High-Speed Transient Recording System

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Significance:

Part 5 – Monitoring instruments, laboratory measurements, and test methods

The recording system described in this report was developed at a time when there were no available commercial probes combining high-frequency response, high-voltage capability, and long connecting cable (to allow removing the oscilloscope from close proximity to the source of the transients to be measured).

The need for such a system arose at the time when pre-strikes and restrikes in high-voltage vacuum switches were emerging as a potential problem for transformer and motor winding insulation, and in some cases arrester failure.

Thirty years later, the problem seems to have abated and the vanishing need for such a custom-built system (even if assembled from components that were commercially available at the time, including a "standard modification" of a Tektronix oscilloscope – no longer available) relegates this system to the museum category and is included in this Anthology only to provide some historical perspective on measurement methods.

GENERAL ELECTRIC

RESEARCH AND DEVELOPMENT CENTER

SCHENECTADY, NEW YORK

TECHNICAL INFORMATION SERIES

AUTHOR	SUBJECT	NO.
Martzloff, FD	transient measurement	68-C-019
		DATE January 1968
TITLE High Speed Transient Recording System		G.E. CLASS ~~2~~ 1
		GOVT. CLASS -
ADDITIONAL COPIES AVAILABLE AT Distribution Unit, Bldg. 5, Room 345 Research and Development Center P.O. Box 8, Schenectady, New York 12301		NO. PAGES 25

Reclassified 9/2/87

SUMMARY

Switching transients have been responsible for equipment failures; however, their accurate measurement is difficult with currently available oscilloscopes and attenuators.

The major difficulties in recording single fast transients are twofold: photographic limitations for a single sweep at high speed, and spurious signals entering the measuring system.

A system based on differentiation-integration of the signal has been developed at the Research and Development Center. This system is used with a Tektronix 544 oscilloscope featuring 24 kV acceleration. The passive differentiator-integrator was assembled from commercially available components. In addition to transient recording, the oscilloscope can also be used as a general purpose laboratory oscilloscope at normal accelerating potential. Thus, a new system, which can easily be duplicated in operating components of the Company, is available for making reliable transient measurements and for making comparisons of results from different laboratories. This system offers excellent recording capabilities, with a response that is flat within ± 10% from 0.3 to 30 MHz.

KEY WORDS

transients, oscilloscopes, probes, shielding

INFORMATION PREPARED FOR:

High Speed Transient Recording System

1. Introduction

It is known that switching transients in power circuits have been responsible for equipment failure; however, accurate measurement of these transients is difficult with currently available oscilloscopes and voltage attenuators[1,2]. Accurate detection and measurement are necessary for an understanding of the problem before appropriate corrective action is taken.

The major difficulties in recording single fast transients (i.e., rise times of less than 0.2 μs) are twofold: the first is the limitation of photographic recording (brightness of the trace vs. film and lens speed) for a single sweep at high speed; the second is caused by spurious responses of the system to signals radiated by the test circuit.

Both problems were solved in 1962 by H. W. Lord, through the use of a special traveling wave Edgerton, Germeshausen & Grier (EGG) oscilloscope with high writing speed, and a special differentiator-integrating amplifier voltage attenuator[3]. However, both the oscilloscope and the differentiator-integrator system are highly specialized, custom made equipment and the active amplifier requires a large power supply. Furthermore, EGG has discontinued the manufacture of the traveling wave oscilloscopes.

A system based on the same differentiation-integration techniques used by Mr. Lord has been developed at the Research and Development Center. This system is used with a modified Tektronix 544 oscilloscope and a 1A1 preamplifier. The change in the oscilloscope is a "standard modification" featuring a 24 kV acceleration anode. The passive differentiator-integrator was assembled from commercially available components. In addition to transient recording, the oscilloscope can also be used as a general purpose laboratory oscilloscope at normal accelerating potential. Thus, a new system, which can easily be duplicated in operating components of the Company, is available for making reliable transient measurements and for making comparisons of results from different laboratories. This system offers excellent recording capabilities, with a response that is flat within $\pm$ 10% from 0.3 to 30 MHz.

This report presents a discussion of the differentiator-integrator approach and of the problems associated with high speed CRT photography. The development of the integrator is discussed in the report. The evaluation of the system is also described, based on single frequency analysis and on high voltage step function methods.

2. The Differentiator-Integrator Attenuator

2.1 Principle

Figure 1 shows the basic circuit, where the signal occurring across the test piece Z is differentiated by the C1-R1 circuit and integrated by the R2-C2 circuit before being applied to the oscilloscope input.

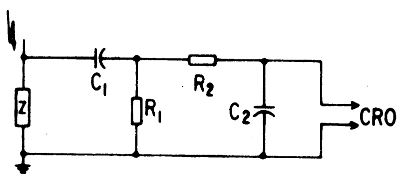


FIGURE 1

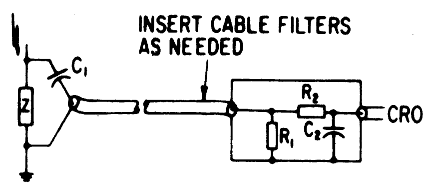


FIGURE 2

Figure 2 shows the circuit as applied to measurement of high frequency, high voltage signals where direct radiation of spurious signals into the oscilloscope becomes a problem.

The differentiator consists of a high voltage capacitor C_1 and an arbitrary length of 50-ohm cable terminated into a 50 ohm load. The fact that this cable length can be arbitrary, makes possible two desirable features: the oscilloscope can be placed at the end of the long cable, far away from the strong radiation caused by the circuit under test, and a cable filter, requiring additional cable length, can be inserted to block circulation of ground currents. In contrast, most commercial high voltage probes are limited to 10 to 12 feet and have limited built-in cable filters[4]. The spurious effects of this limited filtering capability are illustrated in the appendix.

2.2 Practical Limitations

The basic design of the C1-R1/R2-C2 circuit must be refined to compensate for the capacitance of the cable (considered as a pure resistance in the basic circuit), for the stray capacitances of the resistors, and for inductances of the wiring that the basic circuit theory neglects.

It must be recognized that resonances will also occur; they can be eliminated by suitable selection of the component values and careful construction.

The design of an actual integrator will be restricted by theoretical limits such as the frequency roll-off points of the RC's, by practical limitations such as resonances and by the specifications on the gain.

Frequency Limits and System Gain

The attenuation of the R1C1/R2C2 system is: $\frac{E_{out}}{E_{in}} = \frac{R1\ C1}{R2\ C2}$

The -3 dB high frequency point is defined by: $\omega_1 = \frac{1}{C1\ R1}$

The -3 dB low frequency point is defined by: $\omega_2 = \frac{1}{C2\ R2}$

Thus, with a fixed value of R1 and C1, extending the low frequency response of the system can only be done at the expense of the system gain. The desired system gain is determined by the magnitude of the signals to be recorded and by the input requirements of the oscilloscope. For the 544/1A1 combination, performance is slightly degraded for attenuator settings below 0.050 volts/cm, so that optimum performance will be obtained with integrator outputs above 0.1 volts.

Numerical Example

Let us choose $R1 = 50$ ohms (a typical surge impedance for a cable likely to be used)

$C1 = 5$ pF (for minimum circuit loading)

then, $R1C1 = 250\ 10^{-12}$

$\omega_1 = 4\ 10^9$

$f_1 = \frac{\omega_1}{2\pi}$

$= 640$ MHz

For a desired attenuation of 5000:1

$$R2C2 = R1C1 \times 5000$$

$$= 250\ 10^{-12} \times 5\ 10^3$$

$$= 1.25\ 10^{-6}$$

then $\omega_2 = \frac{1}{1.25\ 10^{-6}}$

$$= 0.8\ 10^6$$

$$f_2 = \frac{0.8}{2\pi}\ 10^6$$

$$= 0.13 \text{ MHz}$$

Thus, in this example, the high upper frequency limit resulted from the desire to have minimum loading of the test circuit, while the relatively high low frequency limit resulted from the desire to produce the mild attenuation. A lower value for the low frequency limit could be obtained by more attenuation or by a larger coupling capacitor C1, if the resultant circuit loading is acceptable.

