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RCA REVIEW, published quarterly in March, June, September and December by RCA Laboratories Division, Radio Corporation of America, Princeton, New Jersey. Entered as second class matter July 3, 1950 at the Post Office at Princeton, New Jersey, under the act of March 3, 1879. Subscription price in the United States, Canada and Postal Union; one year $2.00, two years $3.50, three years $4.50: in other countries; one year $2.40, two years $4.30, three years $5.70. Single copies in the United States, $.75; in other countries, $.85.

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RCA REVIEW

a technical journal

RADIO AND ELECTRONICS
RESEARCH • ENGINEERING

Published quarterly by
RCA LABORATORIES DIVISION
RADIO CORPORATION OF AMERICA

in cooperation with

RCA VICTOR DIVISION
RADIOMARINE CORPORATION OF AMERICA
RCA INTERNATIONAL DIVISION
RCA COMMUNICATIONS, INC.
NATIONAL BROADCASTING COMPANY, INC.
RCA INSTITUTES, INC.

VOLUME XIII — MARCH, 1952 — NUMBER 1

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RCA REVIEW is regularly abstracted and indexed by *Industrial Arts Index, Science Abstracts* (I.E.E.-Brit.), *Electronic Engineering Master Index, Chemical Abstracts, Proc. I.R.E.,* and *Wireless Engineer.*

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PERFORMANCE OF THE VIDICON, A SMALL DEVELOPMENTAL TELEVISION CAMERA TUBE*

BY

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Summary—The performance of developmental Vidicons utilizing three different developmental types of photoconductive layers is described in this paper. Data is given on gamma, sensitivity, illumination considerations, spectral response, persistence, and life. Vidicon construction and operation as well as signal-to-noise limitations are discussed.

INTRODUCTION

THE Vidicon is a developmental television camera tube employing a thin layer of photoconductive material as its light-sensitive element. The paper describes the performance of developmental Vidicons employing several different types of photoconductive layers. Although the operation of the Vidicon has been presented in detail in other papers,[1] the principles of operation and a description of its construction will be given so that the significance of the performance data will be evident.

PRINCIPLES OF OPERATION

Figure 1 illustrates the basic principles of Vidicon operation. In this tube the electron beam is of low velocity as in the scanning section of the image orthicon. As shown in the illustration, the photoconductive layer, or photolayer, which is scanned by the electron beam, is backed by a signal plate which is maintained positive with respect to the cathode by an externally applied voltage. The electron beam current is maintained sufficiently high so that each element of surface on the gun side of the photolayer remains near cathode potential. In the interval between scans, wherever the photolayer is conductive due to the presence of light, the migration of charge through the layer causes its surface potential to rise toward that of the signal plate. On the next scan a sufficient number of electrons is deposited to return

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* Decimal Classification: R583.6.

[1] P. K. Weimer, S. V. Forgue and R. R. Goodrich, "The Vidicon—Photoconductive Camera Tube," *Electronics*, Vol. 23, pp. 70-73, May, 1950; also, *RCA Review*, Vol. XII, pp. 306-313, September, 1951.

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the surface to cathode potential. The result of this deposition is a current in the circuit which produces, across the load resistor, a voltage drop proportional to the charge built up between scans. The fluctuations in the voltage across the load resistor become the video signal applied to the first amplifier stage.

Electrical Requirements of the Photoconductive Material

The photosensitivity of the photoconductive material may be as high as attainable, but in order that the signal produced be approximately proportional to the conductivity, the illumination in the picture highlights should be limited to a value such that the surface potential

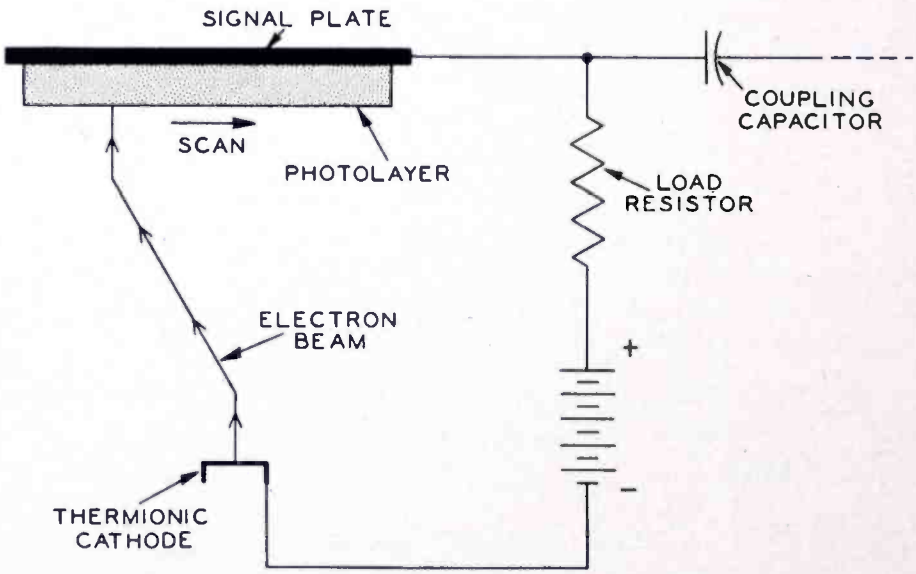

Fig. 1—Basic principles of Vidicon operation.

change is small compared to the signal-plate potential. With the 1/30 second television frame time and the dielectric constant of the order of 10 for photoconductors, the resistivity in the highlights should not be lower than about 10^{10} ohm centimeter. The dark resistivity should be large compared to this value.

