BRIGHT DISPLAY EQUIPMENT FOR SURVEILLANCE RADAR

By

Albert W Randall and Jack S Marshall

Electronics Division

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SUMMARY

Techniques and equipment used to provide a bright display of radar information are described in this report, together with a technical evaluation of the results obtained from experimental equipment Performance requirements for the display equipment are discussed, with consideration being given to the operational requirements It is shown that the resultant display is sufficiently brilliant for satisfactory operational use in a room with a high ambient light level and that the storage tube techniques applied offer advantages over the conventional dark room plan position indicator (PPI) in the detection of weak signals, in ease of operational use, and in flexibility An analysis is made of the characteristics and limitations of the equipment The scope of the comparison data is limited to the extent that accuracy and long term stability characteristics were not quantitively measured

INTRODUCTION

The early and currently available types of surveillance radar PPI have used a cathode ray tube with a screen coating which, when excited by a high velocity electron beam, produces visible light In radar PPI applications this electron beam is intensity-modulated by the video signals and is deflected radially by the magnetic field produced by a saw-tooth current in the deflection yoke Mechanical rotation of the yoke, which is in synchronism with the radar antenna, results in a display of signals throughout a 360° sector to a distance determined by the radar and the indicator sweep deflection period. The most commonly used screen coating provides a long persistence or afterglow, enabling the viewer to observe target positions for several seconds after the radar antenna (and indicator sweep) have passed by In the case of the P-7 screen material, the initial fluorescence is blue, and the phosphorescent afterglow is yellow The phosphors used to provide long persistence do not provide high levels of light output, hence the displays must be viewed in a dark room

The functional requirements of air traffic control personnel are such that frequent and instantaneous reference to the radar displays is necessary for maximum utilization of radar information The requirement that other types of indicators and instruments be readily visible to controllers in order that they may exercise effective traffic control further accentuates the need for a bright radar display Personnel in airport traffic control towers, where the availability of radar information is most important, have an additional problem of eye adaptability from a darkened radar indicator area to the high ambient light level existent in the remainder of the tower

Many attempts have been made during the past several years to produce a bright display which will provide adequate brilliance for viewing in daylight Within the last few years the Radio Corporation of America (RCA) has developed a storage tube known as the Graphechon[1] This tube was developed for an application where it was necessary to store radar information for a predetermined length of time The tube has excellent characteristics for the storage of radar information and, in addition, is suitable for scan conversion use A contract was placed with RCA to further develop the tube and associated circuitry to the extent that an evaluation of the results could be made to determine whether the tube and techniques applied would produce a display with enough brilliance for daylight viewing The results of this work were favorable and showed that the display was usable in a well-lighted room The resolution, however, was very inadequate, providing about 220 lines, and further work was necessary to isolate the causes and improve the performance

This report describes the performance obtained with the development model of the storage tube equipment after a number of modifications and improvements were made Dual channel prototype equipment is being procured under contract for evaluation of its long-term stability, reliability, accuracy, and operational suitability

THEORY

The technique of obtaining a display of sufficient brightness for effective viewing in daylight is that of converting radar signals

[1] L M Seeburger, "Operating Characteristics of the Graphechon," RCA Report No EM-4050, Camden, N J , February 16, 1950

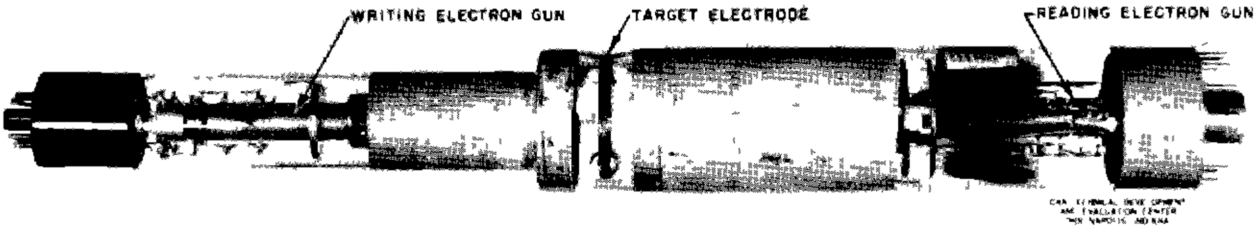


Fig 1 Graphechon Storage Tube

to television signals which are then displayed on a cathode ray tube having a medium persistence screen phosphor. In the conventional PPI using a P-7 screen, the image is retained between successive scans of the radar antenna by the relatively long decay characteristic of the phosphor The bright display equipment differs from this in that the retention of the image is provided electronically by virtue of the storage characteristics of the Graphechon tube Since the storage is obtained in this manner, short or medium persistence cathode ray tubes of the type used for television may be used, with the attendant advantage of their high efficiency in producing visible light This television kinescope is scanned at a television rate to provide maximum brightness and resolution consistent with the requirements of a radar display.