Resonances

Precautions must be taken to keep the input connection inductance low (capacitor C1 and leads) so that these will not resonate at frequencies within the pass-band. For instance, assuming C1 = 5 pF, resonance occurs for an input inductance L1 at ω_{1r} such that:

$$\omega_{1r}^2 = \frac{1}{L1\ C1}$$

For a system with an upper frequency limit in the order of 100 MHz, or 628 10^6 rad/sec, ω_{1r} should be in the order of 1000 10^6 rad/sec or higher. Thus,

$$10^{18} = \frac{1}{L1\ C1}$$

$$\text{hence} \quad L1 = \frac{1}{5\ 10^{-12} \times 10^{18}}$$

$$= 0.2\ \mu H$$

This points out the need for close coupling of the probe to the circuit as 1 foot of wire has an inductance in the order of $0.1 \mu H$.

3. Oscilloscope Photography

High speed recording of single transients is limited by a number of parameters:

a. Cathode ray tube (CRT) - phosphor emission
- beam accelerating potential
- spot diameter

b. Camera design - lens opening
- reproduction ratio

c. Film - speed at phosphor emission
- contrast

Very small spot diameter is useful in producing a brilliant trace if the film contrast is adequate; a poorly focussed beam produces a smeared trace which would be poorly recorded on a soft emulsion.

Polaroid 410 (ASA 10,000) film has the highest available speed at this time. The P-11 CRT phosphor has the highest available writing speed, and is matched with Polaroid 410 characteristics.

Thus, the only parameters which may be improved are the accelerating potential of the CRT, the capability of fine focusing of the CRT, and the camera design.

The EGG oscilloscope mentioned earlier has an extremely sharp beam, and produces a brilliant trace. However, this trace is only 1.5 cm long. Most Tektronix oscilloscopes have a sweep 10 cm long, in contrast to the 1.5 cm of the EGG. Therefore, comparison of photographic records obtained with the two oscilloscopes should be made for the same sweep length, in the same time.

Further ambiguity in recording ability is introduced by the camera design. High speed lenses (f:1.3 or less) are generally associated with an image ratio of 1:0.5, producing a smaller image on the film. This results in more light concentrated on the film and produces a shorter, brighter trace than a conventional camera with a 1:0.9 ratio.

These differences are illustrated (within the limitation of half-tone process) in Figure 3 showing full size reproductions of the original photographs of three oscilloscope-camera systems and reproductions of the same traces enlarged to a comparable trace length for a single transient recording. The transient recorded for this example is the breakdown at about 12 kV of an oil gap with capacitor discharge current in the gap. The differences of picture quality in the original photographs and in the enlargement to equivalent trace size are quite apparent.

The first "trace" (a) was produced by a Tektronix 545 oscilloscope with accelerating potential boosted to 12 kV (a readily available modification kit), and a standard Tektronix C12 camera (f:1.9 lens, 1:0.9 ratio). At this 0.02 μs/cm speed even the original Polaroid picture does not show the faint change in gloss which can sometimes be seen, but not reproduced in print.

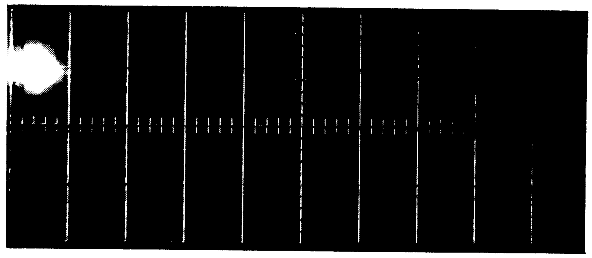
The second trace (b) was recorded by the same system, but at a speed 5 times slower, 0.1 μs/cm. This is the fastest single sweep that can be recorded. The original Polaroid picture does show the front as the faint gloss change mentioned above.

The third traces (c) were recorded with the EGG oscilloscope and Mark I attenuator. A zero line has been added since the EGG oscilloscope has no graticule.

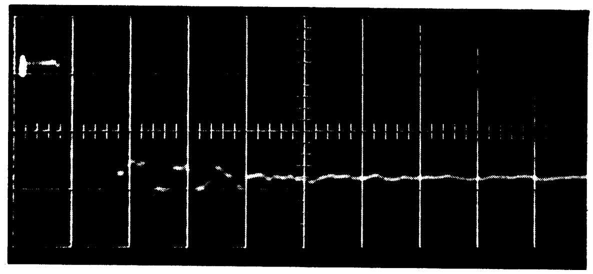
The fourth traces (d) were recorded with the new Tektronix 544 oscilloscope and high speed camera (f:1.3, 1:0.5 ratio). An enlargement has been made to the same scale as traces c and a, with complete resolution of the trace.

The difference on traces c and d, as far as the high frequency oscillation seen on trace c is concerned, will be discussed in Section 4.2.

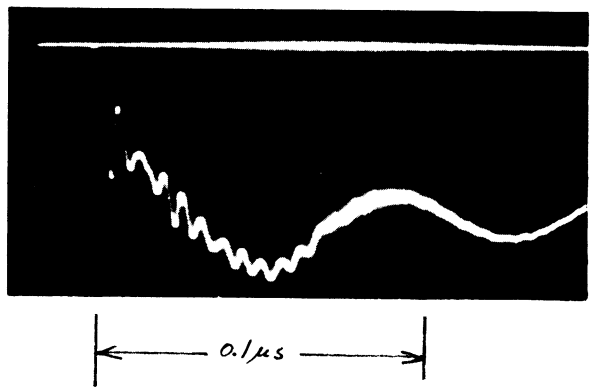
a. Tektronix 545, 12 kV acceleration
0.02 µs/division - P6015 probe
recorded 1:0.9 ratio, f:1.9 lens
(original Polaroid completely blank)
Total sweep time: 0.2 µs

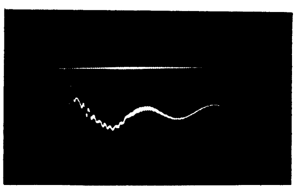


b. Tektronix 545, 12 kV acceleration
0.1 µs/division - P6015 probe
recorded 1:0.9 ratio, f:1.9 lens
(original Polaroid allows reading of the front)
Total sweep time: 1 µs

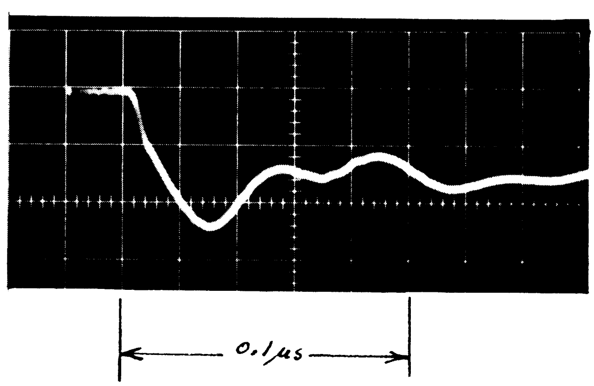


c. EGG oscilloscope, Mark I
0.1 µs/cm on CRT
below: recorded 1:1 ratio, f:1.4 lens
right: enlargement from original below
Total sweep time: 0.15 µs





d. Tektronix 544, 24 kV acceleration
0.02 µs/division - Mark IV
below: recorded 1:0.5 ratio, f:1.3 lens
right: enlargement from original below
Total sweep time: 0.2 µs



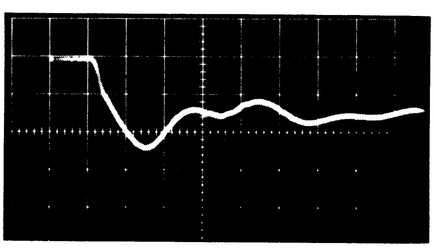


Figure 3

4. An improved Recording System

4.1 Approach

Oscilloscope-Camera

With the objective of using readily available components, the choice of oscilloscopes was narrowed to Tektronix, Fairchild, and Hewlett-Packard. Admittedly, there may have been a slight bias in favor of Tektronix since most oscilloscopes in use at the Research and Development Center and in the Departments tend to be Tektronix. The Tektronix 519 oscilloscope (traveling wave tube) has excellent single transient writing speed, and is a catalog item, but it has a fixed single input (10 V/cm, 125 ohm), making it a highly specialized instrument. On the other hand, the Tektronix 544 oscilloscope is available on special order in a "standard modification" for high writing rate at 24 kV accelerating potential.