Vidicon Construction and Operation

In the developmental Vidicon, the signal plate is a coating of transparent conductive material deposited on the inside of the glass faceplate so that the optical image may be projected through it to the photolayer. Figure 2 shows the arrangement of parts in the tube together with the positioning of the associated components. Grid No. 2 accelerates the beam of electrons emitted by the thermionic cathode. Grid No. 1, the control grid, operates at 0 to —100 volts with respect

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to the cathode. A small fraction of the electron-beam current passes through the small aperture (0.002 inch in diameter) at the faceplate end of Grid No. 2. The beam passing through the aperture is imaged on the photolayer by the magnetic field produced by the external focusing coil. Deflection is obtained by external coils placed within the focusing field. The long electrode, grid No. 3, controls the potential of most of the space through which the electrons move. Focus adjustment is obtained by varying either the current through the focusing coil or the grid-No. 3 voltage, which is slightly less than 300 volts. A 500-mesh screen at the faceplate end of grid No. 3 provides a uniform decelerating field for the electrons. For the particular focusing coil

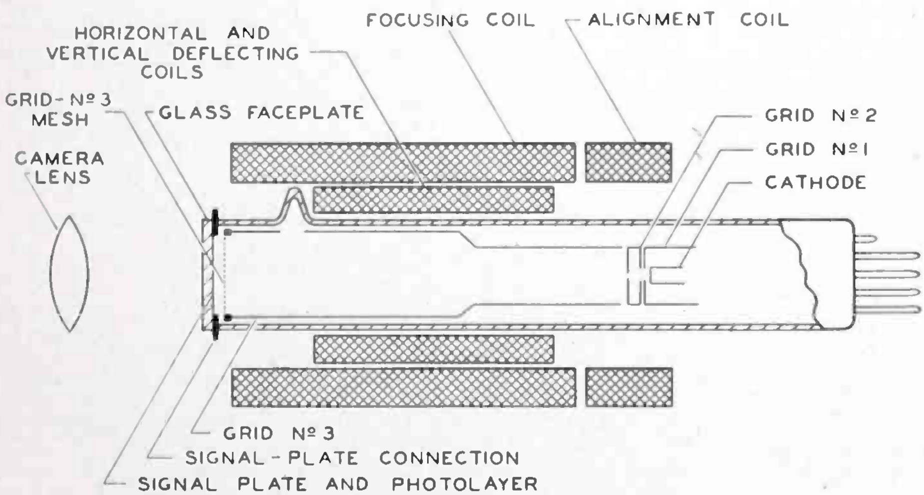

Fig. 2—Arrangement of parts in Vidicon and positioning of associated components.

and focusing-coil-current value used when the data described in this paper was taken, the electrons make one loop between the grid-No. 2 aperture and the photolayer. The potential of the signal plate is approximately 30 volts positive with respect to the cathode. The thickness of the photoconductive layer, approximately 0.0002 inch, is small compared to the diameter of the electron-beam spot and, hence, any lateral conductivity is negligible.

A photograph of the developmental Vidicon is shown in Figure 3. The tube is one inch in diameter, has an over-all length about 6¼ inches, and has a useful sensitive area about ⅝ inch in diameter. For a 3 to 4 aspect ratio the image is ⅜ inch high and ½ inch wide.

Performance Data

The Vidicon is capable of resolving at the center of the picture at least 350 television lines per vertical picture height; with a suitable

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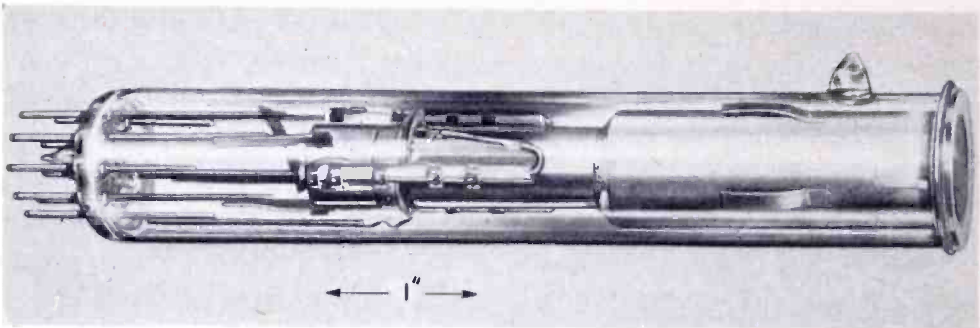

Fig. 3—Photograph of developmental Vidicon.

amplifier, 500 to 600 lines can usually be seen. A more complete specification of the ability of the tube to show detail is given in Figure 4 which shows the amplitude-response-factor curve for a typical tube. This curve indicates that a pattern of 300 lines provides a response about 20 per cent of that of large-area blacks and whites. The curve was obtained with an average signal output of 0.2 microampere. When the signal output is larger, some loss of resolution is observed because the larger beam current required does not provide as sharp a spot.

The noise contributed by the Vidicon is small compared to that contributed by the associated circuit. With the usual peaked amplifier response, the noise is equivalent to about 0.002 microampere in the

