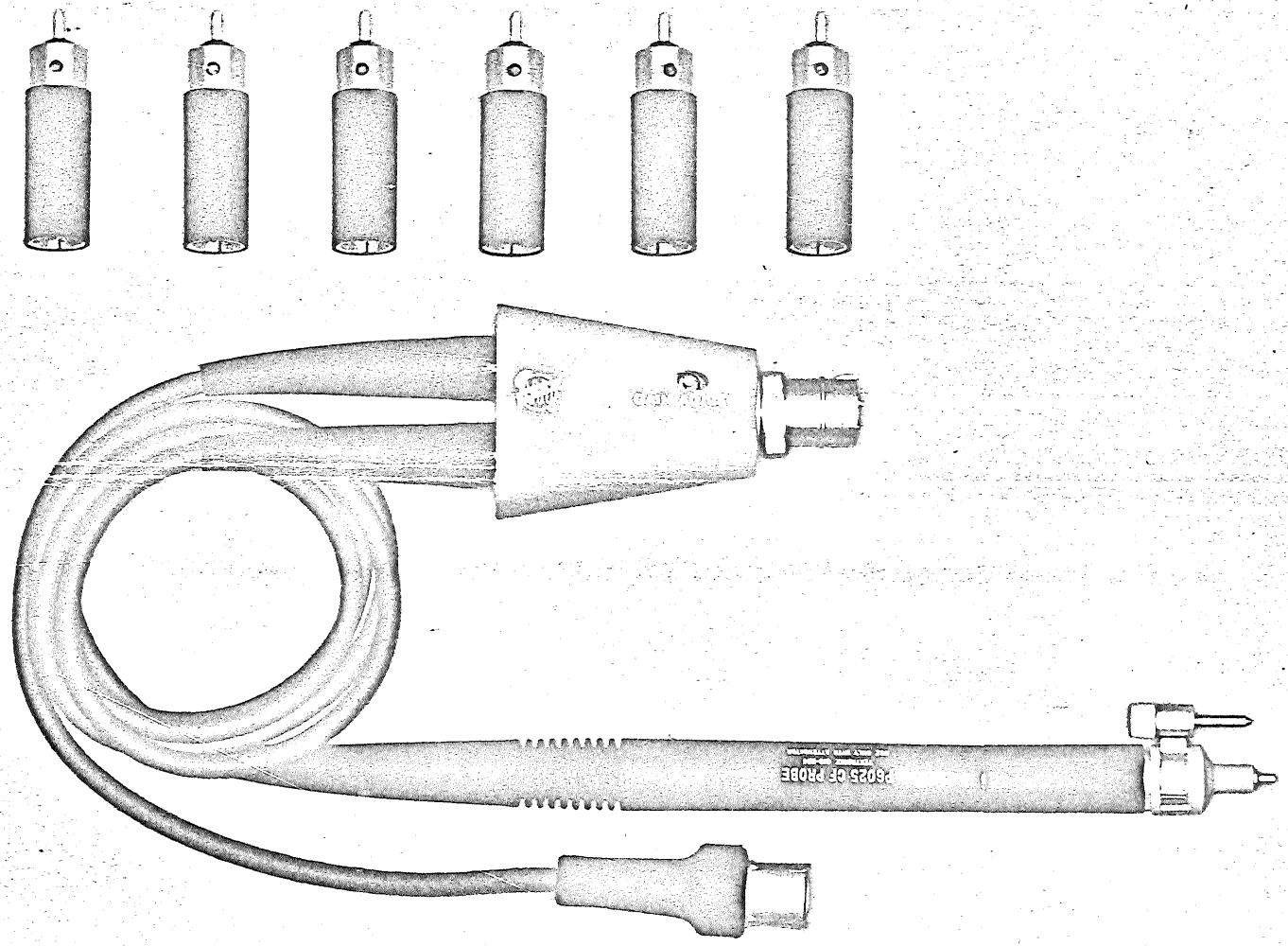

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