The meaning of "standard modification" on a special order is that Tektronix will readily accept orders for this model, since the demand has been sufficient to prepare instruction books, etc. While special order means a delay in delivery, it seems at present that most catalog-listed oscilloscopes, in particular the 519, are in back-order state; consequently, the special order delay does not result in much longer delivery time than that required for catalog items.

The real advantages of the 544 oscilloscope are that it accepts the normal letter-series preamplifiers, and that setting of a switch converts it back to the normal operation of a 544 oscilloscope (i.e., a general purpose oscilloscope suitable for a large number of laboratory applications). This is in contrast to the specialized use of the 519 oscilloscope. Cost of the oscilloscope with modification (without preamplifier) is also lower than that of the 519. Therefore, a Tektronix 544 Mod. 108G with C12 camera was selected and purchased for this system.

The frequency response of the oscilloscope with 1A1 preamplifier is flat within -3dB to 50 MHz for preamplifier settings of 0.05 to 20 v/cm, where the system is expected to operate. For calibration purposes, different attenuator settings must be used. Appropriate corrections are discussed in Section 4.2.

The 6 x 10 cm viewing area under the normal 12 kV acceleration is reduced to 4 cm vertical x 5 cm horizontal at 24 kV. With the sweep magnifier on, the sweep is again 10 cm long on the face of the CRT and is linear, except for the first and last cm of the entire trace. Thus, the useful viewing area is effectively 4 x 10 cm, which is equivalent to that of a conventional Tektronix 545 oscilloscope.

Mark IV Differentiator - Integrator

Earlier approaches to the measurement of high speed transients used the differentiator integrator with an active circuit. These approaches have been described in Reference 5 as Mark I and Mark II. A Mark III designation is reserved for a system built for the Specialty Transformer Department. The new system described here has been designated as Mark IV in order to acknowledge the continuity of the development.

In order to minimize loading of the test piece and to move away the resonant frequency of the probe input circuit, we selected a 5pF vacuum capacitor (Jennings Cat. JCD-5) rated 60 kV for the coupling capacitor, and 50-ohm RG8 or RG 58 as the cable.

The capacitor is actually shielded by a guard at the potential of the low side, which is generally the single ground point of the system.

Filter/Integrator

The complete circuit is enclosed in a copper box, starting with the filter consisting of 20 turns of coaxial cable around a ferrite core. The basic R2/C2 integrator has been refined as shown in Figure 4 in order to provide flat response over the widest possible band. The major integration is performed by the resistor R2 and capacitor C2. Additional compensation is obtained by the R3/C3 integrator, and the output is fed through the R4/50 ohm divider, where the 50 ohm resistance also acts as terminating impedance for the output cable at the oscilloscope panel input.

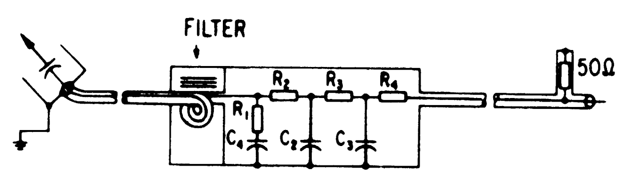


FIGURE 4 - WIDE BAND ATTENUATOR

This terminating resistance was added so that the box could be connected to any oscilloscope through a short cable. As this produced an additional attenuation (the R3 + R4/50 divider) it became necessary to increase the gain of the integrator so that R2 C2 was made smaller. The corresponding increase of the low frequency limit was then compensated by introducing the R1/C4 instead of a single resistance R1. Proper matching of these elements was achieved by actual response curve plotting of circuits until the flat response described in Section 4.2 was obtained.

Camera

The Tektronix C27 camera is available with a f: 1.3 lens; it has no mirrors to decrease the amount of light reaching the film and produces a sharp trace with a 1:0.5 reproduction ratio. Although advertized as recording two graticules per frame of film, this is really not the point of the 1:0.5 ratio; few operators will actually take two exposures of a test without wanting to see the results of the first test.

Shielding Requirements

The perennial pitfalls of transient measurements are ground loops and radiated noise entering the oscilloscope circuits.

The most common type of ground loop is that shown in Figure 5, involving the sheath of the coaxial cable which brings the signal to the oscilloscope.

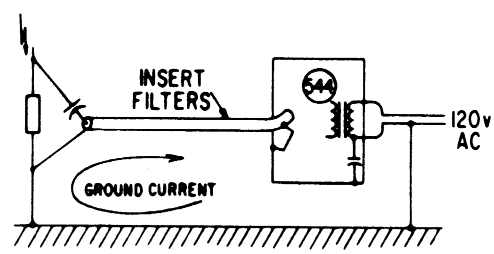


FIGURE 5

This effect is substantially reduced by inserting in the cable a filter, consisting of a number of turns of coaxial cable on a ferrite core. The signal, traveling in the coax is not affected by the filter, while ground currents circulating along the coax sheath are impeded by the inductance of the coil of cable.

Noise radiated to the oscilloscope can be abated by barriers (shielding) or merely by distance. Shielding means an enclosure either for the test circuit or the oscilloscope; depending upon the size of the test circuit, it may be necessary to enclose the oscilloscope rather than the circuit. For the two to be physically close (i.e., in the same area of a laboratory bay), it will be necessary to provide very good attenuation by the enclosure, such as 90 dB at 100 MHz, that is, an "RFI" type design, not just a safety type enclosure.

Since an enclosure may not always be available, considerable attenuation can be obtained merely by removing the oscilloscope from the test circuit, around a metal building corner, etc. Here, the availability of a long cable between the differentiator and integrator becomes a very significant asset.

4.2 System Performance

The performance of the system was evaluated in two ways: by single frequency response and by step function response. The single frequency method allows a separate evaluation of the components and, provided that suitable generators, calibrated attenuators, and receivers are available, it yields an answer in absolute terms. Step function response involves the total system at once, including shielding, and can be performed at high voltage so that it gives a pictorial evaluation of the response; however, since it requires a true step function, which is rather difficult to produce, it really yields an answer in relative terms.

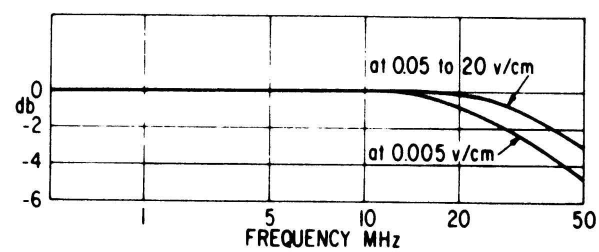
Single Frequency Evaluation

The method consists merely in applying a variable frequency sinusoidal voltage of known amplitude at the input and measuring the output, in this case the deflection on the face of the CRT, as a function of frequency.