The Graphechon storage tube is provided with two electron guns similar to those used in standard cathode ray tubes The electron guns are aligned axially at opposite ends of the envelope, and a target electrode is suspended approximately midway between the guns as shown in Fig 1 The electron beams are focused electrostatically and deflected electromagnetically, and, with the exception of the common target, operation is equivalent to that of two separate tubes

A functional block diagram of the bright display equipment is shown in Fig 2 It will be seen that one electron gun is used to "write" the radar display on the target electrode of the storage tube Both the circuitry involved and the functions are essentially identical to those employed in conventional PPI The prime difference between a normal PPI and the writing section of the Graphechon storage tube is that with the Graphechon, the signal is written on the target electrode, whereas, with a P-7 cathode ray tube, the signal is written on a chemical phosphor screen coating

The target electrode consists of a 500-mesh copper screen upon the reading side of which is deposited first, a 0.1 micron aluminum film, and second, a 0.6 micron magnesium fluoride film A graphite coating on the inside of the tube envelope serves both as the second anode of the two guns and the collector of secondary electrons emitted by the target film

In operation the film side of the target is scanned by a 1,000-volt electron beam from the reading gun at a commercial television rate of 525 lines per frame, 30 frames per second, odd line interlaced Since magnesium fluoride is an insulator, the net current into the surface must be zero. Through secondary emission phenomena, however, more electrons leave the surface than arrive in the reading beam Because of the proximity of the grounded graphite collector, the secondary electrons travel to it until an equilibrium is produced, at which time the front surface of the film is practically at ground potential As a result of the low potential gradient, only the faster secondary electrons then reach the collector while the rest fall back on the target If in some manner a section of the film surface were made more negative than the collector, more secondary electrons would leave If this negative potential were not externally maintained, the surface would be charged back to collector potential by the action of the reading beam The rate of potential decay depends on the initial charge on the

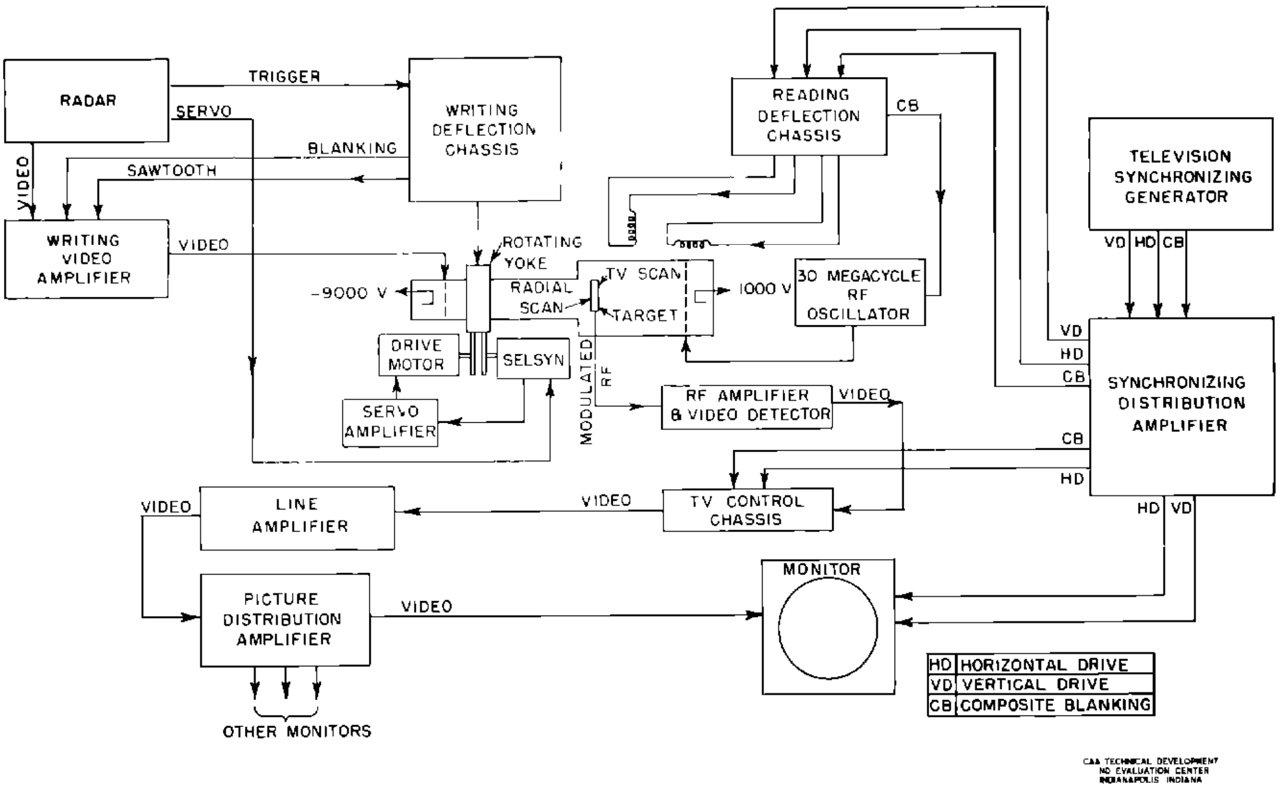


Fig 2 Functional Block Diagram of Bright Display Equipment

film and on the magnitude of the reading beam and therefore varies with reading gun grid voltage

For target potentials greater than -10 volts almost all the secondary electrons are collected, and further increase in current can be obtained only by increasing the reading beam In the existing equipment the aluminum film is maintained at about -50 volts by an external supply. Because the front surface is practically at ground potential, this voltage appears across the magnesium fluoride film (corresponding to a gradient of one million volts per centimeter), but this potential gradient is insufficient to cause breakdown If the writing or high voltage beam has sufficient velocity to penetrate both films, the magnesium fluoride becomes instantly conducting at the point of impact This drives the front film from a slightly positive potential to -50 volts When the writing beam (which is deflected with a radial PPI scan) moves on, the film potential remains unchanged until the reading beam strikes it and charges it part way back toward its original condition The rate of charge is constant, but no charging takes place after the reading beam has passed this particular point The new potential, therefore, remains unchanged until the reading beam returns 1/30 of a second later This process continues until the film has been charged completely, as before The charging current (secondary electrons minus reading beam) flows through the load resistance connected in series with the target and thus develops the useful output signal across the load resistance The amplitude of this signal is constant during each scan of the reading beam until the film potential is less than -10 volts Thus, halftone reproduction is not feasible, since high signal-to-noise ratio precludes the use of the 0 to -10 volt region where halftones theoretically could be differentiated The storage time of the Graphechon is directly proportional to the film dielectric constant, the dielectric strength, and the area of the target, and the storage time is inversely proportional to the reading beam current