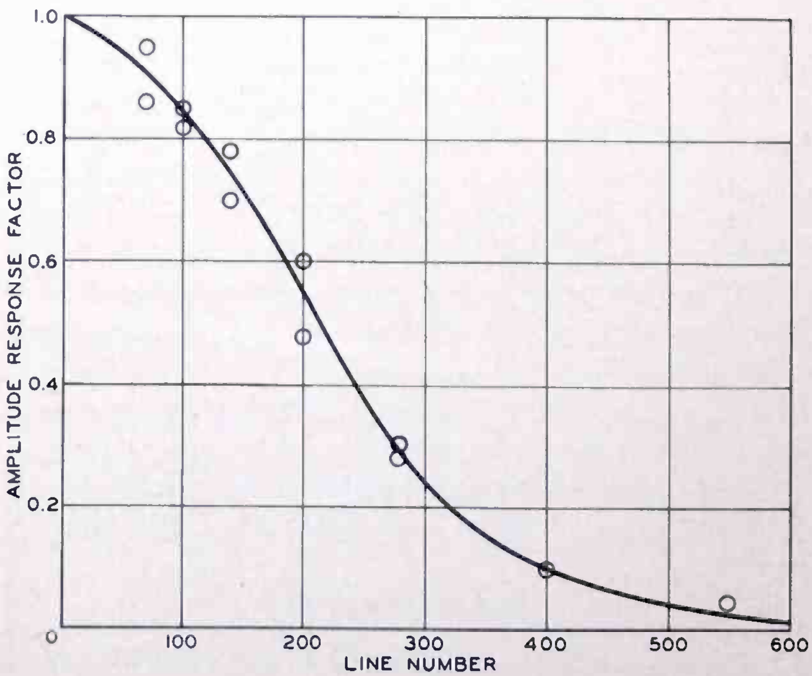

Fig. 4—Amplitude response factor of typical developmental Vidicon.

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load resistor. A 0.2-microampere output signal, therefore, should have a signal-to-noise ratio of about 100 to 1.

Although the sensitivity of the Vidicon increases with increasing signal-plate voltage, a limit is set by the dark current which increases with a higher exponential power of signal-plate voltage than the signal. The useful limit is determined by the amount of nonuniformity in the dark-current signal background which can be tolerated under the conditions of use. The data given in this paper was taken within the limitation of a maximum tolerable dark current of 0.04 microampere.

Photoconductive Layer

Three developmental types of photolayers are discussed in this paper. These types are referred to as 1, 2, and 3. The material of which type 1 is made is amorphous selenium,[2] type 2 is of antimony trisulfide,[3] and type 3 is a modification of type 2.

Gamma, Sensitivity, and Illumination Considerations

Figure 5 is a typical log-log plot of signal output versus light flux for each of the three photosensitive layers. In all cases the slopes of the lines are less than unity; the output, therefore, is not proportional to the applied illumination. In the usual operating range, between 0.02 and 0.2 microampere, the approximate slopes, or gammas, are 0.9 for type 1, 0.75 for type 2, and 0.7 for type 3. A low-gamma camera tube provides compression of the electrical signal range which is desirable for amplification and transmission and which also helps to compensate for the high gamma of the kinescope. Because the response of the Vidicon is nonlinear, it is necessary to specify the light or signal level and to require uniform illumination over the scanned area when sensitivity is being determined. Sensitivity is specified here at a low signal level, 0.02 microampere, because the low-lights are most critical for amplification of the signal. With this definition, the sensitivities of developmental Vidicons having photoconductive layers 1, 2, and 3 are, respectively, 100, 300, and 50 microamperes per lumen. As an example of illumination requirements, one millilumen on the useful photosensitive area ⅜ inch by ½ inch, which yields a signal output in the useful range between 0.02 and 0.2 microampere for any of the three types, represents a tube illumination of

[2] P. K. Weimer and A. D. Cope, "Photoconductivity in Amorphous Selenium," *RCA Review*, Vol. XII, pp. 314-334, September, 1951.

[3] S. V. Forgue, R. R. Goodrich and A. D. Cope, "Properties of Some Photoconductors, Principally Antimony Trisulfide," *RCA Review*, Vol. XII, pp. 335-349, September, 1951.

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about ¾ of a foot-candle. With an f:2 lens and a scene reflectance of 50 per cent, the scene illumination would be about 30 foot-candles of incandescent light.

Spectral Response, Persistence, and Life

There are several possible ways of defining the spectral sensitivity of a nonlinear device. For the data given in this paper the spectral sensitivity is taken as the reciprocal of the amount of energy at each wave length required to obtain the same signal. This signal is chosen to be 0.02 microampere. As shown in Figure 6, the response of photolayer 1 is limited to the blue end of the spectrum, photolayer 2 peaks

Fig. 5—Transfer characteristics.

in the red or yellow, and photolayer 3 peaks in the blue or green but has an appreciable response throughout the visible region. The spectral response curve for 3 is close to that of the image orthicon type 5820.

In general, the persistence of photoconductive materials becomes shorter when they are exposed to higher values of illumination. Figure 7 shows measurements of electrical signal decay made with each of the three photosensitive layers after the illumination had been

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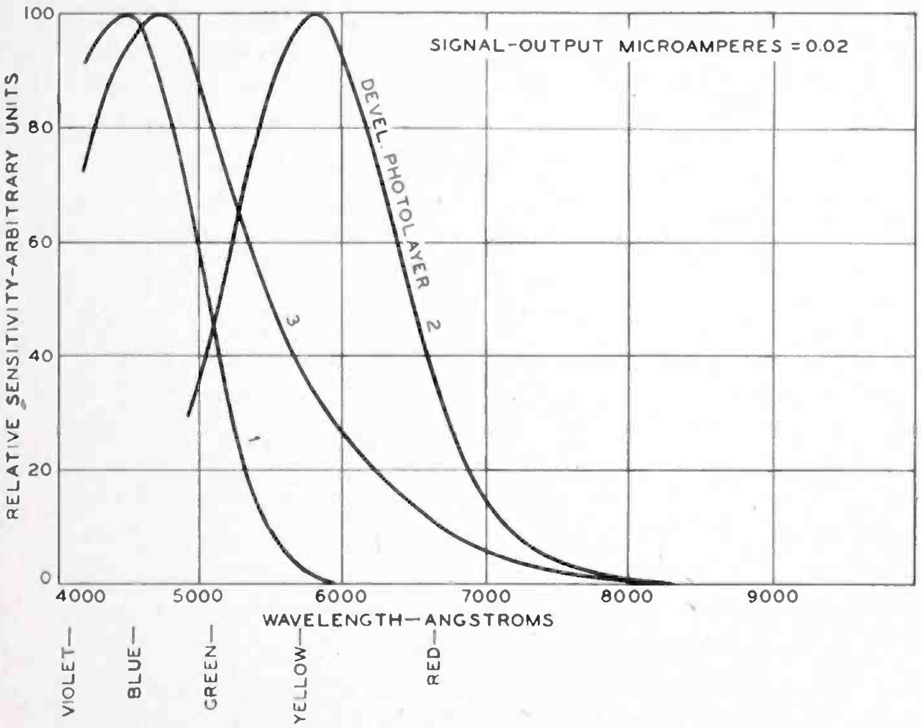