However, since the sinusoidal signal generator has a limited output voltage, such as 10v p-to-p compared to the voltages in the range of 1 to 50 kV which may be involved in the actual measurement, the oscilloscope preamplifier must be operated at high gain. This introduces the response of the oscilloscope/preamplifier at this high gain setting, which at high frequency is poorer than the response at medium gain where the preamplifier will be operating for actual use.

Thus, four steps are required to obtain a quantitative description of the system performance:

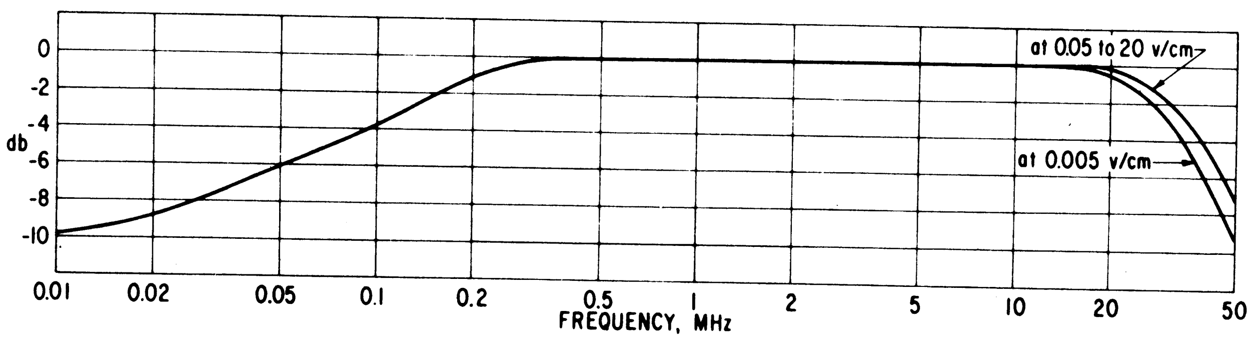
1. Plot response of the oscilloscope and preamplifier at high gain (0.005 v/cm - see Figure 6.
2. Plot response of the oscilloscope and preamplifier at gain for actual use (0.05 v/cm and above) - see Figure 6.



RESPONSE OF TEKTRONIX 544 OSCILLOSCOPE WITH IAI PREAMPLIFIER SETTING AS SHOWN
FIGURE 6

3. Plot response of the complete differentiator-integrator oscilloscope with low level input signal and high gain setting of the preamplifier - see Figure 7.

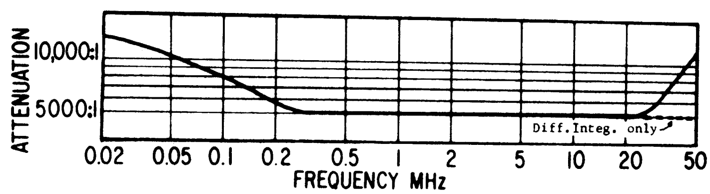
4. From 1 and 2, correct 3 to compensate for the difference in response between the high gain and normal gain settings, and then plot the corrected response point-by-point at high frequency - see Figure 7.



RESPONSE OF COMPLETE SYSTEM- DIFFERENTIATOR, INTEGRATOR, IAI PREAMPLIFIER WITH SETTINGS AS SHOWN, 544 OSCILLOSCOPE
FIGURE 7

From 1 and 3, calculate the response of the differentiator-integrator alone and make a point-by-point plot at high frequency - see Figure 8.

The system attenuation is shown in Figure 8. This attenuation is equal to 5,000:1 $^{+20\%}_{-0\%}$ from 300 kHz to 30 MHz, and produces usable information below and above this flat range.



ATTENUATION OF COMPLETE SYSTEM
DIFFERENTIATOR-INTEGRATOR-IAI PREAMP AT 0.05 V/cm-544 OSCILLOSCOPE
FIGURE 8

For reference, a similar evaluation was made of the earlier Mark I system[(5)] using the 544 oscilloscope and 1A1 preamplifier. The corresponding curve is shown in Figure 9a. The Mark I has been previously used with the EGG oscilloscope which does not show any drop in response at 50 MHz, so that the response of the complete system, Mark I + EGG oscilloscope would exhibit the rise shown in dotted line in Figure 9a. The attenuation of the Mark I and EGG oscilloscope is shown in Figure 9b.

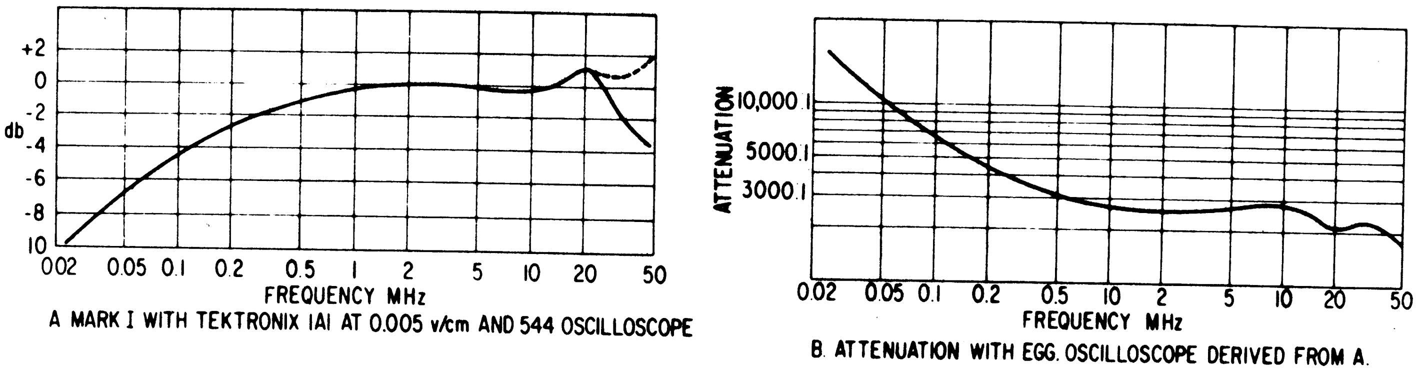
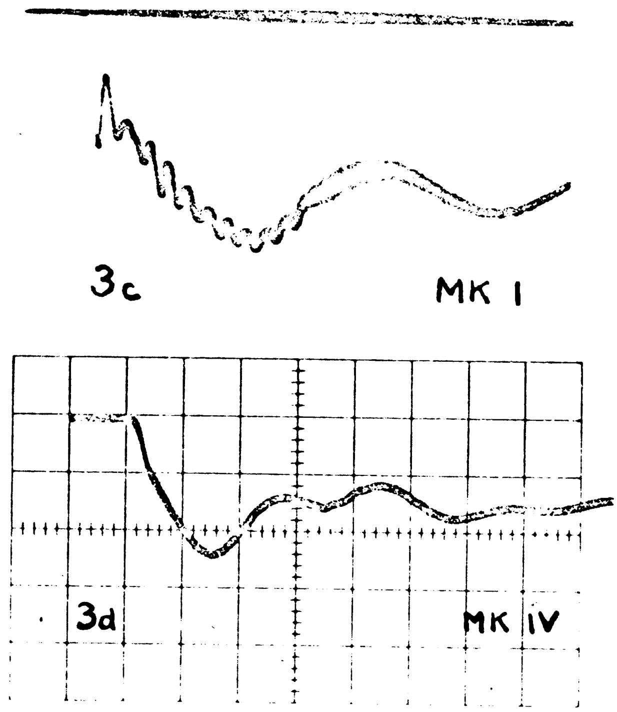


FIGURE 9
PERFORMANCE OF MARK I ATTENUATOR
UNDER SAME TEST CONDITIONS AS MARK IV EVALUATION

At this point, we can discuss the difference in Figures 3c and 3d which were mentioned earlier, and are reproduced on this page as negatives.