The impact of the writing beam produces a signal of opposite polarity to that of the reading beam and one which may be one thousand times as large If this output voltage were fed directly to a video amplifier, the pulse would overload the amplifier and block all signals through it for some time after the writing pulse has passed Since it is desired to write and read simultaneously, the two signals are separated by a frequency selective amplifier A 30-megacycle (Mc) voltage is fed to the grid of the reading gun which operates as Class C The target load consists of a tank circuit tuned to 30 Mc. The writing pulse then has no effect on the output signal but applies a charge pattern to the target as before The 30-Mc pulses of reading beam current cause secondary emission from the target, as before, and the 30-Mc component is amplified and detected to recover the video signal Thus, with the reading beam deflected with a rectangular television scan at a television rate, a complete television picture signal is available for transmission to the display monitor, and conversion of the radial radar scan to a rectangular television scan is accomplished

Synchronous deflection of the electron beams of the reading gun and the display monitor are assured by the derivation of synchronizing pulses from a commercial television synchronizing signal generator and a multichannel distribution amplifier unit, as indicated in Fig. 2 Blanking signals also are provided by the synchronizing generator for the purpose of blanking the return traces of the display tube. These same blanking pulses are used to key off the 30-Mc oscillator signal during retrace periods of the reading gun Since the operation of the reading gun is Class C, no reading beam current flows during retrace periods in the absence of the 30-Mc signal In practice, the blanking signals for the display tube are mixed with the reading video signal obtained from the radio-frequency amplifier and detector in a control and mixer amplifier unit, and then they are further amplified in a line amplifier unit, where the composite signal is amplified sufficiently to compensate for transmission losses in a long coaxial cable to the display unit. Equalization for high frequency losses in the transmission line is accomplished in the line amplifier. Vertical and horizontal synchronizing pulses are transmitted over separate coaxial cables to the display unit A bandwidth of 6 Mc is maintained throughout the reading section, video circuits, and the display unit video amplifiers to permit full utilization of the available resolution of the Graphechon.

TEST EQUIPMENT

The apparatus used in determining the performance characteristics of the bright display equipment consists of a composite group of commercially available units, some of which were modified to provide certain special characteristics In Fig. 3 are shown the television synchronizing generator, distribution amplifiers, and the Graphechon scan conversion unit The display monitor is shown in Fig. 4. The experimental equipment does not provide controls on the display unit for radar range selection and other functions normally provided on PPI Such remote controls can be provided in a conventional manner, however

Signals from two sources were used to write information on the target of the Graphechon The first of these were video signals from an L-band surveillance radar whose important characteristics, insofar as the display equipment is concerned, are a one-microsecond pulse, a pulse repetition rate of 1,400, and a maximum antenna scan rate of 20 revolutions per minute (rpm) Both normal and moving target indicator (MTI) video were supplied to the scan conversion unit

The second signal source used for specific tests was the radar signal simulator shown in Fig 5 This simulator provides one or two simulated aircraft signals with simulated range, azimuth, and signal strength controlled separately. The simulator also provides a variable amplitude noise source to simulate noise from a radar receiver All tests described in this report, except the resolution test, were made using the above signal sources.

