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EVALUATION OF THE TONOTRON STORAGE TUBE FOR RADAR DISPLAY SYSTEMS

FOR LIMITED DISTRIBUTION

by

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EVALUATION OF THE TONOTRON STORAGE TUBE FOR RADAR DISPLAY SYSTEMS

SUMMARY

A Hughes Aircraft Co. 21-inch Tonotron, a direct-view storage tube, was evaluated as a radar plan position indicator display unit. This tube was an early experimental model and not a production model.

Measurements show that the Tonotron is capable of a resolution equivalent to 800 to 1,000 television lines. Brightness ranged from 40 to 180 foot-lamberts, depending upon storage mesh and view screen voltage. Writing speed is adequate for display ranges as small as 10 miles. The Tonotron provides a bright radar presentation with trail information under a high incident light level. The erase characteristics are good. The tube will operate for an extended period of time at a fixed erase-pulse level without loss of picture quality. Background level and target trail can be controlled by adjustment of erase-pulse amplitude and/or frequency.

Deficiencies noted in this tube are: (1) the inability to erase heavily written signals as rapidly as may be desired under some conditions of use, and (2) excessive shading of the picture in certain areas.

It is recommended that further development and evaluation of the Tonotron be undertaken, as it is believed that shading problems can be reduced and other improvements can be made. A plan position indicator which can accommodate the Tonotron should be built for operational evaluation purposes.

INTRODUCTION

The Hughes Tonotron is a direct-view storage tube which can be used to display a radar or television (TV) picture at a high level of brightness. It was developed and built in the research laboratories of Hughes Aircraft Co. Some of the development was supported by Lincoln Laboratories of Massachusetts Institute of Technology. The tube was tested to some extent in the Hughes laboratories as a display device for slow-scan television. It then was loaned to the FAA Technical Development Center (TDC) for evaluation to determine its possible application in a radar indicator display unit.

Evaluation of this tube is a part of a continued effort[1 2 3] by TDC to develop improved radar displays for use in control towers and Air Route Traffic Control (ARTC) Centers. In these areas, the high level of ambient light necessary for the usual operational procedures renders normal radar displays unsatisfactory. These displays use cathode-ray tubes (CRT) with persistent, low-brightness phosphors.

DESCRIPTION

The Tonotron is a glass, cathode-ray, direct-view storage tube which is 21 inches in diameter. Its over-all length is 22 inches and the maximum usable diameter of the view screen is 19 inches.

The internal construction is similar to other direct-view storage tubes of this type. It has two electron guns, a writing gun, and a flood gun, and a storage assembly consisting of a collector screen, a storage screen, and a view screen. The flood gun is centrally located at the rear of the tube shell, while the writing gun is located in the tube neck, 2 inches off center with its axis parallel to the axis of the tube.

The fine-mesh collector and storage screens are formed by punching to have, as near as possible, the same curvature as the inner face of the glass view screen. Deposited on the storage screen is a thin layer of insulating material (magnesium fluoride). The two screens are mounted close to the inner face of the tube, separated from it and each other by small insulating spacers. Connection to the collector, storage, and view screens is made by means of small metal studs in the outer edge of the tube face.

THEORY OF OPERATION

The radar information is written, in the form of electrical charges, on an insulated screen within the tube.[4] This screen is constantly

[1]William E. Miller, Marvin H. Yost, and David S. Crippen, "Evaluation of the DuMont SRD-1 Bright-Radar Display and Initial Study of Other Display Techniques," Technical Development Report No. 288, October 1958.

[2]Loren S. Foote, Arnold W. Grimes, Fred S. McKnight, William G. Covell, and Fred H. Ottersberg, "Initial Evaluation of Two Bright Radar Displays in the Indianapolis Tower," Technical Development Report No. 339, February 1958.

[3]William E. Miller and William G. Covell, "Evaluation of the TI-440 Picture Transformer Equipment and Notes on Television-Type Air Traffic Control Displays," Technical Development Report No. 388, March 1959.

[4]N. J. Koda, N. H. Lehrer, R. D. Ketchpel, "Twenty-One-Inch Direct-View Storage Tube," Hughes Research Laboratories, Technical Memorandum No. 496, August 1957.

flooded by electrons from the flood beam, and wherever a charge is stored, the flood electrons pass through to strike the view screen and imprint the picture. The result is a bright picture on the view screen.

The writing function results from a high-velocity beam from the writing electron gun. This beam is deflected, focused, and modulated by voltages and currents in the same manner as the electron beam of any standard CRT. The high beam velocity is obtained by operating the writing cathode in the neighborhood of 5,000 volts negative, while the storage mesh is within a few volts of ground potential.

Where the writing beam impinges upon the insulating material of the storage screen, secondary emission in excess of a 1:1 ratio takes place, leaving a positive charge at this point on the storage mesh. The secondary electrons from the insulator are attracted to the collector screen which is at a 200-volt positive potential and hence, do not fall back on the insulator surface to cancel any of the written charges. The written charges remain on the storage mesh insulator until neutralized by electrons from the flood beam.

The quantity of charge stored on the insulator screen is determined, within limits, by the intensity of the writing beam. This charge regulates the number of flood electrons which can penetrate the insulating screen to travel on to the view screen and consequently, affects the brightness of the picture element.

The flood gun, centrally located at the rear of the tube, emits a dense beam of electrons (5 to 10 milliamperes). This beam is collimated by an electrostatic lens and then carried to the front of the tube by a small voltage gradient. If the flood electrons approach the storage mesh at a point where there is no written charge, most of them are repelled back to the collector since the storage mesh potential is maintained near the cutoff point.[5] A few electrons pass through and establish the background brightness of the picture. When the flood electrons approach the insulator at a point where a positive charge is stored, most of them pass through, are accelerated by the positive high-voltage (4 to 6 kilovolts) on the view screen, and strike the phosphor with sufficient energy to release light. The written charges remain on the storage mesh with only a gradual neutralization by those flood electrons that do not penetrate the storage insulator entirely. It is necessary to establish a method of erasing the information stored on the storage mesh insulator to control the length of target trails and to prevent confusion due to excessive buildup of ground clutter, precipitation returns, and noise.

Erasure may be accomplished by application of a positive voltage to the storage mesh screen. This voltage, by capacitive coupling between the

[5]The term "cutoff point" or "cutoff potential" in this report is defined as that potential in volts on the insulator surface of the storage mesh screen which will repel all the flood electrons back to the collector if there are no written charges. In the cutoff condition, the view screen is dark except for written areas.

screen and the insulator surface, raises the potential of the storage mesh insulator above the cutoff region. Flood electrons then are attracted to the insulator surface where they neutralize the positive charges. Thus, a positive pulse of adjustable width, frequency, and amplitude may be used to obtain constant controlled erasure. Each pulse partially erases the picture. The amount of erasure also affects background brightness.

Since erasure takes place at a uniform rate, a moving radar target will leave behind it a trail which decreases in brightness to the point where it is completely erased or is masked by residual background illumination. By adjustment of erase-pulse frequency, width, and amplitude, the rate of erasure can be varied and the target trails can be lengthened or shortened to a certain extent.

Another method of controlling erasure is to connect the erase pulse to the grid or cathode of the flood gun. With this particular tube, it was not feasible to pulse the flood gun cathode because it was connected internally to one side of the filament. Pulsing the flood gun grid was tried experimentally; however, no conclusive results were obtained.

INSTALLATION AT TECHNICAL DEVELOPMENT CENTER

Before an evaluation of the Tonotron could be started, it was necessary to obtain a special mu metal shield to enclose the glass envelope of the tube. According to the Hughes Laboratories engineers, good magnetic shielding is required to prevent the earth's magnetic field, and/or stray magnetic fields, from affecting collimation of the flood beam. This is essential for proper operation of the Tonotron since any disturbance of collimation will affect picture uniformity and quality. Upon receipt of the magnetic shield, the Tonotron was installed within it and securely fastened in place by sponge rubber padding and wood supports. The entire assembly then was mounted in a wooden, cradle-like suuport and placed upon a table, as shown in Fig. 1.