Fig. 6—Spectral sensitivity characteristics.

suddenly cut off. Photosensitive layers 1 and 3 have persistence short enough for use in motion-picture work where the subject does not normally move rapidly across the field of view. As shown by the curve, type 2 has the slowest decay. The corresponding signal build-up when

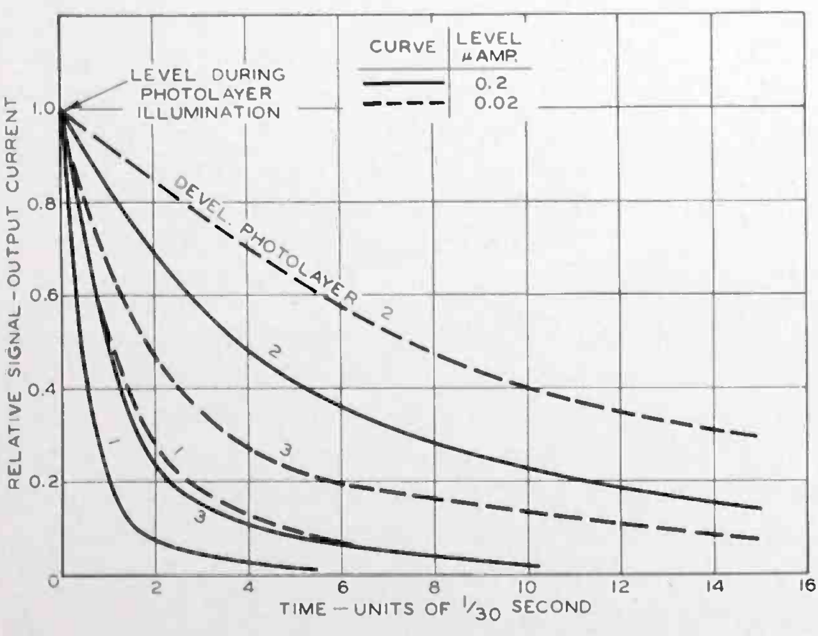

Fig. 7—Decay characteristics.

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light is suddenly applied to a Vidicon previously in the dark is as fast or faster than the rate indicated by the decay curves. The light output of a kinescope excited by a decaying signal will decay faster than the signal due to the greater-than-unity gamma of its transfer characteristic.

The most serious disadvantage of type 1 is its short useful life which is in the order of 300 hours even when operation is at the low faceplate temperature of around 35°C. Development has not progressed far enough to lengthen this life materially. Types 2 and 3 have better life which should be more nearly commercially acceptable, and, in addition, in these types, the faceplate temperature may safely be 60°C in operation.

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THE RCA COLOR TELEVISION CAMERA CHAIN*†

By

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***Summary**—This paper describes the results of a program whose purpose was to design a commercial color television camera based on the camera which was developed by RCA Laboratories Division and demonstrated before the Federal Communications Commission. Monitoring and control functions of the camera chain are discussed.*

Introduction

BASIC development work on the problem of providing simultaneous camera equipment for the direct pickup of live programs in color was done several years ago at RCA Laboratories. Several developmental type camera chains produced there have been used successfully since 1946. Early in 1950, the RCA Victor Division undertook the development of color television camera equipment of commercial design, capable of fulfilling present-day programming requirements. The result of this engineering effort was the production of several color camera chains which were installed in New York. The new equipment has been used for the field-test programs broadcast by NBC since July, 1951.

The purpose of this paper is to describe the technical features incorporated in the commercial color camera. The discussion will be limited to those parts of the camera chain required to produce three simultaneous color video signals. The methods used to encode the simultaneous signals for transmission in the complete RCA color television system have been discussed elsewhere in the literature.

Color Camera

The color camera was designed for direct pickup of both studio and outdoor programs. To insure programming flexibility comparable to that practiced in current monochrome television productions, definite requirements were established before the development was begun.

For example, one requirement was that the program director have available for color television an objective lens complement identical to that available for monochrome television. The lenses might vary in

* Decimal Classification: R583.12.

† The work described in this paper reflects developments prior to the middle of 1951.

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focal length from 50 millimeters to 25 inches, depending upon the nature of the program. Not only must the camera be operable with these lenses, but the selection of one of four prearranged lenses must be made easily and rapidly by the camera operator. Another requirement, therefore, was that the camera must be equipped with a lens turret.

Figure 1 is a photograph of the final camera design which shows the view finder in place, the lens turret, tally lights, and focus knob. The length of the camera from front panel to back panel is approximately 39 inches. The height of the camera proper is 15 inches. The width at the rear is 21 inches but tapers to 16 inches at the front. Doors are provided on either side for easy access to components. Essential components consist of a light-splitting optical system, three image orthicon camera tubes, associated scanning circuits, and three video preamplifiers.

Fig. 1—Color television camera.