It is possible that the high frequency (about 200 MHz) shown in the Mark I trace is present in the circuit. However, the increasing gain of Mark I beyond 50 MHz which turns into a resonance towards 250 MHz[(5)] will show this 200 MHz oscillation with a magnification in the order of 3 to 1.

On the other hand, the Mark IV trace does not show any of these, since its response begins to drop at 30 MHz. Were any of these frequencies actually present in the circuit, Mark IV has "edited out" the ambiguity existing in the Mark I recording. Thus, Figure 3d represents more useful and less confusing information with, of course, the understanding that one should not expect frequencies beyond 50 MHz to be recorded.

Step Function Evaluation

Breakdown of an oil gap at 10-12 kV was used as the high voltage step function generator. A .001 μF capacitor was slowly charged from a DC supply until the gap would break down. The complete circuit (DC supply, capacitor, gap) was contained in the shielded enclosure, and only the coaxial cable after the differentiator was brought out. An additional filter on the signal cable, identical to that contained in the integrator box, was installed at the point of exit from the shielded enclosure - see Figure 10. This may or may not be necessary in actual use of the system. Figure 11 shows the recording obtained with this system, where a rise time of 25 ns is completely resolved, even in a negative line type print. The photograph in Figure 13 shows the installation at the Research and Development Center.

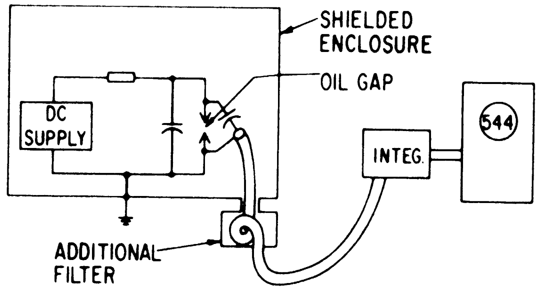
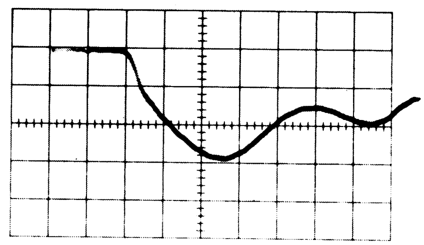


FIGURE 10
CIRCUIT FOR FAST RISE TRANSIENT RECORDING

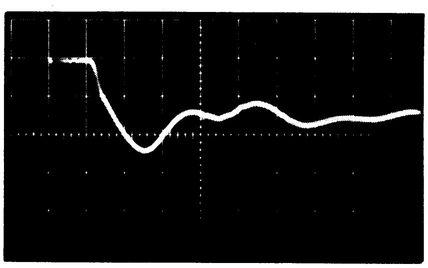


Sweep: 10 ns/div.

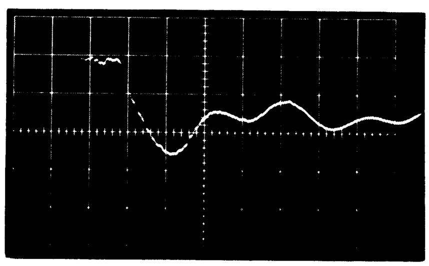
Figure 11

5. Precautions

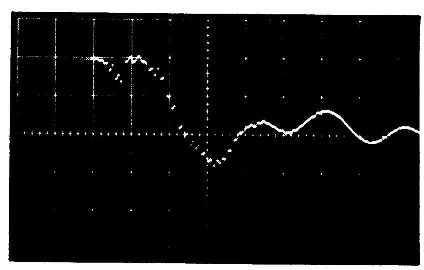
The clean and credible recording shown in Figure 11 will be obtained only if the necessary shielding precautions are taken. In order to illustrate what happens when these precautions are not observed, the series of oscillograms in Figures 12a, 12b, 12c were recorded under various conditions of inadequate shielding, using the step function evaluation setup described in Figure 10. Half tone process was used to show the effect of oscillations on trace brightness.



Sweep: 20 ns/div.
a - test piece in enclosure, door tight



Sweep: 20 ns/div.
b - door ajar



Sweep: 20 ns/div.
c - door open

Figure 12

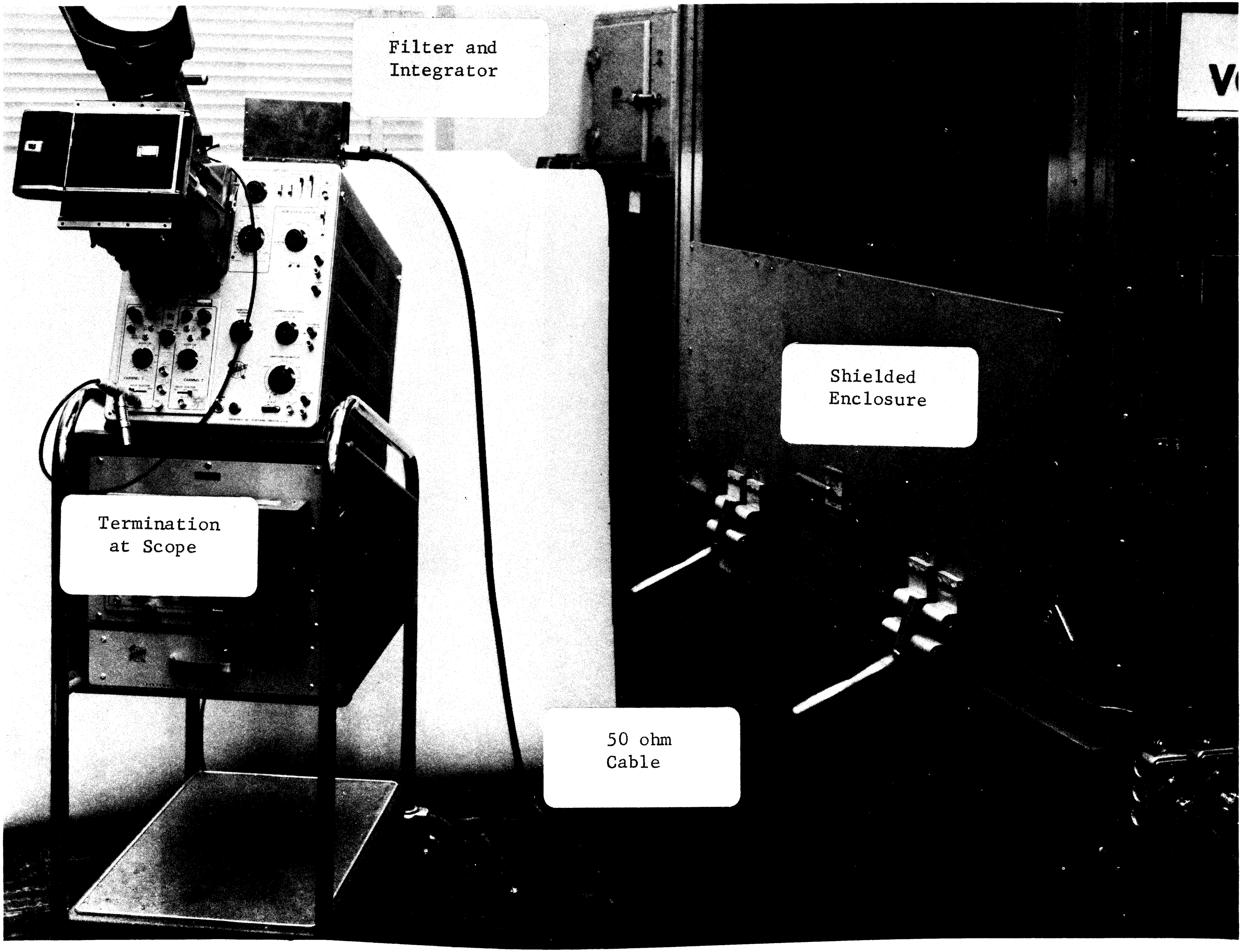
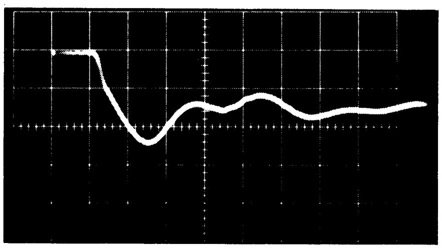
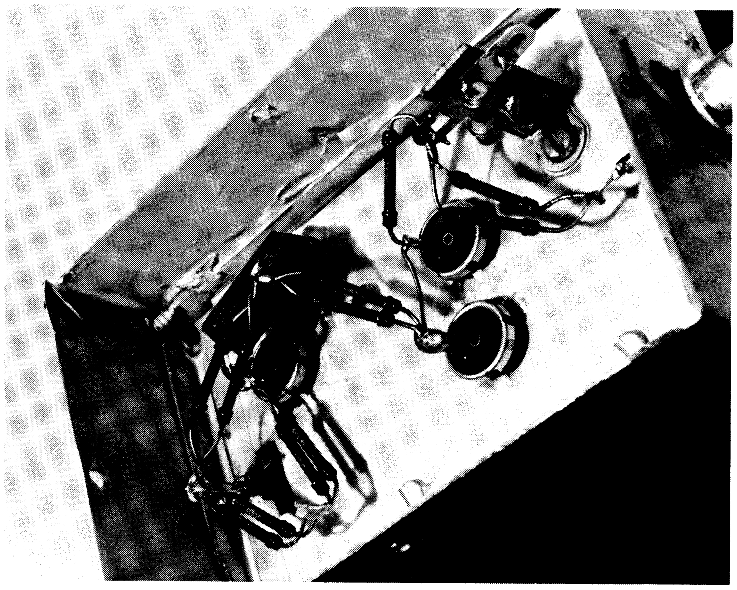