Several regulated B+ power supplies, a regulated high-voltage supply, and a nonregulated high-voltage supply were obtained and mounted in an equipment rack to provide operating voltages for the tube. A Hazeltine universal radar indicator, Type AN/UPA-35, was installed nearby to provide deflection voltages, unblanking, and video to the Tonotron. Deflection voltages from the UPA-35 were brought out to the arms of two DPDT switches. One set of poles was connected to the deflection coil of the UPA-35 and the other set was connected to a fixed deflection coil which was used to deflect the Tonotron writing beam. This provided for switching of deflection voltages to either the tube in the UPA-35 indicator or the Tonotron tube. Focusing of the Tonotron writing beam was accomplished by using a TV focus coil, which was comprised of a 1,200-ohm coil wound on a permanent magnet. One of the regulated B+ power supplies was used to provide focus coil current.

Design and construction of an erase-pulse generator were necessary to obtain an erase pulse which was variable in width, frequency, and amplitude. Also, a voltage-dropping network, to provide voltages for the flood gun and storage mesh, was designed and built.

Preliminary operation of the tube indicated that some circuit changes were necessary. First, range compensation of the writing beam was required to obtain equal writing intensity from the center to the outer diameter of the tube. Second, the various flood gun voltages required individual decoupling to decrease interaction between voltages from current changes in the tube elements. To meet the first requirement, compensation of the radar writing was provided by coupling part of the deflection sawtooth voltage into the unblanking waveform. This caused the writing intensity to increase in a linear manner as the writing beam was deflected from the center to the outer diameter of the tube face. Secondly, the flood gun B+ voltages were made more stable by putting each element on a separate dropping network or, in some instances, by providing individual electronic regulation from a regulated primary supply. Figure 2 is a circuit diagram of the dropping network. The collector screen was connected to a separate regulated power supply.

Another modification was necessary to incorporate video limiting in the UPA-35 video amplifier. It was desirable to provide means to increase video gain to the point where noise was being written heavily on the Tonotron picture. Without video limiting, when the gain was brought up to this point, the amplitude of targets and other signals was so great as to cause excessive "blooming." By limiting peak signal amplitude to a value approximately twice the noise level, normal target resolution could be obtained while writing noise.

TECHNICAL EVALUATION

Resolution.

A measurement of resolution was made by feeding two pulses from a double-pulse generator into the writing video input circuits and observing them on the viewing screen. The spacing between the pulses was varied until they were just resolvable by an observer. This spacing was measured on an oscilloscope and the number of spots per radial was calculated. The resolution is expressed in TV lines by multiplying the spots per radial by four.

Figure 3 is a block diagram of the test setup for making these measurements. As shown, radar trigger was connected from the UPA-35 indicator to a Rutherford pulse delay generator which in turn was connected to a Beckman/Berkley double-pulse generator. The output of the double-pulse generator was connected to the video input jack of the UPA-35 radar indicator. These pulses were adjustable in width and separation. By using the pulse delay generator to trigger the double-pulse generator, the range of the pulses as displayed on the Tonotron could be varied by changing the amount of delay in the delay generator. The resolution tests were made with the pulse width of the double pulses adjusted to 1 microsecond, and with pulse amplitudes of 1 volt measured at the output of the pulse generator.

The double pulses appeared on the Tonotron as two closely spaced range rings. The writing signal amplitude was adjusted by means of the video gain control on the UPA-35 indicator to write a solid, double ring without blooming. Video limiting in the UPA-35 video amplifier was disabled during this test.

Resolution tests were made with indicator range settings of 100, 40, 30, and 10 miles. At each of these range settings, resolution checks were made near the outer edge of the picture, near the center, and at several intermediate points. Average resolution near the center of the tube was 1,000 TV lines while near the outer diameter it dropped off to about 800 TV lines. Figure 4 is a curve showing average resolution measured for the tube in terms of TV lines. It indicates how the resolution varied from the center of the tube outward.

Brightness.

A Luckiesh - Taylor brightness meter mounted on a tripod was used to measure the light output of the tube. Measurements were made at the center of the tube only, looking at an area where ground clutter from the radar was painted as a solid bright area. The brightness curves, Fig. 5, show that a considerable increase in brightness is obtained as the view-screen voltage is increased. A small increase in brightness results when the storage mesh voltage is increased. No tests were made with a view-screen voltage less than 4.0 kv because of the low level of brightness; nor was it considered advisable to use view-screen voltages greater than 6.0 kv because of the possibility of an arc damaging the storage assembly. Under normal operating conditions, using a view-screen voltage of about 5.0 kv and the storage mesh at plus 2 volts, the brightness was about 120 foot-lamberts.

Use of the Luckiesh - Taylor brightness meter depends upon visual matching by the operator of the brightness of the object being measured to the brightness of an internal figure. Also, all readings were made in an area of maximum brightness. However, it is believed that these figures are indicative of the capabilities of the tube. The brightness of strong targets and areas of precipitation appeared to the eye to be about the same as that of the clutter in the center area.

Erase Characteristics.

The erase characteristics of the Tonotron are good. It is possible to control the background intensity and target trails by varying the erase-pulse amplitude, or frequency, or both. There is little buildup of background brightness. Blooming or spreading of strong targets, such as has been experienced in other tubes of this type, is practically nonexistent.

The stability of the erase function is such that, once the characteristics of erase pulse have been set, the tube will maintain the same picture quality for extended periods of time. During the evaluation, the Tonotron was operated without any adjustment for several hours. During a 2-hour period, there was a gradual change in background and shading and a slight increase in erase-pulse amplitude, which required a readjustment of flood beam collimation at the end of the period. Slight adjustments of erase were made at 1-hour intervals following the 2-hour period to maintain the desired background and trail.

A major deficiency in the erasing characteristic of the Tonotron is that it is difficult to erase quickly and completely the storage mesh insulator in those areas where heavy ground clutter or precipitation has been written solidly for several sweeps. This deficiency is most evident when the indicator range or centering is changed. If these parameters of the display remain constant, then the ground clutter area does not change and the constant erasure holds the brightness of this area at a fixed level. The erasure of areas of precipitation is such that targets behind the storm area are visible since movement of precipitation is relatively slow. However, the development of a method of quick erasure is needed to improve the flexibility of operation of this tube in a radar display.

As with most storage tubes, the amount of storage is limited by operational requirements. Erasing can be increased to the point where there is practically no storage and the targets are erased almost as soon as they are written. On the other hand, with proper collimation, a strong target may be made to show a trail of 7 or 8 scans which represents a storage time of 70 to 80 seconds for an antenna rotation rate of 6 rpm. Decreasing the erase-pulse amplitude to obtain storage time in excess of 80 seconds usually allows the background level to increase to a point where it is objectionable to the viewer and the background partially masks the target trails.

Storage is affected also by collimation of the flood beam. Under certain conditions of beam collimation, there was little storage of targets near the outer diameter of the view screen, while targets written near the center had long trails. By adjusting collimation to another condition, good over-all storage was obtained.

This difference of storage time at the outer diameter of the tube probably is due, to a large extent, to the angle at which flood electrons approach the storage mesh surface. If the beam is well collimated, the angle of incidence of the flood electrons to the storage mesh is zero or very near zero over the entire area, and under this condition the electrons, attracted to the storage mesh surface by a charge, are more likely to continue on through to be post-accelerated to the view screen. Thus, the same number of electrons will pass through a charge of the same magnitude near the outer edge of a picture as near the center. However, when the flood beam is collimated so that the electrons approach the outer edge of the storage mesh at an angle of incidence that is not zero, the component of velocity normal to the storage mesh is less, and more electrons remain on the dielectric surface of the insulator instead of going through to the view screen. Thus, the written charges in this area are neutralized at a faster rate than those in the center. This condition is partly responsible for the shading which is apparent when the storage mesh voltage approaches cutoff.