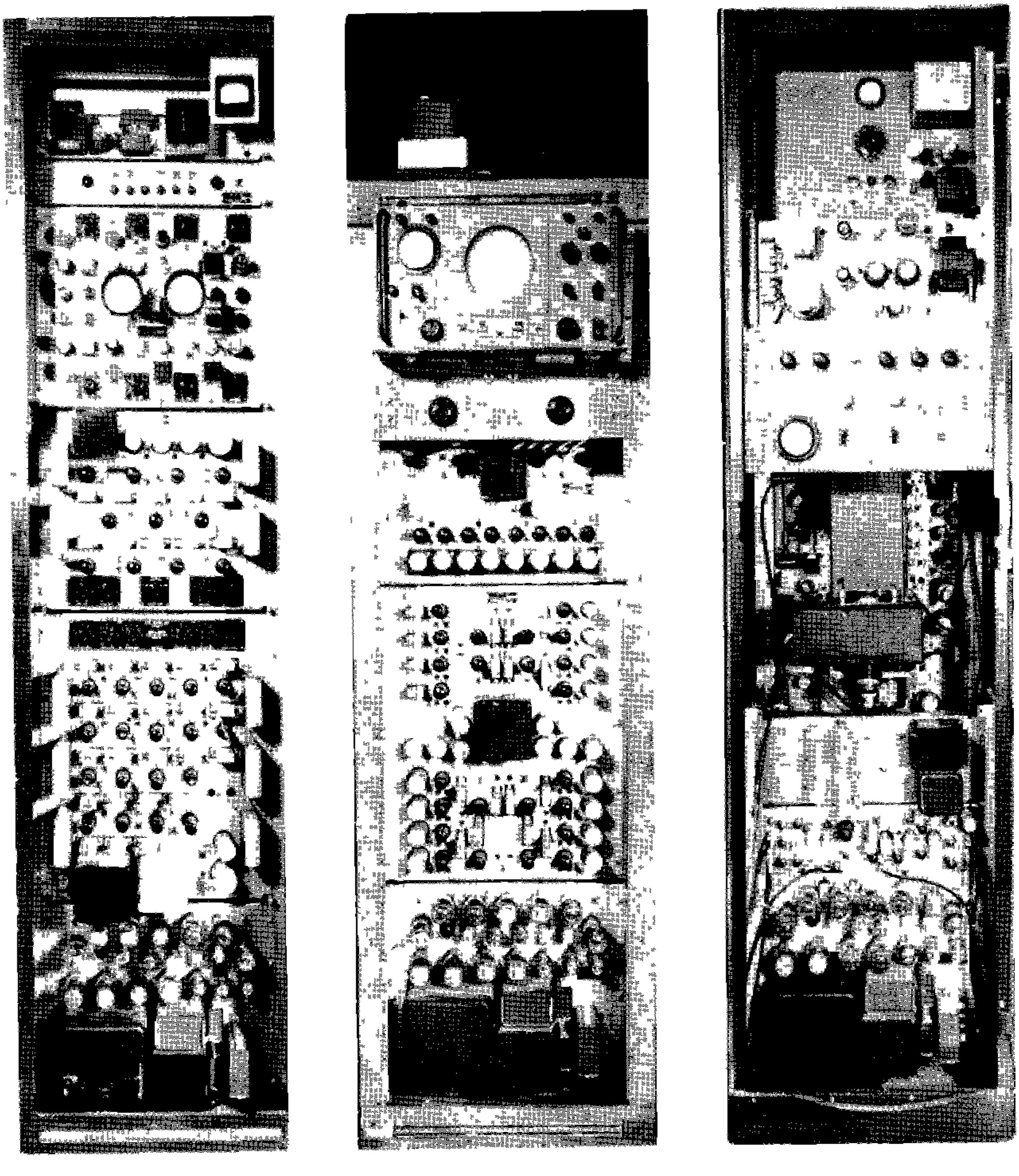
PERFORMANCE MEASUREMENTS AND PROCEDURES

The measurements which were made on the development model of the bright display equipment are divided into five groups These are

1. Display brightness
2. Display contrast.
3. Signal-to-noise ratio.
4. Storage time and resolution.
5. Ability to display weak signals

It should be recognized that the performance obtained in Items 2 through 5 can be made to vary appreciably by varying the parameters which affect the operation of the Graphechon tube For this reason a specific set of operating conditions and voltages was selected and maintained The selection of the operating parameters was made on the basis of the present application of the equipment

The choice of operating parameters for the Graphechon was based on known limitations of the bright display equipment and full consideration of the various air traffic control operational requirements A complete discussion of the operational



(A) TELEVISION SYNCHRONIZING GENERATOR

(B) SYNCHRONIZING DISTRIBUTION AMPLIFIERS

(C) GRAPHECHON SCAN CONVERSION UNIT

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Fig 3 Bright Display Equipment

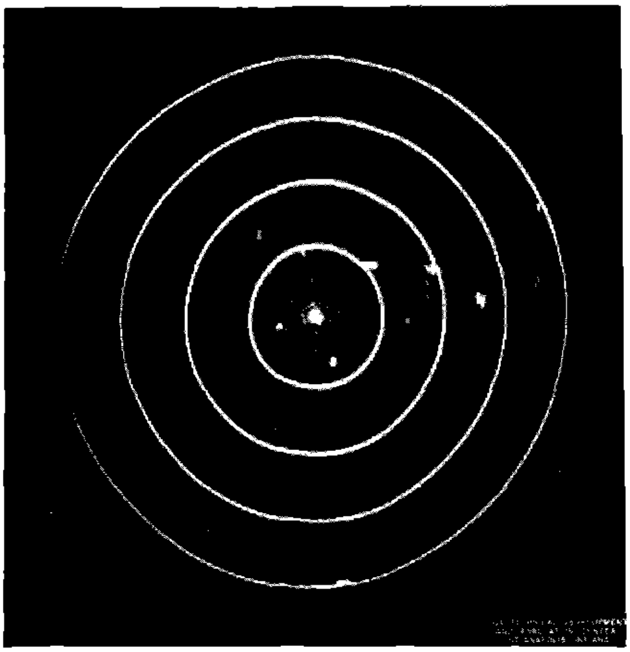

Fig 4 Bright Display Monitor

requirements[2] is beyond the scope of this report, however, an analysis of the performance data clearly shows that the operational requirements can be met with this equipment

1 Display Brightness

To determine the maximum usable display brightness, the display monitor was placed in a dark room so that neither the ambient light level nor reflections from the face of the kinescope would affect the readings obtained on an illuminometer. The monitor was adjusted in the conventional manner for visual extinction of an undeflected focused spot. A signal from a monoscope unit, which provided a standard Indian head test and resolution pattern, was applied to the video input terminals of the monitor, and the amplitude of this signal was increased to the point where there was a noticeable deterioration of the picture detail The signal then was reduced in amplitude to the point at which the finest detail in the resolution pattern could be clearly resolved The monoscope tube beam current was cut off, leaving on the face of the kinescope an all-white raster which was measured with an illuminometer. Measurements were made at various points over the face to take into account any effects of shading The results

[2] Radio Technical Commission for Aeronautics, Report of Special Committee 31, Paper 27-48/DO-12, May 12, 1948