The lens and turret requirements, mentioned previously, demanded the solution of certain optical problems. The distance between the lens mount and image plane is approximately $1\frac{1}{8}$ inches for standard monochrome camera lenses. This distance is too small for the inclusion of necessary light-splitting devices such as dichroic mirrors. To overcome this difficulty, an image-dividing relay optical system was de-

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veloped. The characteristics of the optical system are fully described in a companion paper.[1]

In the early development of the relay system, close coordination between optical and camera engineers was required. The focal length of the relay lens, for example, determined to a great extent the over-all length and width of the camera. In order to mount the camera tube yoke assemblies parallel with the camera axis, long focal length relay lenses were required to obtain sufficient back-working distance. This arrangement resulted in a long, narrow camera. Mounting the red and blue yoke assemblies at an angle to the camera axis, with front ends pulled in toward the camera centerline, reduced the distance from photocathodes to dichroic mirrors. Hence, the required relay lens focal length was reduced. Consequently, the over-all camera length was reduced, but the width was increased. A compromise was chosen which resulted in a pleasing length-to-width ratio and a relay lens of practical focal length.

To achieve the desired spectral response, it was necessary to add Wratten gelatin color filters in the light paths. These filters were selected on the basis of the response of the dichroic mirrors and the response of the camera tube. They are fastened to the sides of the dichroic block by spring clips.

To achieve operation of all camera tubes over identical portions of the sensitivity curves, neutral density filters were inserted in the red and green channels to balance the amount of light reaching each camera tube. The image orthicons are operated so that high lights fall just below the knee of the sensitivity curve. These neutral density filters are mounted with the color filters on the dichoic block.

After the design of the image-dividing relay optical system had been established, a means of focusing the optical image and for indexing the lens turret was required. Focusing is accomplished in monochrome cameras by positioning the camera tube longitudinally. It was judged impractical to follow a similar practice in the color camera. Instead, the lens turret was designed so that both longitudinal motion for focusing and rotation for lens selection could be obtained.

Figure 2 shows the detachable lens turret with a 50-millimeter Ektar lens in place. Lens mounts in this turret are threaded for standard Kodak Ektar and Ektanon lenses.

The turret support in Figure 2 is attached to the front panel of the camera. The turret slides over it to form a light trap. One of the field-

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[1] L. T. Sachtleben, D. J. Parker, G. L. Allee and E. Kornstein, "Image Orthicon Color Television Camera Optical System," *RCA Review*, Vol. XIII, pp. 27-33, March, 1952.

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lens holders appears in the elliptical slot. After loosening screws on either side of the field-lens holder a half turn, it can be rotated slightly and removed. A matching field lens must be selected to accompany each objective lens.

The rear view of the turret support shows the field lens drum, the driving spider, and the focus tube. The lens turret is mounted on a spindle which passes through a bearing in the turret support. To provide turret rotation for lens selection, the spindle is keyed to an indexing shaft inside the focus tube. The outer focus tube is coupled to the spindle by a circular collar so that longitudinal focusing action can be obtained by sliding the turret spindle along the indexing shaft.

A drum which carries the field lenses fits over the turret spindle bearing. It is driven from the spindle by means of a long stud and spider assembly as shown in Figure 2. Thus rotation is imparted to

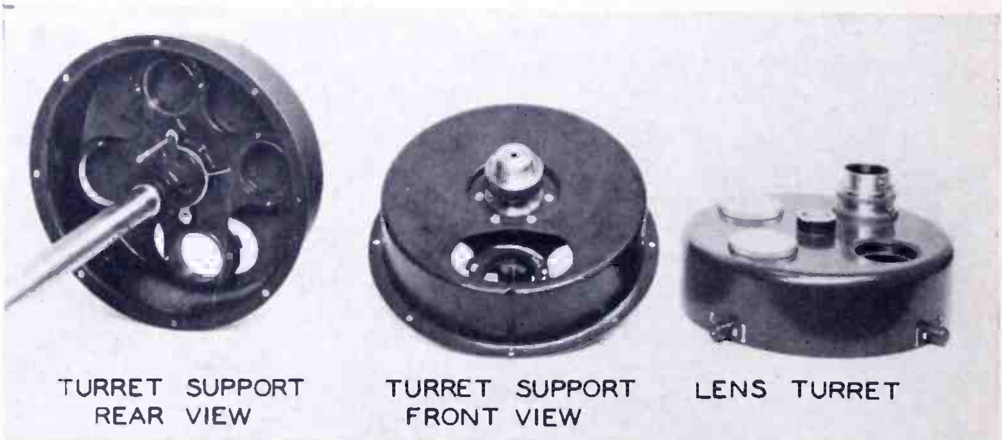

Fig. 2—Color camera lens turret assembly.

it for maintaining a given field lens in juxtaposition with its mating objective lens. After the lens choice is made, the field lens remains in a fixed plane during focussing operation.

Figure 3 is a photograph of the focus mechanism which mounts on the rear panel of the camera. The focus tube is coupled to the gear box by means of a lead screw. The inner indexing shaft extends through a bearing in the panel mount. An indexing handle is attached to the rear end of the indexing shaft. Motion of the focus crank is imparted to the gear box through a gear train, shown at the left of the photograph, two universal couplings, and an interconnecting shaft.