Mathematically this may be expressed as follows:[6] If the velocity of the electrons arriving at the storage mesh is equal to V_T, the normal component of velocity V_n of an electron at the center and one at the outer edge will differ by $V_T - V_T \cos \Theta$, when Θ = angle of incidence. See Fig. 6A. From Fig. 6B

$$V_n = V_T \cos \Theta \qquad (1)$$

Assuming two different angles of incidence for the electrons approaching the storage insulator, Θ_{max} and Θ_{min}, the normal component of velocity for these two cases would be

$$V_n\ (max) = V_T \cos \Theta_{min} \qquad (2)$$

$$V_n\ (min) = V_T \cos \Theta_{max} \qquad (3)$$

The total velocity of a flood electron traveling from cathode to collector screen is (assuming initial velocity is zero) [7]

$$V_T = \sqrt{\frac{+2QE}{m}} \qquad (4)$$

where

E = collector screen potential

m = mass of the electron

Q = charge of the electron

Then, substituting for V_T

$$V_n\ (max) = \sqrt{\frac{2QE}{m}} \cos \Theta_{min} \qquad (5)$$

and

$$V_n\ (min) = \sqrt{\frac{2QE}{m}} \cos \Theta_{max} \qquad (6)$$

Kinetic energy $W = \frac{m}{2} V^2$

[6]Koda, Lehrer, and Ketchpel, op. cit.

[7]Arthur B. Bronwell and Robert E. Beam, "Theory and Application of Microwaves," McGraw-Hill Book Co., Inc., 1947, pp. 11-40.

The normal component of kinetic energy is

$$W_n\ (max) = \frac{m}{2}\left(\sqrt{\frac{2QE}{m}}\ \cos\theta_{min}\right)$$

$$= QE\ \cos^2\theta_{min} \qquad (7)$$

By the same reasoning

$$W_n\ (min) = QE\ \cos^2\theta_{max} \qquad (8)$$

The difference between them

$$\triangle W_n = W_n\ (max) - W_n\ (min) = QE\ \cos^2\theta_{min} - QE\ \cos^2\theta_{max}$$

$$= QE\ (\cos^2\theta_{min} - \cos^2\theta_{max}) \qquad (9)$$

If we assume that the beam is collimated so that $\theta\ min = 0$
then $\cos^2\theta_{min} = 1$

$$\triangle Wn = QE\ (1-\cos^2\theta_{max}) = QE\ \sin^2\theta\ max \qquad (10)$$

The cutoff voltage at the collector E for a set value of storage mesh bias will vary with this change in kinetic energy. Thus

$$\triangle E = E\ \sin^2\theta_{max} \qquad (11)$$

If θ max is assumed to be small, thus

$\theta^2 \cong \sin^2\theta$

and

$$\triangle E \cong E\ \theta^2\ max \qquad (12)$$

Conversely, where storage mesh and collector potential are held constant, the angle of incidence of the flood electrons to storage mesh insulator will determine whether the electron penetrates to the view screen or returns to the collector. Differences in the angle of incidence cause shading of the view screen.

The shading of the Tonotron tube tested appeared to be, to a great extent, due to physical parameters built into the tube. Certain areas of the view screen always were a little darker or a little brighter than the over-all background illumination, and adjustment of collimation, while it had an effect, never eliminated these areas completely. This type of fixed shading was more pronounced than any other. It is believed that this effect is caused by a slight variation of spacing between the storage mesh and view screen or between the storage mesh and collector screen. If this is the case, better spacing accuracy should improve or eliminate this particular deficiency. This shading of the Tonotron picture, although slight, still is a major drawback in obtaining the best picture quality. If the background intensity were the same over the entire face of the view screen, the storage mesh screen voltage and erase pulse could be adjusted to obtain the desired target trail characteristics and background illumination for all areas of the view screen; but since the background is slightly shaded, a compromise adjustment must be made with the result that certain areas of the picture are too far into the black region whereas other areas are too bright. This shading is depicted in Figs. 7 and 8. As a result, weak targets and noise may not be written in the dark areas while target trails may be masked partly by the background of the light areas.

Background brightness is controlled by the erase pulse and the storage mesh voltage. When no signals are written, the background for a given storage mesh setting may be established by adjustment of the erase-pulse amplitude, frequency, and width. When signals are written, an increase of erase-pulse amplitude may be required if much noise is written, since this will tend to increase the background level. Increasing the storage mesh voltage to a more positive value will increase over-all brightness and generally requires an increase in erasing to regain the same background level. Shading becomes more noticeable at the higher storage screen voltages. Figure 9 shows background shading and the type of picture obtained at a storage mesh voltage of plus 6 volts.

Writing Speed.

The estimate of writing speed given by the manufacturer was about 20,000 inches per second. For the Tonotron with an effective diameter of approximately 18 inches, this corresponds to a radar sweep range of approximately 36 nautical miles (450-microsecond radius). Preliminary tests, during which information from an ASR-2 radar was displayed on a 15-mile range scale, did not give any visual indication of writing speed deficiency.

As a further check of writing speed, the following test was devised:

1. The external sweep gate from a Tektronix 512 oscilloscope was differentiated and used to furnish a trigger of adjustable prf to the radar indicator.

2. The sweep of the radar indicator was allowed to continue rotation at 6 rpm.

3. With the indicator sweep generator triggered at a very low rate, so that only 4 to 6 sweeps were written during one complete rotation, delayed pulses from the double-pulse generator were connected to the indicator video amplifier and adjusted to write on the Tonotron. These pulses were 1 microsecond wide and appeared as two dots of light on each sweep strobe.

4. The writing intensity was adjusted very carefully until the strobe was barely visible.

5. The amplitude of the double pulses into the indicator was adjusted until the pulses were distinguishable. The amplitude of the double pulses was recorded for 10- and 100-mile display ranges.

6. The amplitude of the double pulses was increased to write at normal brightness on the Tonotron and observed on the 10- and 100-mile ranges.

Results.

Minimum pulse amplitude:

10-mile range - 20 volts
100-mile range - 20 volts

Normal brightness test. No discernible difference in brightness between pulses written at 10-mile or 100-mile ranges.

These tests are not conclusive since there was no exact measurement of writing speed. However, they indicate that the Tonotron is capable of a writing speed of at least 73,000 inches per second when used as a radar indicator. This is equivalent to a 10-mile display range.

Halftone Writing.

Capabilities for halftone writing are shown in Fig. 8. The three closely spaced rings were written at levels of 5, 12, and 17 volts, respectively, from the center out. This indicates three steps of grey plus the background.

Operational Notes.

Figures 10 and 11 are block diagrams of various voltage connections to the Tonotron. High-voltage supplies for writing and for the view screen should be regulated. For this evaluation, the Tonotron writing supply was electronically regulated but a regulated supply for the view screen was not readily available. Consequently, whenever a change was made which affected view screen current, the view screen high voltage changed, and it was necessary to wait for the condition to stabilize and for the view screen high voltage to return to normal value. The B+ bias and focus current power supplies also should be regulated.

The dropping network providing the various flood gun voltages should be thoroughly decoupled. It is believed that the best approach would be to provide individual electronic regulation for the voltage to each element. The collector screen requires a well-regulated voltage source.

In addition to the special mu metal shield around the tube shell, shielding of the deflection and focus coils from the flood beam should be provided. During the foregoing tests, it was noted that a small periodic change in collimation appeared to result in synchronism with the antenna rotation rate.

CONCLUSIONS

The Tonotron evaluation has demonstrated that this tube has several characteristics which are very desirable for use in a radar display. It has brightness sufficient for viewing in a high ambient light level, and the necessary storage required for presentation of trail information. Storage is variable from a few seconds up to 1 1/2 minutes. It was possible to obtain good writing sweep linearity. Collimation was adequate but improvement is needed to decrease shading and obtain a more uniform storage over the face of the tube. Although no limitation to picture quality due to writing speed characteristics could be observed when the display range was reduced to 10 miles, it is believed that the writing speed is marginal. Writing speed should be increased to provide for shorter radar ranges and TV scanning. The erase characteristic was such that erasing could be accomplished and controlled by use of a continuous erase pulse of variable amplitude and frequency.

RECOMMENDATIONS

In view of the favorable results obtained with this early model Tonotron, and the possibility that refinements and improvements can be made in later models, consideration should be given to the possible use of this tube as a radar display in control towers or other areas of high ambient light.

For further evaluation in an operational environment, it is believed that a special indicator equipment is necessary for this tube. Because additional element voltages are required and because of its physical size, it is not practical to modify an existing indicator to accommodate it. Therefore, a development program to design and build a radar indicator utilizing an improved 21-inch Tonotron as the display tube should be considered.