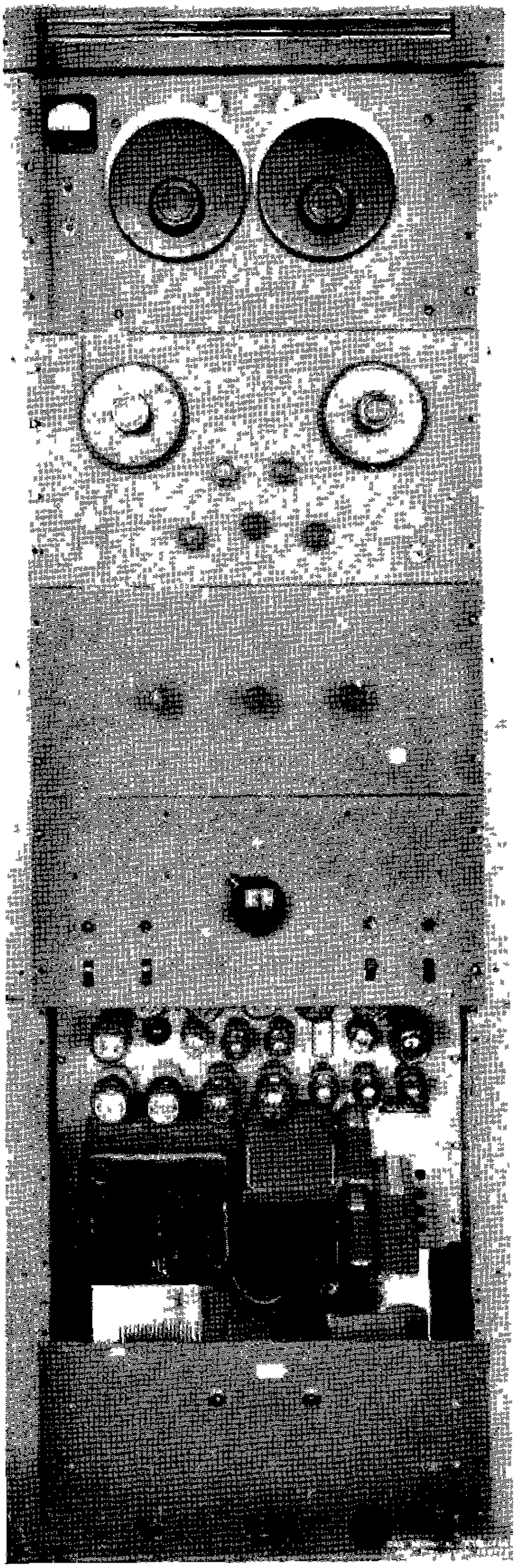

Fig 5 Radar Signal Simulator

TABLE I

Position Number	Brightness in Foot-Lamberts
1	46
2	44
3	42
4	53
5	52
6	42
7	42
8	49
9	45
10	42
11	42
12	42
Average	45

First anode voltage = 270 volts
Second anode voltage = 13 kilovolts
Filament voltage = 6 3 volts

of this measurement are given in Table I The average brightness was 45 foot-lamberts

2 Display Contrast.

The measurement of contrast in a television display is an exceedingly difficult one, inasmuch as it is not specifically defined and can be interpreted in many ways For the purpose of this report, contrast will be defined as that change in light output brought about by a given change in signal voltage applied to the grid of the kinescope The effects of ambient light level and reflected light from other sources will not be taken into account because of the many variables and attendant difficulties of considering all of the possible conditions. Thus, contrast will be directly related to the transfer characteristic of the kinescope and the ratio of the video signal voltages applied The transfer characteristic of the 10FP4 kinescope tube is shown in Fig 6 It will be noted that the middle and upper regions of the curve are not linear and do not exactly follow published transfer curves The deviation results from series resistance and from poor regulation effects introduced by necessary circuit elements This curve, therefore, shows the transfer characteristic obtained in practical equipment

The linearity of the video amplifiers following the radio-frequency amplifier and detector was measured in the conventional manner Signal voltages of known amplitudes were applied to the input of the control mixer-amplifier in place of those obtained from the radio-frequency amplifier and detector The signal voltages appearing at the grid of the kinescope were measured and plotted against input signal voltage, as shown

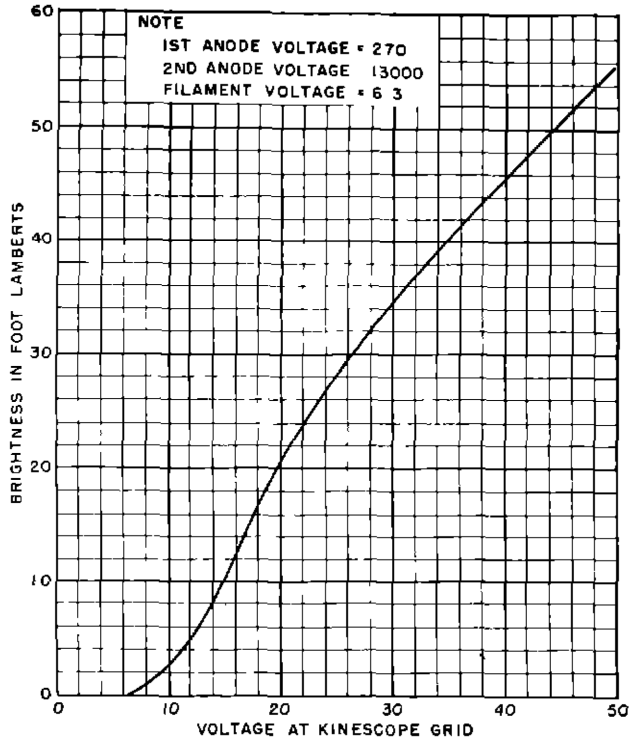

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Fig 6 Transfer Characteristic of a 10FP4 Kinescope

in Fig 7 Since the linearity of the intermediate amplifiers is extremely good, the displayed contrast may be determined from Fig 6 when both the maximum and one other signal voltage amplitude are known Therefore, excluding the effects of ambient light, the display contrast will be determined by the maximum and minimum signal voltages appearing at the output of the detector in the radio-frequency amplifier unit

3 Signal-to-Noise Ratio.

The 30-Mc reading signal appearing at the target connection of the Graphechon tube is very low in amplitude and contains noise components Since the maximum output under normal operating conditions does not exceed approximately 50 microvolts (μv), a high gain radio-frequency amplifier is required to provide approximately one-volt output from the detector Every effort was made to minimize the generation of noise in this radio-frequency amplifier Since the storage time for a given writing signal amplitude is determined by the reading beam current, the reading signal voltage appearing at the target load resistance is directly proportional to that current In practice, then, the gain of the radio-frequency