Figure 13 Installation of Mark IV at the R&D Center

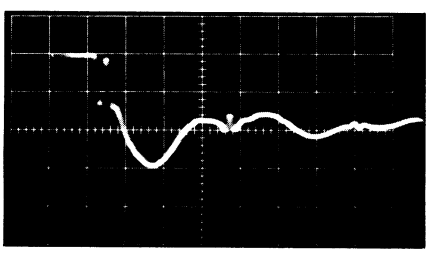
Furthermore, care is required in the construction of the integrator circuit, by selecting components with low inductance as well as by correct layout of the components and bonding of the integrator housing. Figure 14a shows the inside of the integrator circuit that was built with the utmost care, while Figure 14b shows the same circuit built with less care. The response of the two integrators to the same signal is illustrated in Figures 14a and 14b.

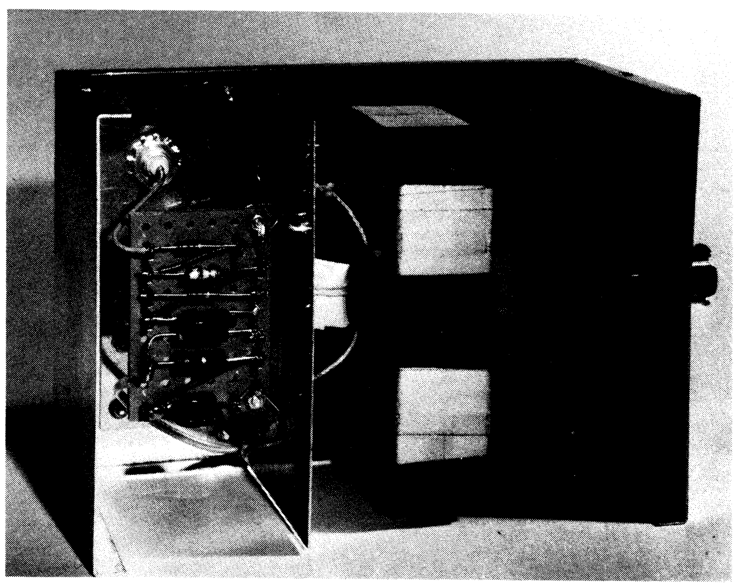




Sweep: 20 ns/div.

Figure 14a





Sweep: 20 ns/div.

Figure 14b

6. Detailed Specifications

6.1 Oscilloscope (Reprinted from Tektronix 544 Mod. 108G instruction book)

Introduction

The Type 544 Oscilloscope is a versatile laboratory instrument designed for use with all Tektronix lettered or 1 Series plug-in units.

Vertical Deflection System

The plug-in unit and probe used with the Type 544 determine the overall characteristics of the vertical deflection system. Refer to Table 1-1 for the characteristics.

Sweep Generation

Sweep Rates (at 1X magnification)	0.1µsec/cm to 5sec/cm in 24 calibrated steps. Sweep-rate accuracy is ±2% of the indicated rate.
Sweep Magnification	Any sweep rate can be increased by expanding the center portion of the display horizontally in fixed steps of 2X, 5X, 10X, 20X, 50X, and 100X. Sweep-rate accuracy is within 5% in the magnified positions at effective sweep rates up to 10 nsec/cm.
Trigger Source Selection	Internal normal, internal plug-in, external, and line.
Trigger Coupling Selection	Dc, ac, and ac low-frequency rejection.
Trigger Signal Requirements	Internal (ac): Minimum deflection is 2mm with signals at about 150 cps, rising to 1 cm at about 50 mc. Internal (dc): Minimum deflection is 5mm at dc. Internal (ac low-frequency rejection): Minimum deflection is 2mm with signals at about 2 kc, rising to 1 cm at about 50 mc. External: Frequency ranges are the same as internal. Minimum amplitude is 200 mvolts peak-to-peak (ac), 200 mvolts change in dc level (dc), and 200 mvolts peak-to-peak (ac low-frequency rejection). A MAXIMUM INPUT OF ± 30 VOLTS must not be exceeded in the EXTERNAL trigger position. Minimum trigger level range is greater than ± 2 volts with the TRIGGER LEVEL control pushed in and ± 20 volts with the control pulled out.

Horizontal Deflection System

The following characteristics apply when the HORIZONTAL DISPLAY switch is set to the EXT position.

Deflection Factor Variable in fixed steps of .1, 1, and 10 volts/cm. Accuracy is ± 5% when VARIABLE control is set to CALIBRATED.

Frequency Response	Dc to 400 kc (3-dB down at maximum sensitivity).
Input Characteristics	(approximately) 1 megohm paralleled by 55 pf.

Amplitude Calibrator

Output Voltages	0.2 mvolts to 100 volts peak-to-peak in 18 steps. In addition, a 100-volt dc output is available.
Frequency	Approximately 1 kc square wave.
Output Current	5 ma squarewave available at the front panel current loop.
Output Impedance	50 Ω in .2 to 200 mVOLTS positions. Progressively higher output impedances in the .5 to 100 VOLTS positions.
Amplitude Accuracy	Peak-to-peak amplitude accuracy is ± 3% of indicated value when working into an impedance of 1 megohm or higher in the .5 to 100 VOLTS position. When working into a 50 ohm load, in the .2 to 200 mVOLTS positions, output amplitude is one-half of the indicated voltage. (Nominal accuracy in this case, is ± 3% assuming the external load impedance is an accurate 50 ohms). The 5 ma current accuracy is ± 3%.

Front-Panel Output Signals

+ GATE OUT	At least a 20 volt peak-to-peak squarewave pulse having the same duration as the sweep. Minimum dc load resistance is 5 k.
SWEEP OUT	Approximately a 100 volt peak-to-peak sawtooth voltage having the same duration as the sweep. Minimum load impedance is 100 k.
VERT SIG OUT	Vertical signal output connector. Output amplitude is approximately 0.4 volt per centimeter of deflection on the crt. Rise time is 20 nsec or faster. Output is ac coupled.
External Single-Sweep Input Signal Requirements	Requires a positive-going step or pulse of at least + 20 volts with a risetime of 0.5 μsec or faster.