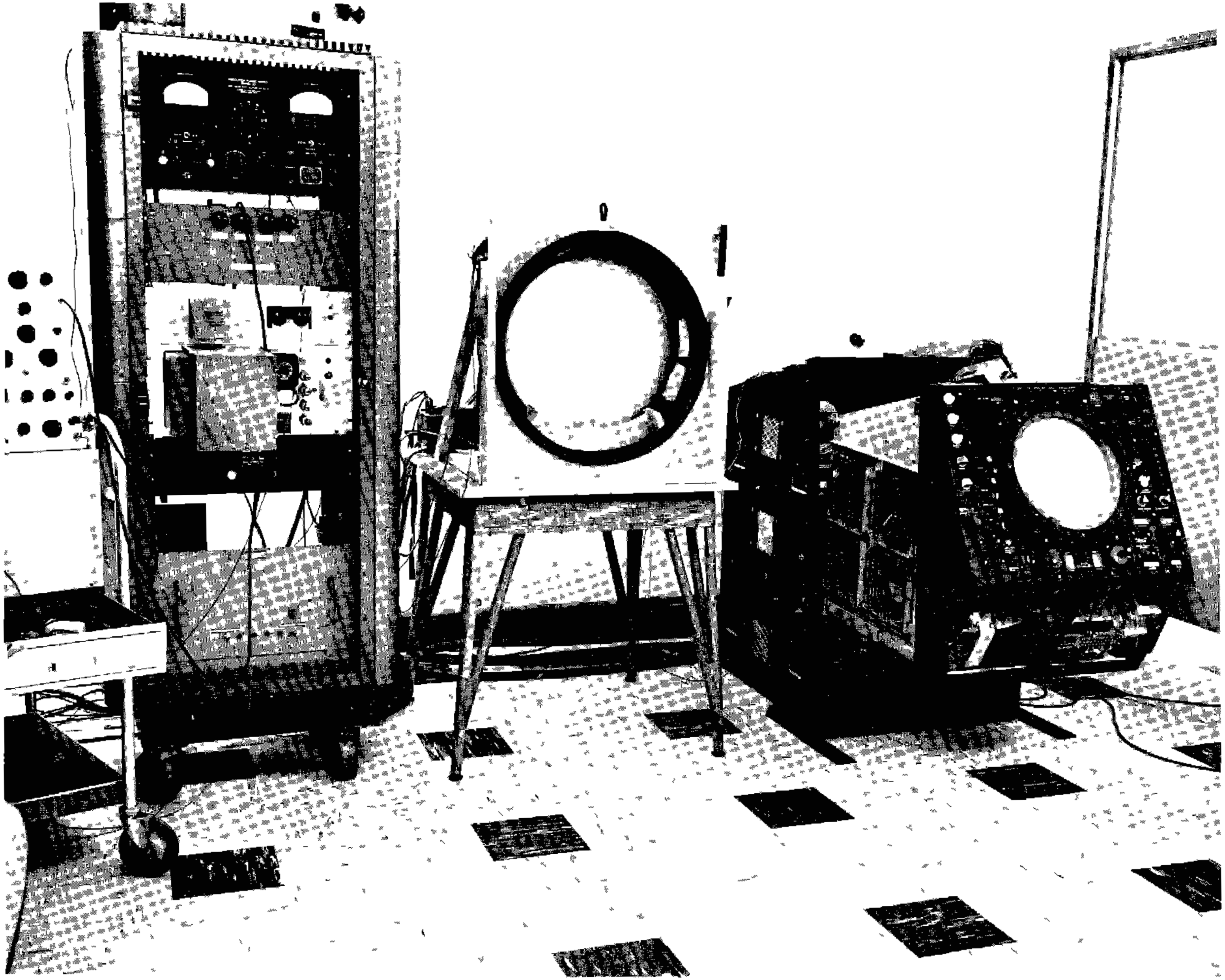


FIG. 1 TONOTRON WITH UPA-35 INDICATOR AND ASSOCIATED EQUIPMENT

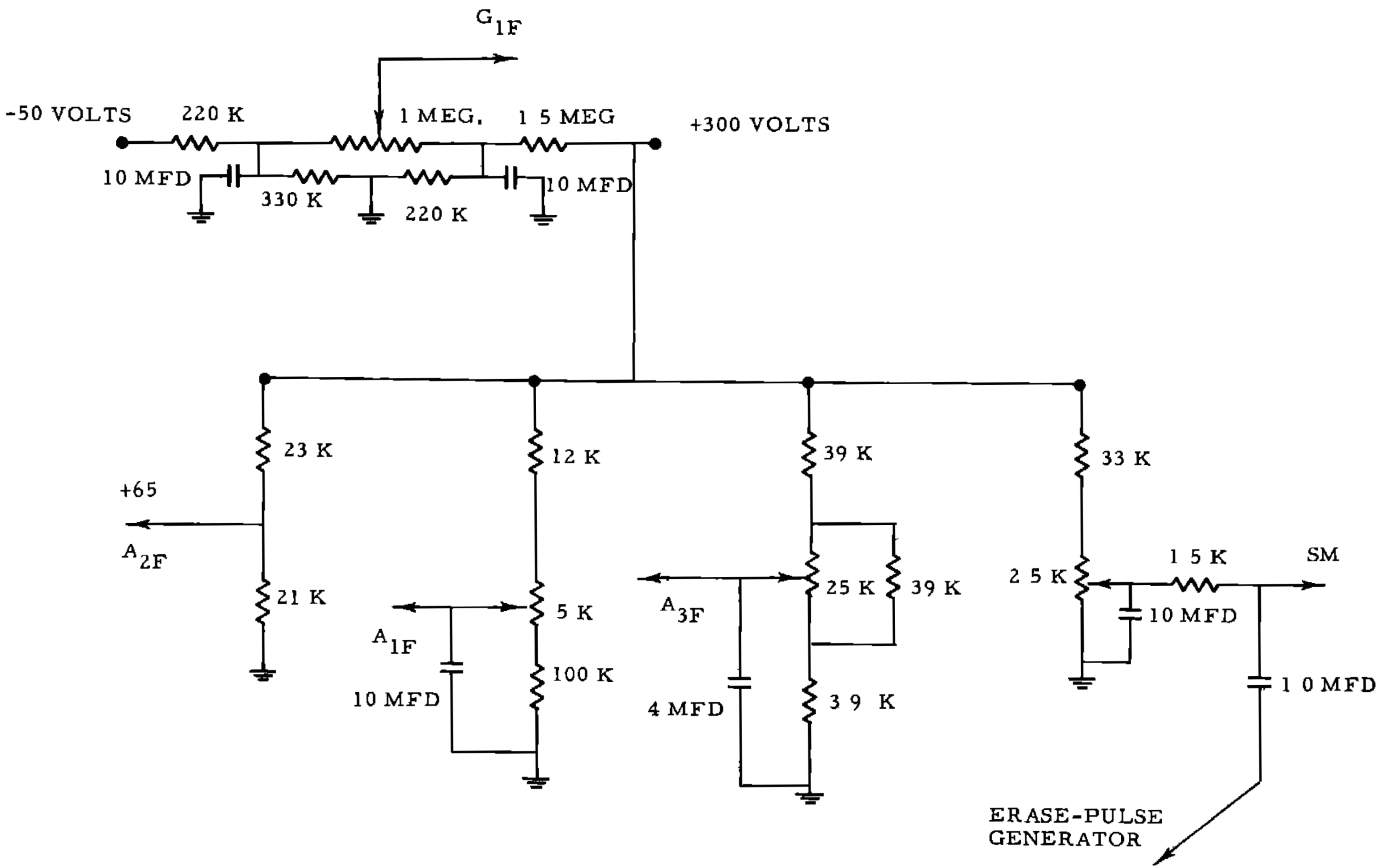


FIG. 2 DROPPING NETWORK FOR FLOOD VOLTAGES

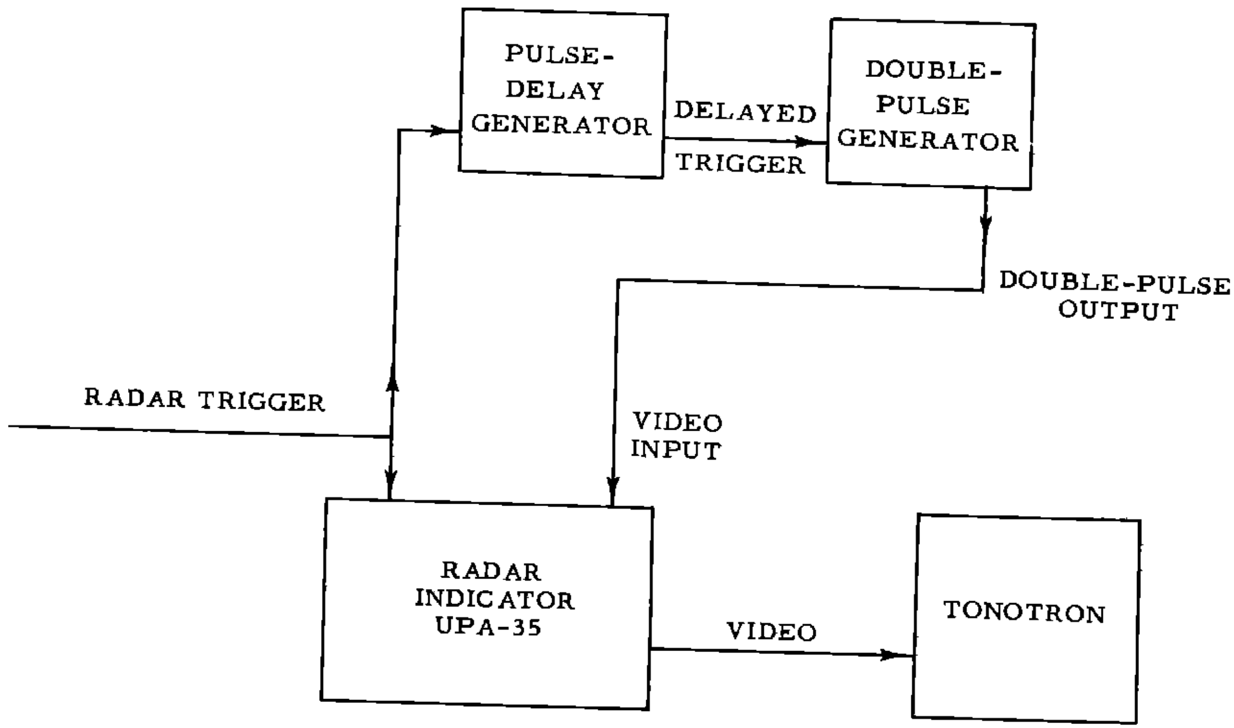


FIG. 3 BLOCK DIAGRAM OF EQUIPMENT FOR RESOLUTION MEASUREMENT