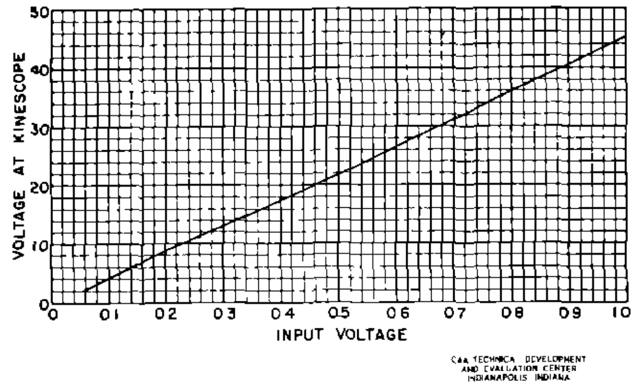

Fig 7 Amplification Response of Reading Video Amplifiers

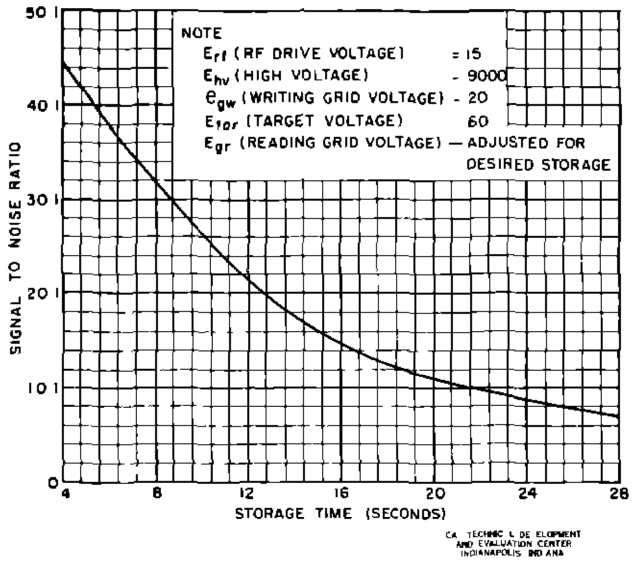

Fig 9 Signal-to-Noise Ratio Versus Storage Time for Reading Section

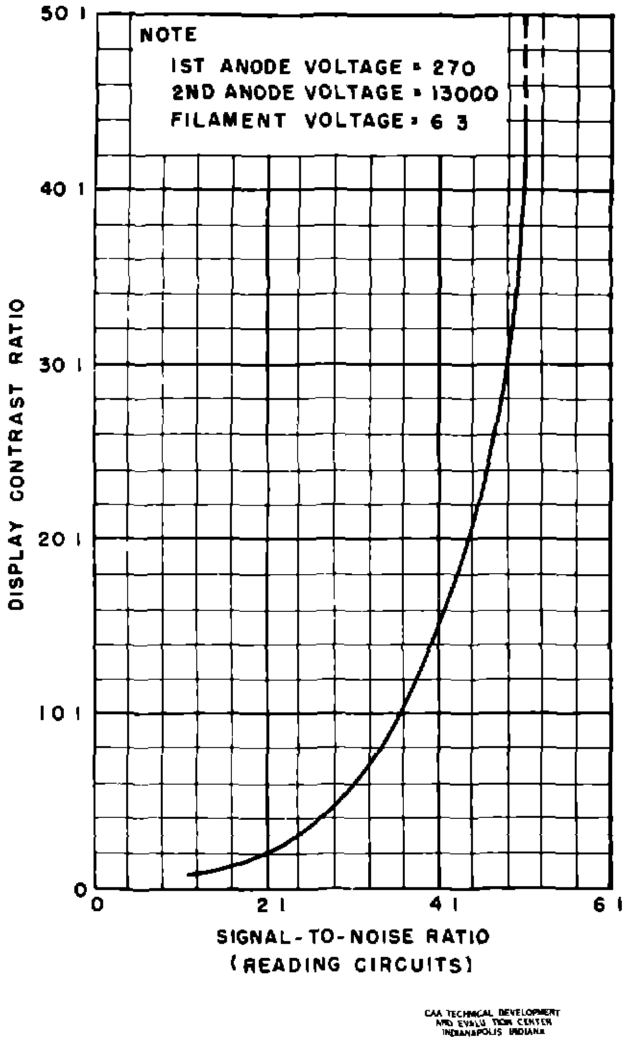

Fig 8 Display Contrast Versus Signal-to-Noise Ratio

amplifier is varied to deliver a one-volt peak signal at the detector output to maintain a constant peak signal brightness at the display tube for all usable storage times Hence, it can be seen that the signal-to-noise ratio for a given maximum display brightness is determined by the storage time and that the maximum display contrast is largely determined by the signal-to-noise ratio The contrast for various signal-to-noise ratios is shown in Fig 8 Fig 9 shows the relative signal-to-noise ratio versus storage time obtainable under typical operating conditions In Fig 9, a signal-to-noise ratio of 1 1 is defined as the peak signal level equal to two times the average noise level Measurements of signal-to-noise ratio were made with a Tektronix Model 513D oscilloscope having a Y-axis bandwidth of 20 Mc and a 5XP2 cathode ray tube with 12-kilovolt (kv) anode potential

4 Storage Time and Resolution.

The storage time available with the Graphechon tube is dependent upon a large number of factors, including target voltage and other operating conditions[3] Optimum operating conditions of the Graphechon for surveillance radar applications have been established, and storage time results in this report are based on those parameters