Figure 4 is a photograph of the camera in the initial stage of assembly. This view shows the mounting of the image dividing relay optical system and the image orthicon yoke mounts on the main base of the camera. The red channel yoke assembly can be seen in its

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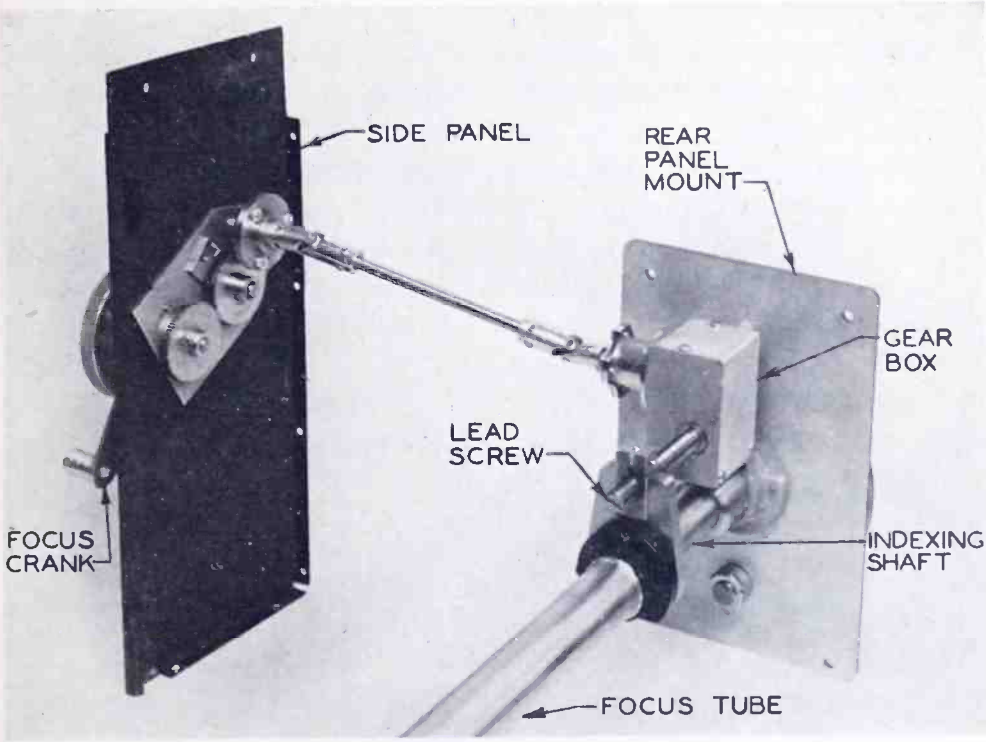

Fig. 3—Color camera focusing mechanism.

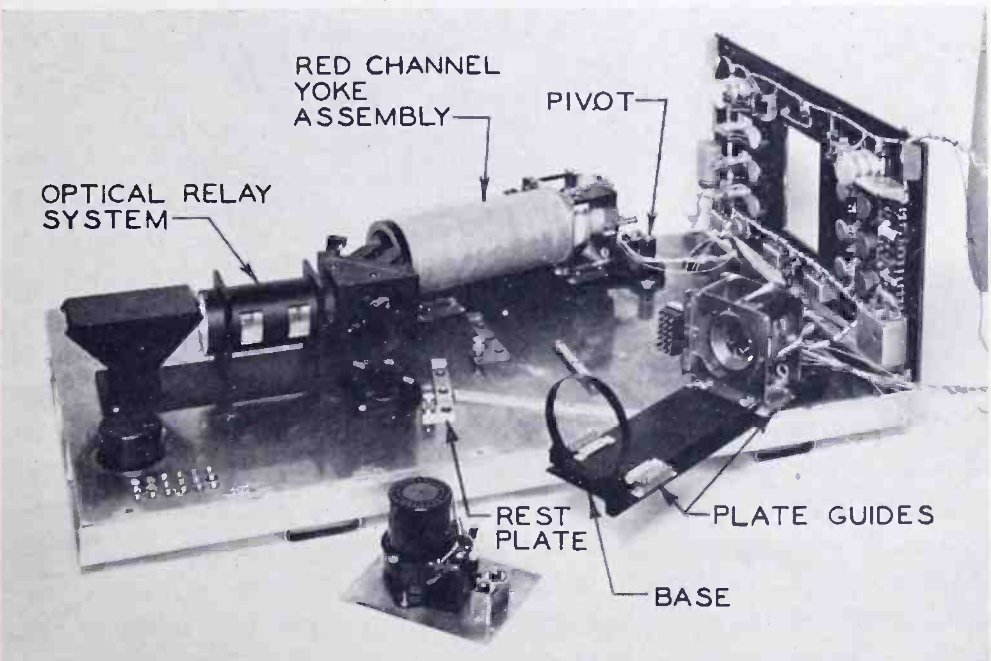

Fig. 4—Color camera in initial stage of assembly

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normal position. The blue channel yoke is swung out in the position for camera tube replacement. The yoke assembly for the green channel is not shown, but it mounts between the red and blue assemblies.

To accomplish easy camera tube replacement, the base plate of each yoke assembly was pivoted at one of the rear corners in such a manner that the yoke assemblies could be swung out the sides of the camera and thus expose the front end of the focus coil. To insure accurate optical alignment when returning the image orthicons to their normal positions, the mounting bases were designed with short vee rails at the front corners which mate with fixed vee blocks on rest plates.