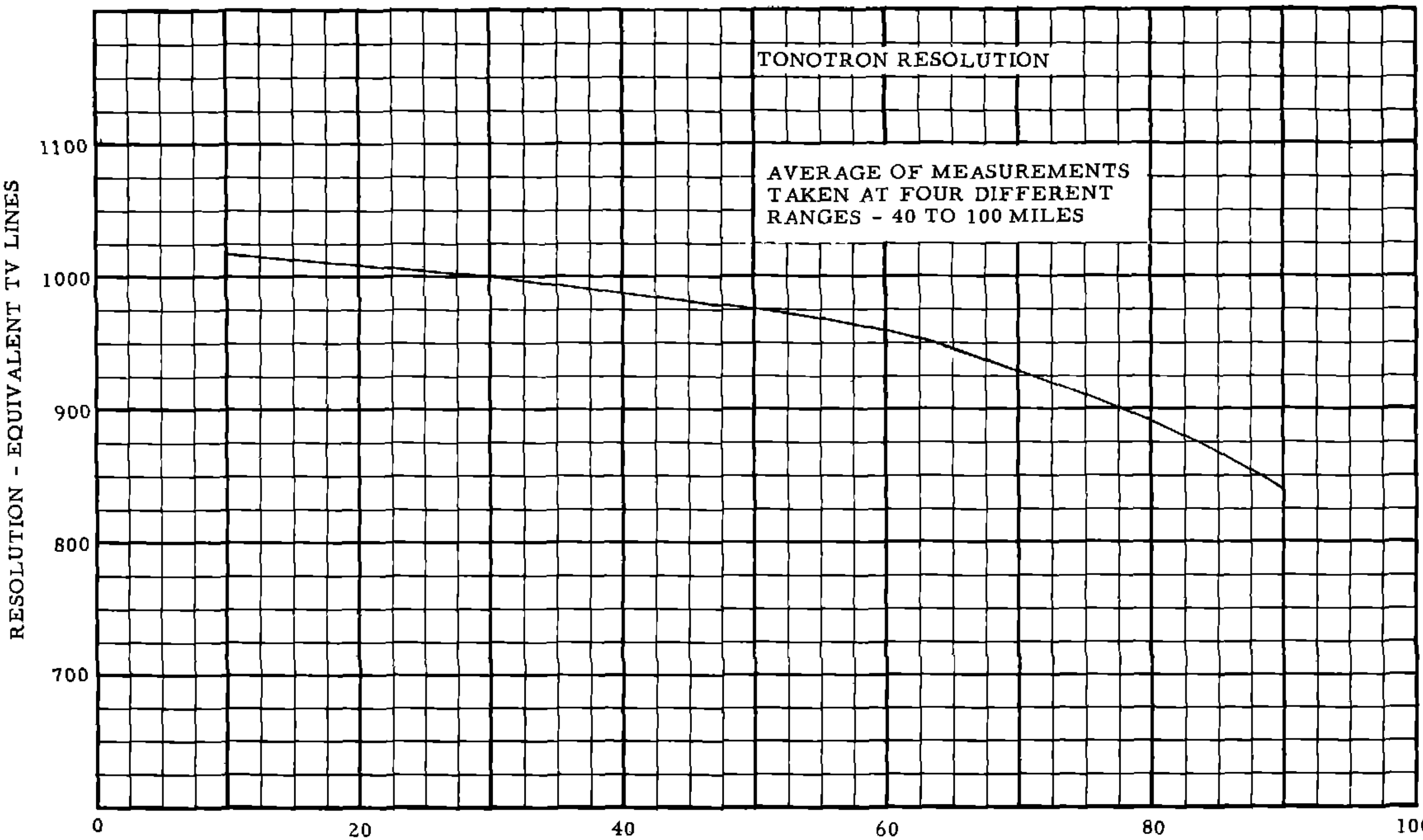


FIG. 4 RANGE IN PER CENT OF FULL-SCALE DEFLECTION FROM THE CENTER

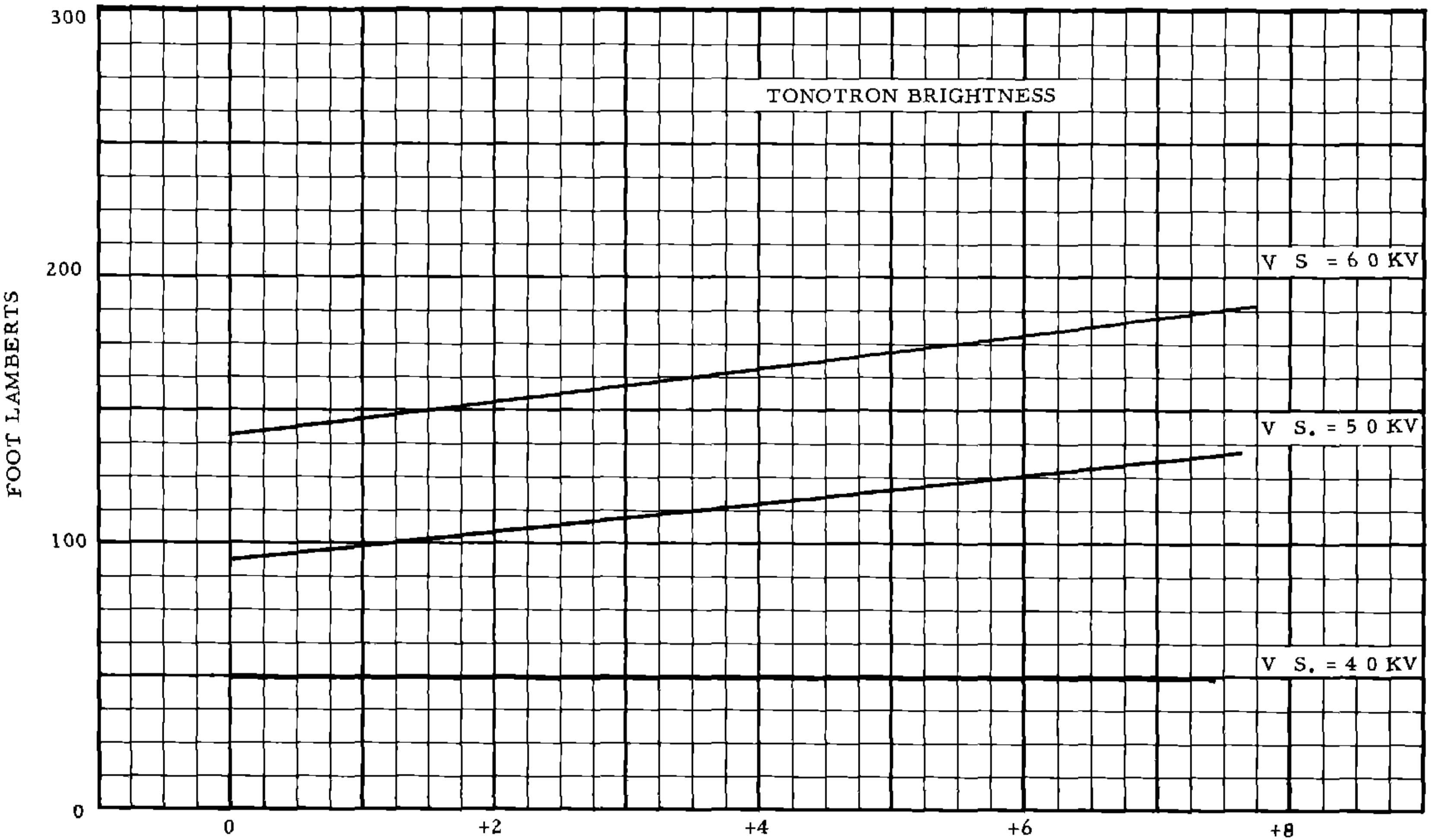
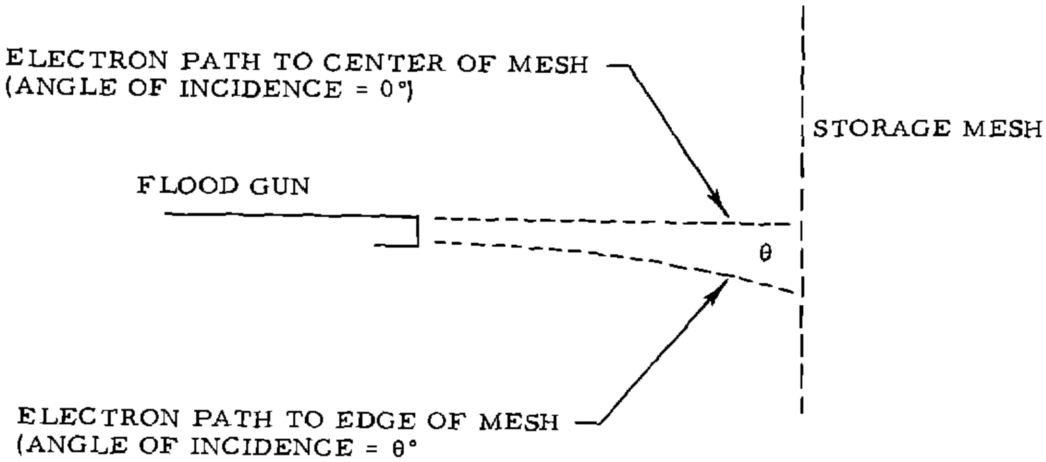
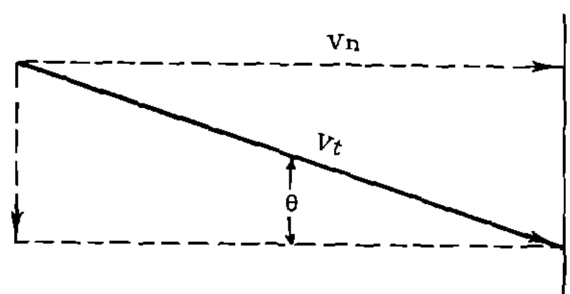


FIG 5 STORAGE MESH VOLTAGE



A - DIAGRAM OF TWO ELECTRON PATHS FROM CATHODE TO STORAGE MESH



B - VECTOR DIAGRAM OF ELECTRON VELOCITIES AT ANGLE OF INCIDENCE θ

FIG 6 DIAGRAMS INDICATING VARIATION OF ANGLE OF INCIDENCE AT STORAGE MESH AND VARIATION IN VELOCITY NORMAL TO STORAGE MESH