Storage time is primarily a linear

[3]Seeburger, op cit. This gives a more complete discussion of the factors affecting storage time

function of target voltage The maximum storage time is limited by the dielectric strength of the target insulating layer and is determined primarily by the writing signal amplitude and the writing gun acceleration potential. Storage time herein refers to the time required to discharge the target completely at a standard Radio Manufacturers' Association television scan rate and has been measured by establishing the time interval between the end of a writing period and the time that the signal becomes indistinguishable from noise, as observed on a Tektronix 513D or similar oscilloscope

The maximum usable writing signal amplitude is in turn determined by the required display resolution Surveillance radars used for traffic control purposes are capable of relatively high degrees of resolution For the sake of simplicity, the range resolution is approximately equal to the radar pulse width, and the azimuth resolution is determined by the beam width of the radar antenna in the horizontal plane. The resolution requirements for a given radar and radial sweep range can readily be computed. Surveillance radars such as the Type ASR-2 require indicators capable of high resolution, if maximum use is to be made of the radar information. Air traffic control applications require that the resolution of a bright display indicator be at least equal to that[4] of a conventional PPI, using a P-7 tube. Examination of Fig. 10 shows that the writing signal must be limited to approximately 20 volts to obtain a resolution of at least 400 lines The ease with which these lines may be resolved is somewhat dependent upon signal-to-noise ratio in the display and therefore also dependent upon contrast, as is the case with the conventional PPI

The resolution capabilities of the Graphechon equipment were determined by electronically writing a number of concentric circles on the target in place of radar range marks and video signals. These signals were derived from a Tektronix Type 105 square wave generator which was synchronized by the radar trigger The kinescope was adjusted for maximum brilliance, as described under "Display Brightness," and the number of concentric lines was increased by increasing the frequency of the square wave generator until the individual lines were no longer easily and quickly resolved

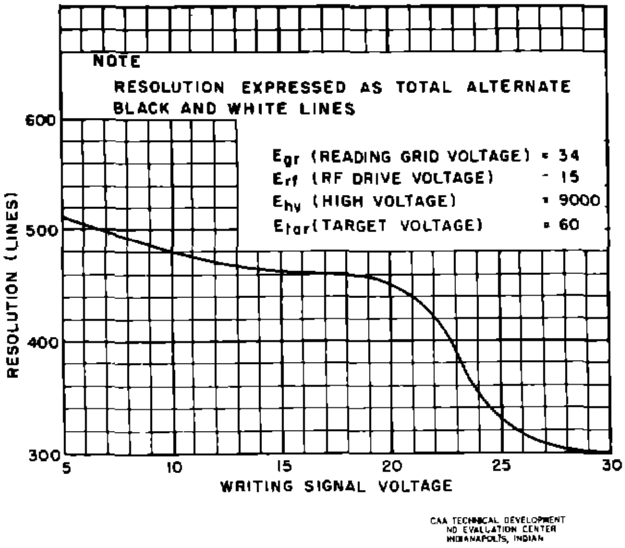

Fig 10 Graphechon Resolution Versus Writing Signal Amplitude

with an ambient illumination of 150 foot-candles The number of equally spaced alternate black and white lines are determined by visual count or by the equation

$$R_L = 2(T_s 2F)$$

where

R_L = number of lines resolution,

T_s = radial radar sweep time in seconds,

F = frequency of square wave generator, cycles per second (cps)

The factor of 2 is applied to double the radius and determines the resolution in lines for the display diameter.

The measurements made on the developmental model show that, with the Graphechon and display monitor adjusted as described above, more than 400 lines of equal width and spacing are easily resolved under ambient illumination of approximately 150 foot-candles

The 400-line resolution provided by the Graphechon equipment exceeds that attainable from a P-7 tube. Theoretically, a radar with a one-microsecond pulse will permit resolving two targets at the same azimuth position when they differ in range by 500 feet The Graphechon equipment will provide this range resolution to 18 6 statute miles, whereas a P-7 phosphor provides this resolution to only approximately 13.6 miles From an operational point of view this

[4]Louis N. Ridenour, "Radar System Engineering," M. I T Radiation Laboratory Series, Vol I, p 548, 1947