Horizontal Deflection System

The following characteristics apply when the HORIZONTAL DISPLAY switch is set to the EXT position.

Deflection Factor Variable in fixed steps of .1, 1, and 10 volts/cm. Accuracy is ± 5% when VARIABLE control is set to CALIBRATED.

Frequency Response	Dc to 400 kc (3-dB down at maximum sensitivity).
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Output Voltages	0.2 mvolts to 100 volts peak-to-peak in 18 steps. In addition, a 100-volt dc output is available.
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+ GATE OUT	At least a 20 volt peak-to-peak squarewave pulse having the same duration as the sweep. Minimum dc load resistance is 5 k.
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External Single-Sweep Input Signal Requirements	Requires a positive-going step or pulse of at least + 20 volts with a risetime of 0.5 μsec or faster.

Power Supplies

Line Voltage	$\pm$ 10% of nominal line voltage. (See Operating Instructions).
Line Frequency	50-60 and 400 cps.
Power Consumption	400 watts typical.
Protection	Primary of power transformer is fused and a thermal relay is installed that interrupts power in the event of overheating.

Cathode-Ray Tube

Type	T5470-31-2
Unblanking	Dc coupled.
Accelerating Potential	10 kv
Useable Viewing Area	6 cm high by 10 cm wide
Focus	Vertical: 2 horizontal lines/mm distinguishable over the center 4 cm. 1.5 horizontal lines/mm distinguishable in the top and bottom 1 cm. Horizontal: 2 time markers/mm distinguishable over the middle 8 cm. 1.5 time markers/mm distinguishable in the first and tenth cm.
Construction	All glass 5 inch, flat-faced crt.
Graticule	Internal, adjustable edge lighting, 6 x 10 cm with vertical and horizontal 1 cm divisions with 2 mm markings on the center lines.

Mechanical

Construction	Three piece, blue-vinyl covered textured aluminum. Front panel is photo-etched and anodized. Chassis is aluminum alloy.
Net Weight	80 pounds 7 ounces

Mod 108G Features

A special high-voltage power supply, which can be switched for either 12 kV or 24 kV operation, has been installed.

A high-voltage slow-up circuit has been installed. When the instrument is turned on, in the 24 kV position, it will take 1-1/2 to 2 minutes to reach proper voltage. Also, this circuit turns the high-voltage off in the event of any power line interruptions of 15 milliseconds or longer.

The auto stability circuit is disabled during 24 kV operation.

For CRT phosphor protection, a circuit has been added to prevent triggering on a repetitive signal during 24 kV operation.

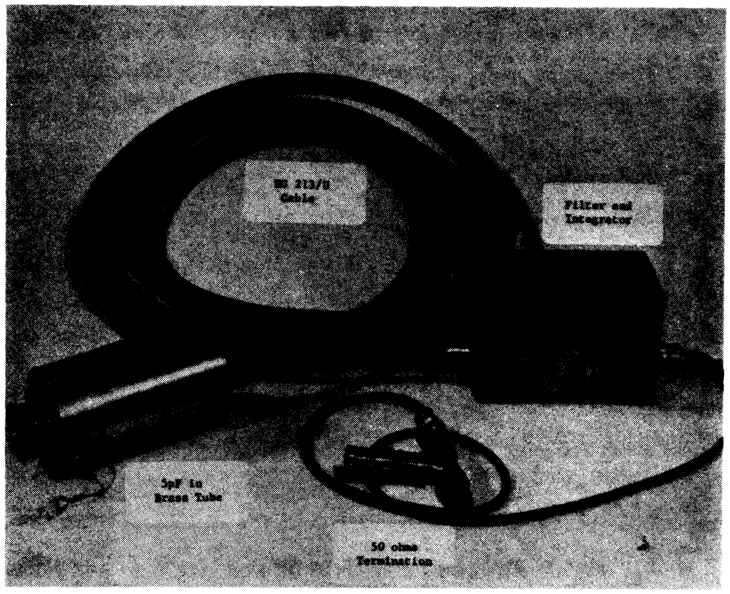
The unblanking circuit provides normal 60 volts unblanking at 12 kV in all sweep speeds. At 24 kV, unblanking has been increased to 110 volts in the .2 μSEC through 20 μSEC positions of the TIME/CM switch. At 40 μSEC through 10 SEC, unblanking is reduced to 40 volts to remove the probability of burning the CRT phosphor.

The linear scan area when in 24 kV operation is 4 cm vertically by 5 cm horizontally. With the MAG on, the linear display area is 4 x 8 cm.

6.2 Camera

Tektronix C12, f:1.3 lens, roll-film back, electric shutter actuator order #C-27-662-RS.

6.3 Differentiator-Integrator



Complete Mark IV Attenuator

Differentiator

The differentiating capacitor Jennings Cat. JCD-5. A brass tube serves as electrical shield and mechanical protection.

RG 213/U is a 50-ohm cable with non-contaminating jacket (RG 8/U is 52 ohms).

Filter

20 turns of RG 58 on Ferroxcube 1F10-3C5 "U" core (Elmira Ferrite Laboratories, Inc.) or equivalent.

Construction of the integrator as seen earlier, requires care. The components are identified in Figure 4 and in the photograph. Exact specifications are:

R1: 4 series parallel 50 Ω IRC-HFR

R2: 4 series parallel 300 Ω IRC-HFR

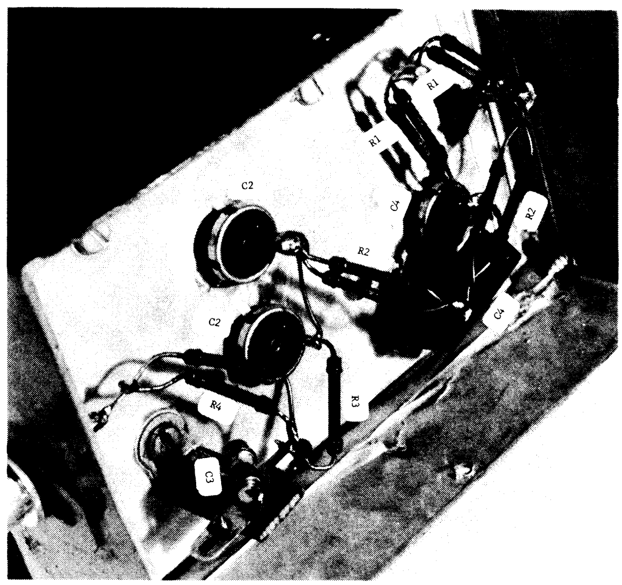
R3: 1 150 Ω IRC-HFR

R4: 1 150 Ω IRC-HFR

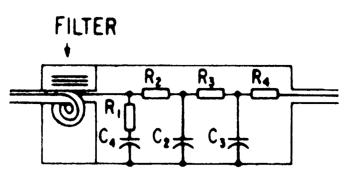
C2: 2 parallel Erie 654-017 251 K
250 pF each

C3: 1 single TCZ-33 Centralab 33pF

C4: 2 parallel one Erie 654-017 251 K
250 pF
one Cornell-Dubilier 5RST-J
500 pF



Integrator and Filter



Substitute Component List for the Integrator

R1:	2 series 24.9 Ω 1RC-DCC	
R2:	2 series 150 Ω 1RC-DCC	
R3:	1 single 150 Ω 1RC-DCC	
R4:	1 single 150 Ω 1RC-DCC	
C2:	1 single Erie 662-003 501 K 500 pF	
C4:	2 parallel	one Erie 662-003 501 K 500 pF
		one Erie 662-003 251 K 250 pF

7. Conclusions

1. The new Mark IV system provides a 5,000:1 attenuation, flat within 10% from 300 kHz to 30 MHz.

2. Photographic recording of single transients is possible at sweep speeds up to 10 nanoseconds per centimeter.

3. Further development work is required to extend the response of Mark IV towards lower frequencies.

8. Acknowledgements

The basic differentiator-integrator approach was suggested by Mr. H. W. Lord, formerly on the R&D Center Staff, now retired.