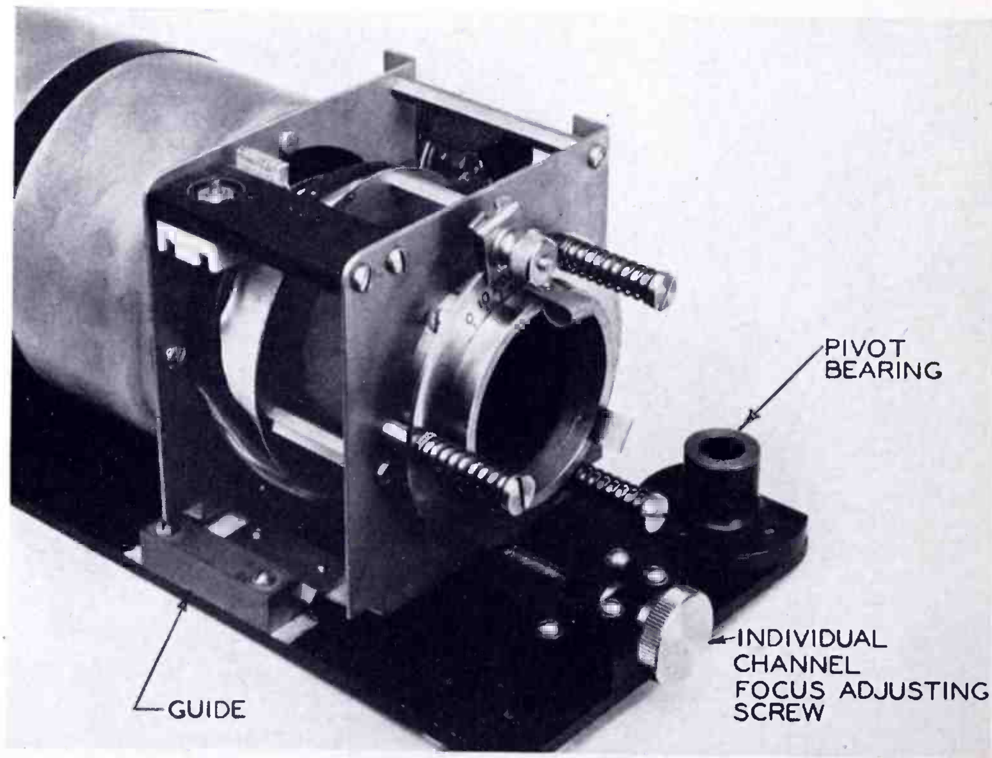

Fig. 5—Yoke assembly.

Knurled thumb screws on opposite sides of the rest plates secure the bases in the normal position.

Vernier focusing of individual camera tubes is accomplished by turning a lead screw at the rear of the yoke mount and thus moving the yoke assembly longitudinally in fixed guides. Figure 5 shows the lead screw with its knurled knob and one of the guides.

After the three optical images have been formed on the photocathodes of the camera tubes and converted to electron images on the targets, the targets are scanned with electron beams to produce three video signals corresponding to the red, blue, and green images. The

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three scanning beams must land on the same point in all three images at the same time. If the scanning beams are not synchronous, misregistry of the red, blue, and green images will be apparent in the reproduced picture.

The most practical method of achieving registry is to drive the three deflection yokes from a common voltage source. Figure 6 illustrates schematically the circuit for horizontal scanning. The horizontal windings of the red, blue, and green yokes are connected across the secondary of the horizontal output transformer. These yokes are made as nearly alike as careful production techniques permit.

In the process of registering the three scanning beams, one must be able to change the scanning amplitude of one beam with respect to the others. In the circuit shown in Figure 6, scanning amplitude is changed by means of the variable inductance marked "width." Increas-

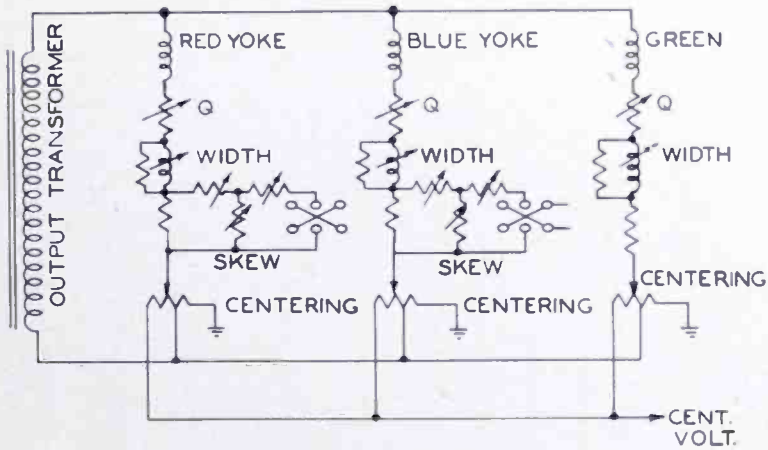

Fig. 6—Horizontal scanning circuit.

ing the inductance in a single yoke circuit decreases the peak-to-peak current in that circuit. The width coils are critically damped by shunt resistors to prevent ringing following the retrace period.

When the total inductance in the yoke circuit is altered for width adjustments, the circuit Q is altered also. In order to maintain scanning linearity, the Q values of the three yoke circuits must be identical. potentiometers labeled "Q" in series with each yoke are adjusted in conjunction with the width controls to maintain linearity.

Another control which has been found essential in registering the scanning beams is the control labeled "Skew." It is possible in adjusting electrical focus in the camera tube, to reach an optimum condition for focus which results in a scanning pattern with a rhombic shape. In a single picture, the rhombic effect would not be evident. When three pictures are superimposed, however, misregistration may appear. Correction is supplied by inserting a vertical frequency voltage of

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saw-tooth wave shape in series with the horizontal winding. A double-pole, double-throw switch reverses polarity of the applied voltage, and the T-pad controls the amplitude. Since the red and blue channels are matched to the green channel, only two skew controls are necessary.

The remaining controls required to produce registry of the horizontal scanning beams are the centering controls shown in Figure 6. These controls vary the amount and direction of direct current in the horizontal yoke windings.