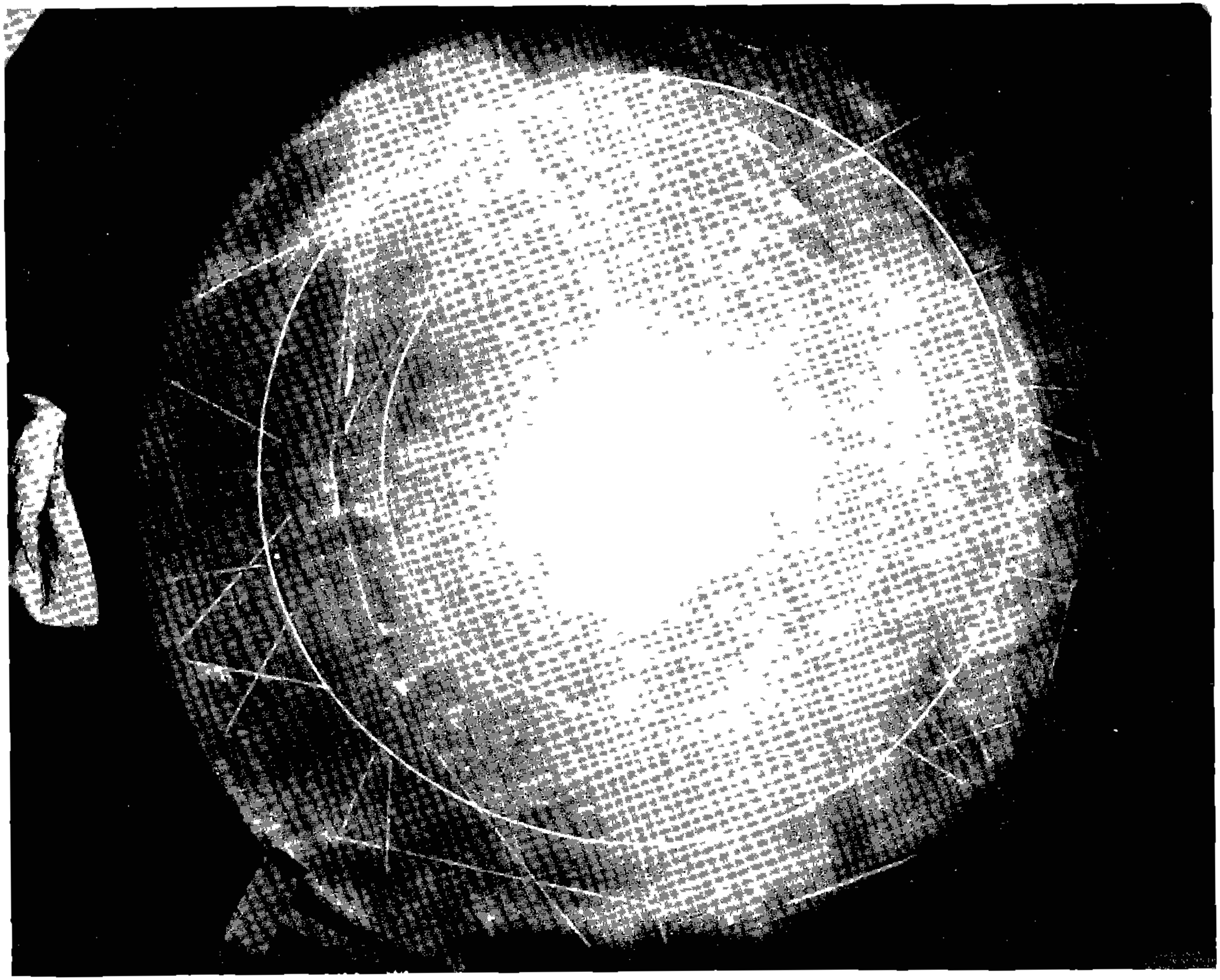


FIG 7 TONOTRON PICTURE OF INDIANAPOLIS ARSR-1 RADAR
AT 80-MILE RANGE

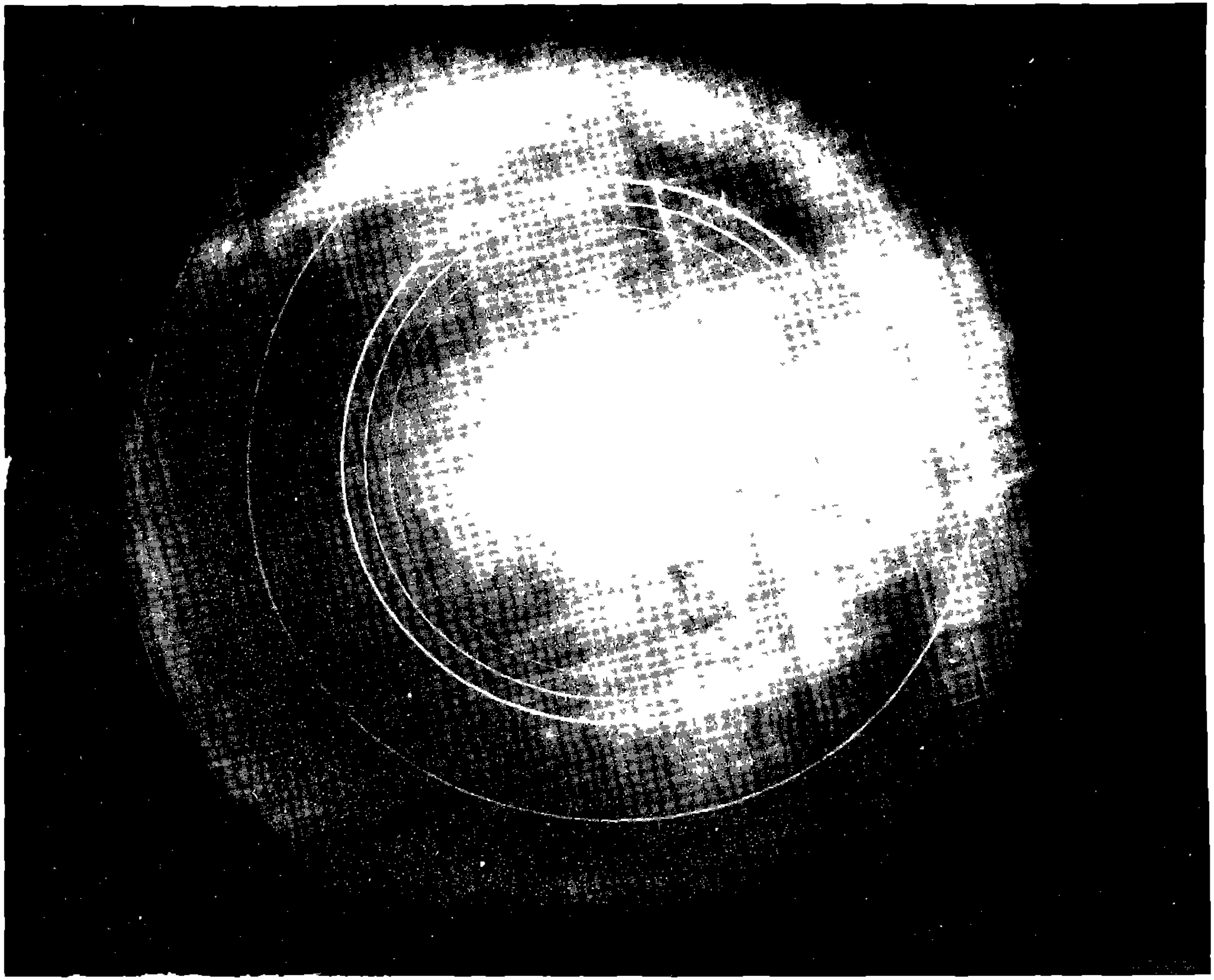


FIG 8 TONOTRON SHOWING "TONAL" WRITING

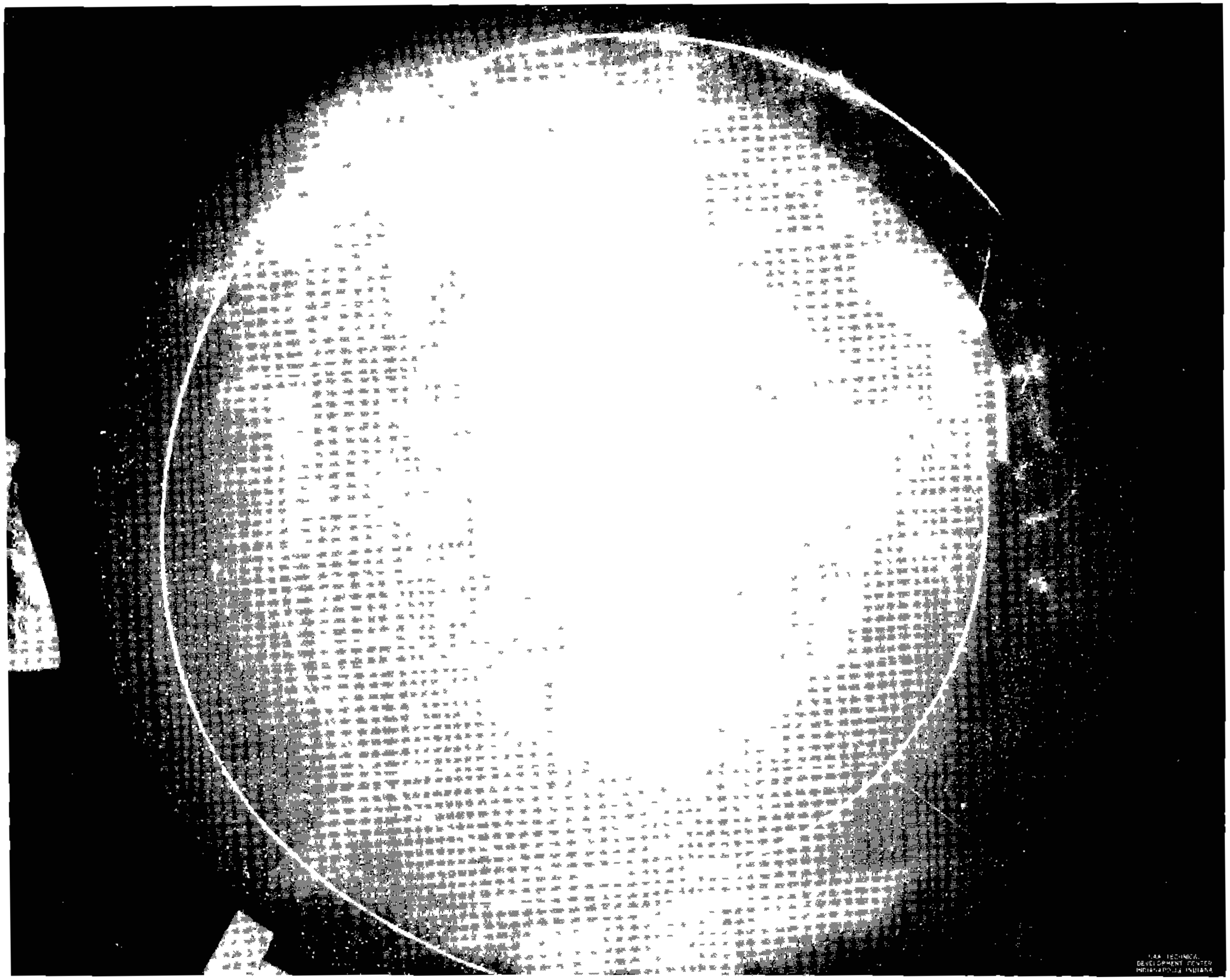