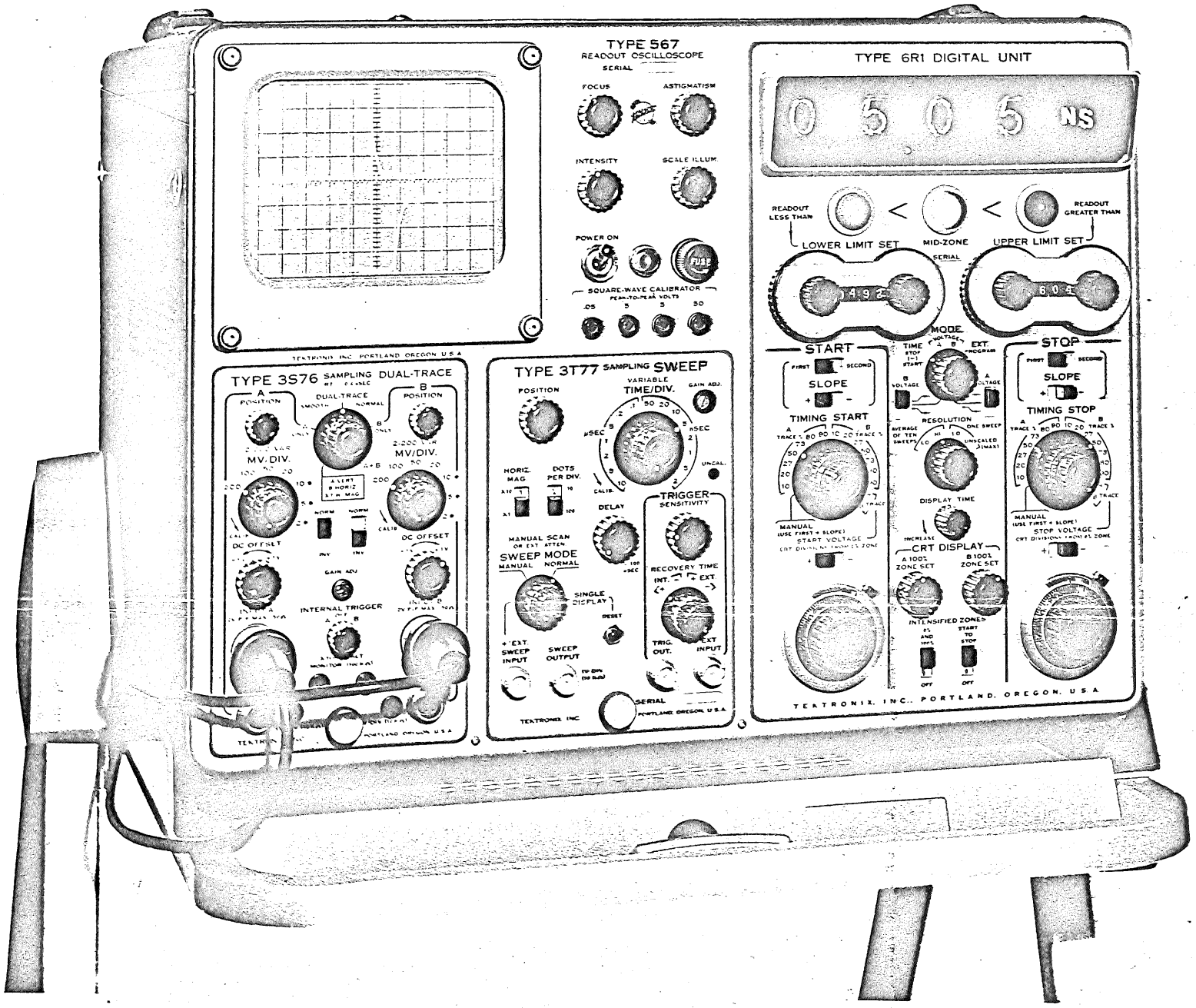

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