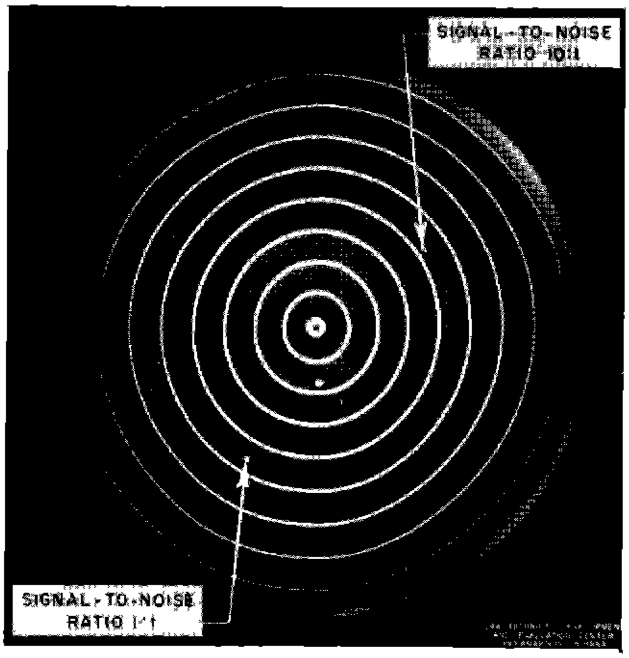

Fig 11 Display Monitor Showing Targets With 1 1 and 10 1 Signal-to-Noise Ratios

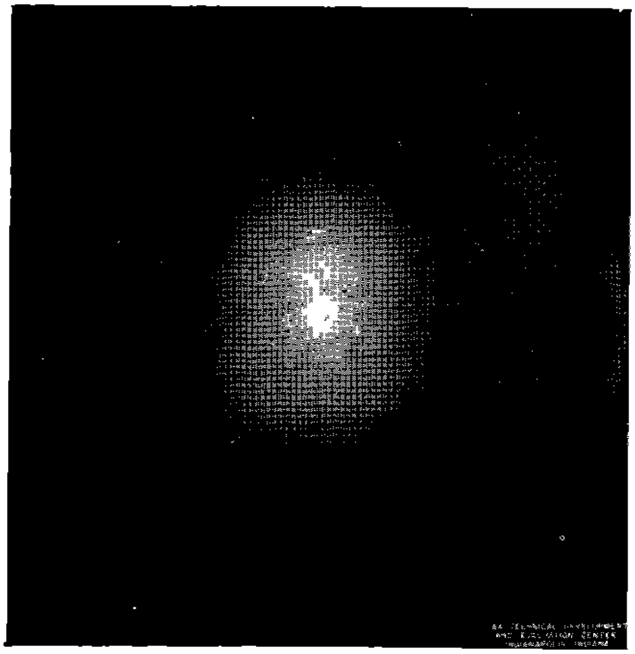

Fig 12 Charge Distribution on Target of Graphechon

resolution is very good, inasmuch as it permits resolving targets 1,000 feet apart in distance to more than 37 miles Air traffic control procedures require a minimum radar separation of three miles for aircraft on approach or at the same altitude, hence, it can be seen that the range resolution is more than adequate.

5 Ability to Display Weak Signals.

It has been stated previously that the Graphechon is not capable of writing half-tones This does not mean that the Graphechon is not satisfactory for the simultaneous display of both weak and strong aircraft signals It will be shown that weak signals having an amplitude equal to or slightly lower than the peak noise level from the radar receiver can be displayed with a brilliance nearly equal to that of a radar signal having a 10 1 or better signal-to-noise ratio The radar signal simulator was used for this test The characteristics of the Graphechon are such that a low amplitude signal voltage occurring at a regular rate, as does a radar signal, develops a high level charge through integration at the target. On the other hand, noise occurring at random rates does not integrate If sufficient amplification is provided for low amplitude video signals to obtain approximately 20 volts of writing signal and if higher amplitude signals are limited to a 20-volt level, then all signals will produce approximately the same storage and display brightness In this mode of operation the writing grid is biased to a point just below the noise peak writing level Fig 11 is a reproduction of a photograph of the display of signals having 1 1 and 10 1 signal-to-noise ratios This method of operation appears to increase the useful range of a radar by approximately 3 to 6 decibels (db), depending on the antenna scan speed In reality it has eliminated the loss characteristic of a PPI using a P-7 tube, in that a large amount of time is not required to build up the light output from phosphors

EQUIPMENT LIMITATIONS

The kinescope display illustrated in Fig 12 shows that the background, which is actually an electronic reproduction of the target, is not evenly illuminated This shading effect is caused by the variation in the charge distribution over the target and, with the tube design in its present state of development, cannot be eliminated Some speculation has been made concerning the manner in which the charge may be equalized One method proposes the placement of a barrier grid in front of the target, which method (to the authors' knowledge) has not been tried to date In fact, there is little agreement among users of the tube concerning justification of the additional development work The shading has a minor effect on storage time, increasing it near the center of the tube From a practical point of view, the lighter area near the center is masked by a small amount of ambient light and is therefore not considered objectionable

CONCLUSIONS

The bright display equipment in its basic form, as described in this report, is large and complex in comparison with the currently used PPI using a P-7 tube. Experience has shown that the design requirements are very rigid This is easily understood when it is recognized that there are three deflection circuits for the storage tube instead of one, as in the normal PPI, and very high orders of deflection linearity are required to provide root mean square target positional errors not exceeding those of a well-designed PPI Regulated power supplies and thorough shielding of the storage tube are also requisites Deflection linearity in the display monitor need not be of such a high order, since no errors are introduced at that point unless an overlay map is used

The experimental equipment has shown that a signal or highlight brightness of 50 foot-lamberts is readily obtainable while providing the maximum required display resolution for surveillance radar applications This display brightness is adequate for continuous or intermittent viewing over long periods of time in ambient light levels up to 150 foot-candles without requiring close scrutiny or unduly concentrated effort on the part of a traffic controller A study of ambient light in a traffic control tower on a clear, bright, sunny day discloses that ambient illumination from approximately 25 to 350 foot-candles is encountered in various areas In all probability, an area in the tower having an ambient illumination not exceeding approximately 150 foot-candles over a 24-hour period can be provided

Storage time is believed to be more than adequate with good signal-to-noise ratios over the useful range and exceeds that of currently used PPI A range of from 2 to 30 seconds is provided. Numerous other operational advantages are obtained as follows

1 Weak signals are easily detected, resulting in a worth-while increase in effective radar range. Signals that are undetectable on a P-7 PPI are clearly and brightly displayed.

2 No radar controls need be provided at the display unit, thereby eliminating the possibility of operating personnel deteriorating radar and display performance by inadvertent maladjustment

3. Display brightness may conveniently be varied to meet operational requirements without affecting accuracy or sensitivity

4 Flexibility is provided, thereby permitting the addition of a large number of small, low cost repeater displays. An accurate and simple television video mapping system may be added at any time

5 All modes of operation obtainable with the normal PPI are available with the bright display equipment.

6 Aircraft vectoring operations can be accomplished with greater ease and accuracy, particularly at low antenna scan speeds, by virtue of the long storage

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