FIG 9 TONOTRON PICTURE OF INDIANAPOLIS ASR-2 RADAR AT 40-MILE RANGE

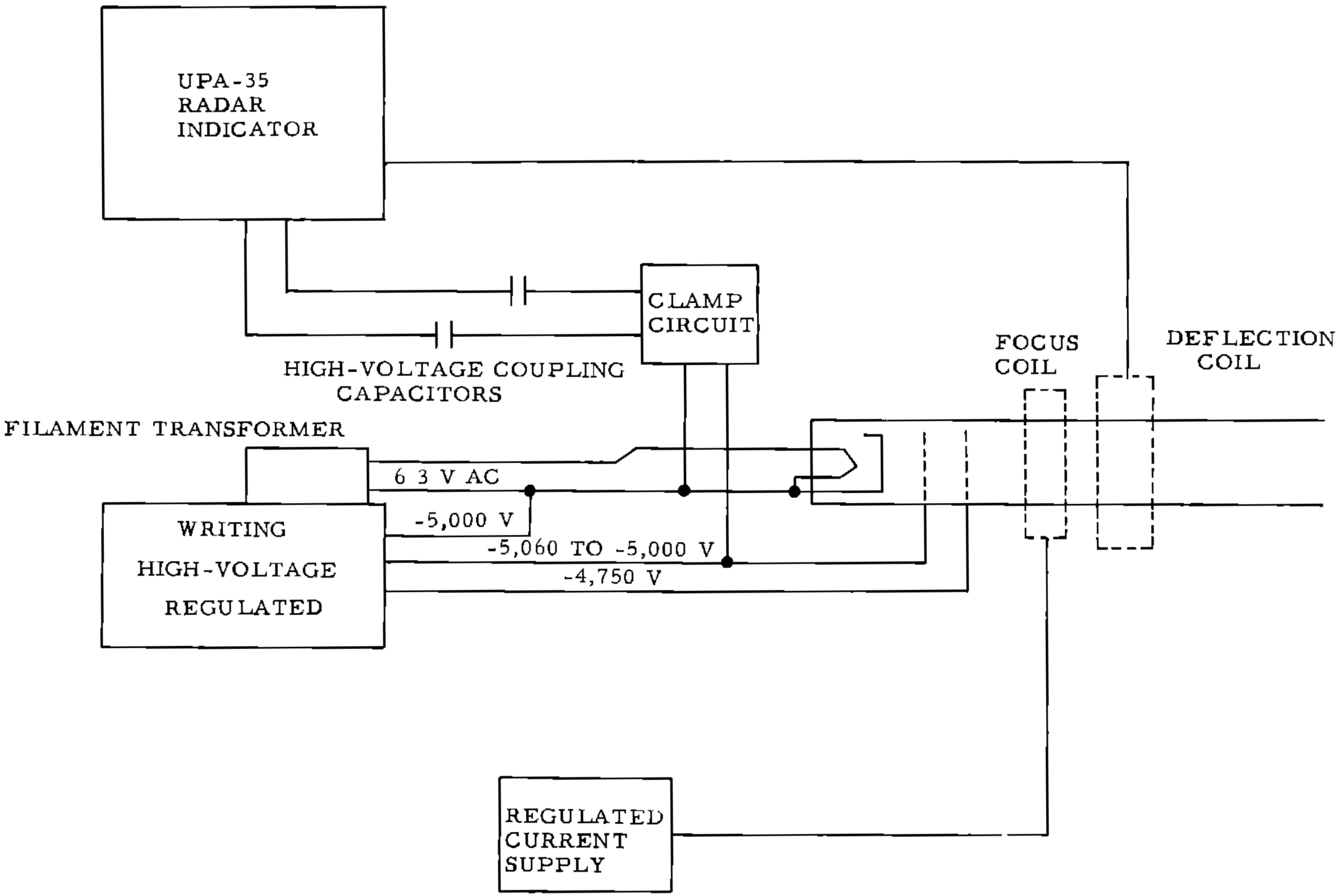


FIG 10 TONOTRON WRITING GUN DIAGRAM

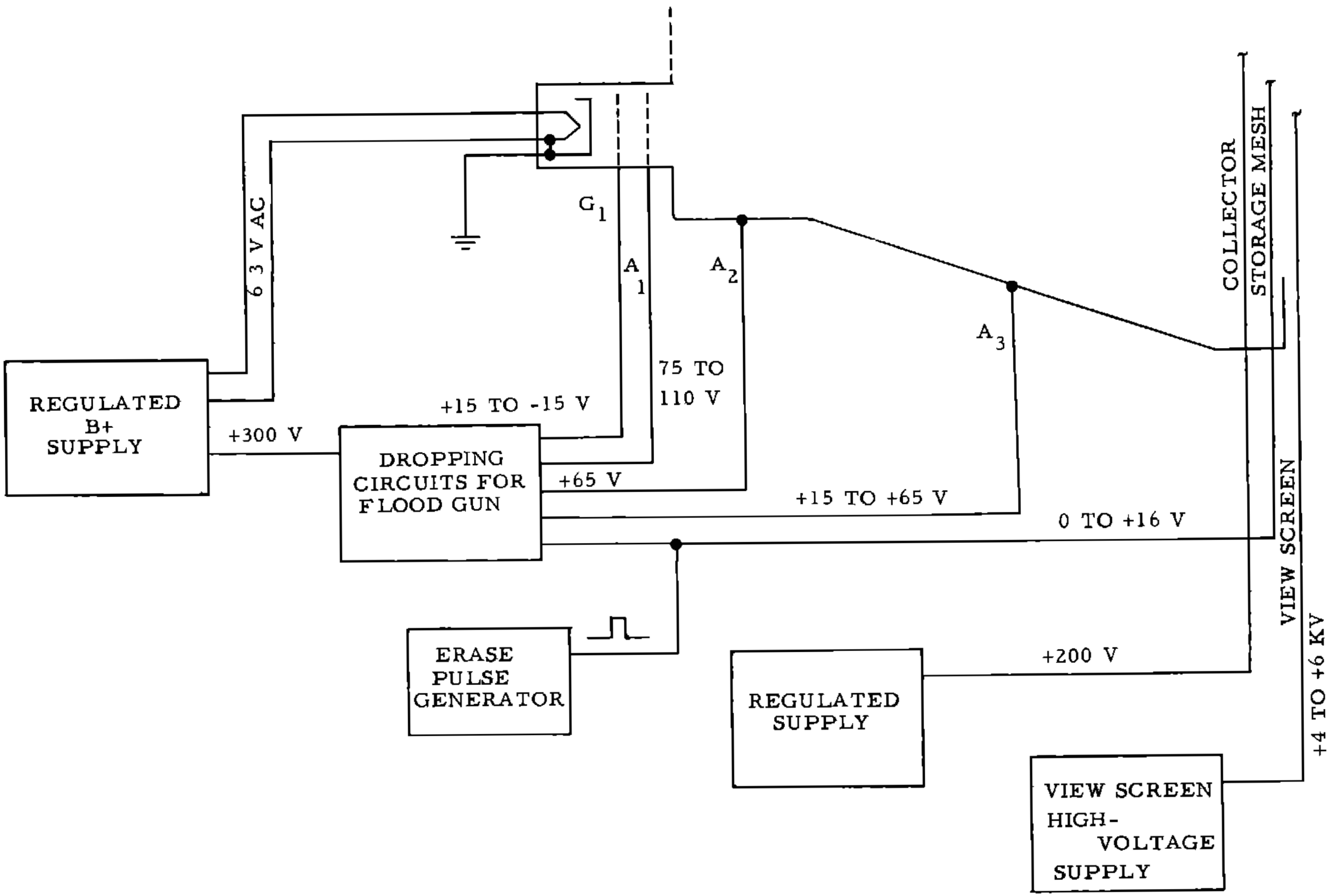


FIG 11 TONOTRON FLOOD GUN AND STORAGE ASSEMBLY BLOCK DIAGRAM