The design and development of the integrator, evaluation tests and photography were contributed by H. S. Lasher.

9. References

1. Electrical Transients in Power Systems - General Electric Course, by A. N. Greenwood

2. On Potential Dividers for Cathode Ray Oscilloscopes, by F. P. Burch, Phil. Mag. S.7 Vol 13, N. 86 (1932) p. 760.

3. 62-RL-3020E — High Speed Transient Voltage Measuring Techniques by H. W. Lord

4. DF 67LC 1920 — Voltage Probes for Measurement of Transients at Remote Points, by P. Chowdhuri

5. 62-RL-3021E — Instrumentation for Wide Band Observation of High Voltage Transients by W. N. Coffey

Appendix

Limitations of the Tektronix P6015 Probe

Comparisons with Mark I and Mark IV

A voltage transient has two characteristics which are significant: the initial rate of rise and the total transient. The instrumentation discussed in the present report is mostly concerned with the recording of the initial rise, as being the most difficult, and does not provide for total transient recording since the attenuation of the probe increases rapidly for frequencies below 300 kHz.

However, it is still desirable to record both characteristics so that one method of obtaining such recording might be a combination utilizing the Mark IV attenuator and the modified 544 oscilloscope at 0.02 μs/cm for the initial rate of rise, and a "slower" oscilloscope such as the 545 with the P6015* high voltage probe for the total transient, at a sweep speed such as 0.2 μs/cm or slower.

However, in the presence of fast rise time transients, unexpected problems arise in the use of the P6015 probe and 545 oscilloscope, as demonstrated below.

The oscilloscope response appears to suffer from saturation of the preamplifier and/or amplifier, which lasts long enough to interfere with the desired reliable measurements.

The saturation of the preamplifier is attributed to insufficient filtering of the probe ground sheath, allowing large currents associated with the fast rise time to flow in the probe cable sheath. These currents cause a voltage drop in the ground sheath of the probe and preamplifier ground connections; this spurious voltage is added to the true signal and has such a large magnitude that the preamplifier is saturated and does not recover in time. The following three oscillograms illustrate this measurement problem, which has not yet been solved, and adds to the incentive of extending the response of Mark IV towards lower frequencies to produce complete reading with a single attenuator.

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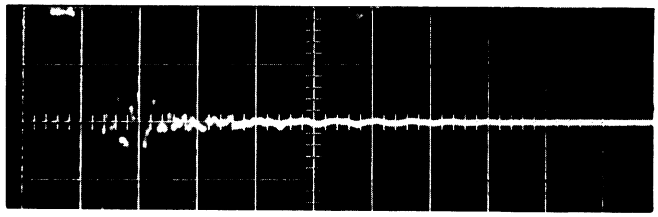
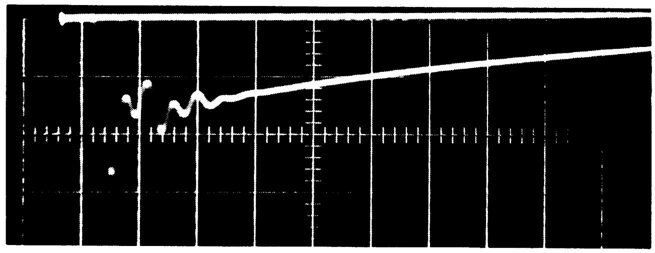
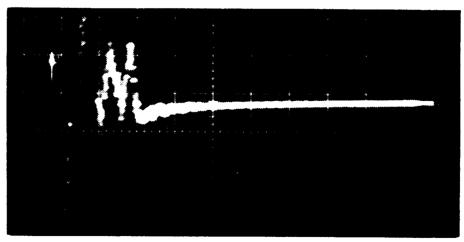
* The high voltage probe Tektronix P6015 is rated 1:1000 attenuation, 40 kV peak, bandpass Dc to 50 MHz (flat within 2%) and has a limited built-in filter in the 12 ft. cable to reduce the effect of ground currents.



This trace was recorded with the P6015 probe and 545 oscilloscope at 0.2μs/div and 5 V/cm (5,000 V/div). The trace, barely visible, overshoots to "17 kV", in contrast with the next trace below which shows a peak of only 13 kV, when the same gap breakdown is recorded with Mark IV and the 544 oscilloscope, at the same sweep speed and 1 V/cm (5,000 V/div).



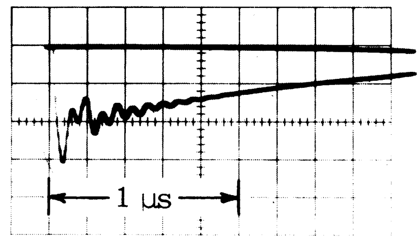
Here, another difficulty of photography is illustrated: since the sweep speed was set slower (0.2μs/cm) than in most records shown in this report, the beam intensity was set lower, producing a trace that would not cause any "bloom". However, the fast oscillations at the front almost caused the trace to disappear.



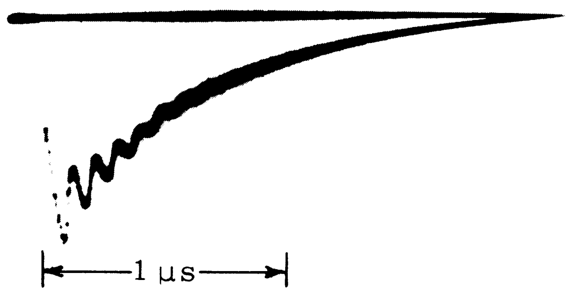
Then, trying to use the P6015 probe again, with the 544 oscilloscope which would have improved the recording capability compared to the first trace above, we obtained the trace shown at right only after having reduced the oscilloscope sensitivity to 10 V/cm (10,000 V/div) and still the trace goes off screen, indicating severe disturbance of the preamplifier.

The improvement in lower frequency response, as well as the "editing" of questionable high frequencies which was discussed earlier are illustrated in the four oscillograms below, recorded with Mark I and with Mark IV.

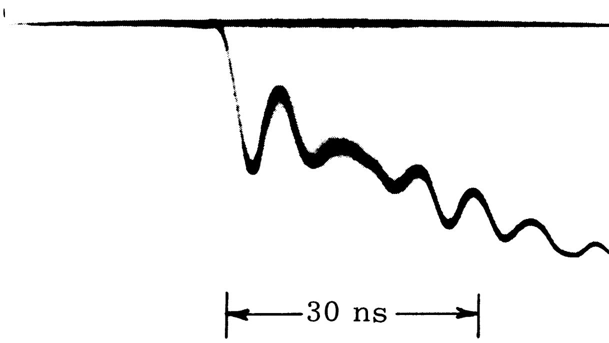
This trace, recorded with the Mark IV, shows 2 μs of sweep with appreciable droop, but at 1 μs, there is still a useable signal recorded, compared to the ideal flat step function which the P6015 would deliver, if it were not subject to the difficulties mentioned above.



In contrast, the Mark I recording, showing almost 2 μs in this trace, already suffers from considerable droop at 1 μs.



While the capability of Mark I and the EGG oscilloscope for recording fast rising fronts are outstanding, as shown in this single sweep trace of only 45 ns, there is some doubt on the existence of the fast front shown here, as the frequency involved approaches the resonance of Mark I.



This trace, also single sweep, made with Mark IV and the 544 oscilloscope leaves little to be desired in resolution. While admittedly frequencies above 50 MHz will be recorded with appreciable attenuation, it is a substantial improvement over presently available systems.