The vertical scanning circuit is similar to the horizontal circuit. Since the vertical yoke winding can be considered resistive for all

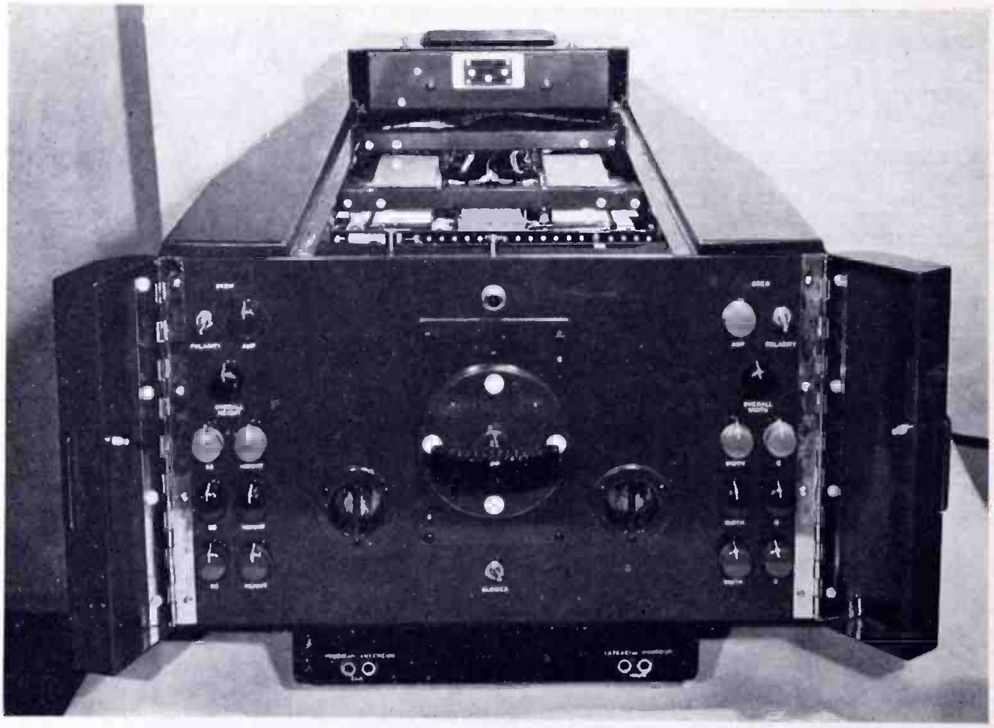

Fig. 7—Rear view of color camera.

practical purposes, scanning amplitude can be adjusted by a simple series resistance. Also, it is not necessary to provide skew controls since this function is accomplished entirely in the horizontal circuit.

Figure 7 shows the layout of the registration controls on the rear panel of the camera. These controls are adjusted during the initial camera alignment before show time. After they have been adjusted, the hinged covers are closed to prevent accidental misadjustment.

Figure 8 is a photograph of the left side of the camera with the side door opened. This photograph shows the mounting of the vertical deflection chassis. It is hinged at the front so that it can be swung out of the camera to expose the optical system. The horizontal circuit is mounted in a similar manner on the opposite side of the camera.

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The video signals generated by the three camera tubes must be amplified before they can be transmitted through the camera cables to the channel amplifiers. Three video preamplifiers constructed in small plug-in chassis are used for this function. Six stages of amplification are used. The first four stages are simple shunt-peaked amplifiers with additional high frequency compensation of two of the stages. The last two stages are used as a feedback pair to feed the view finder and the camera cable.

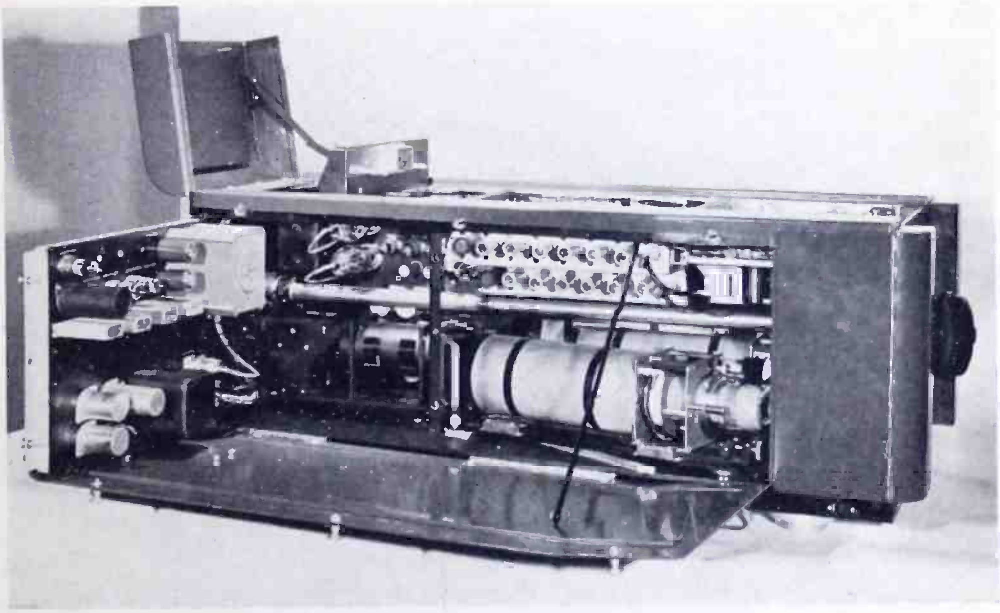

Fig. 8—Side view of color camera.

Camera Channel Amplifiers

After leaving the camera preamplifiers, the red, blue, and green video signals pass through the camera cables to the camera channel amplifiers. The channel amplifiers amplify the video signals, insert blanking and shading, perform clipping operations, and shape the over-all transfer characteristic. Figure 9 is a photograph of the channel amplifier chassis. It is approximately 48½ inches high and is designed for mounting in a standard 19-inch cabinet rack. Terminal facilities for the camera cables are shown in the enclosure at the bottom.

The three video signals enter the channel amplifiers at the top of the chassis. After passing through two stages of amplification, they are clamped and applied to the grids of the blanking mixer tubes. Before blanking is applied to the mixer, it is combined with saw-tooth and parabolic shading signals at both vertical and horizontal fre-

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quencies. These shading signals can be varied both in amplitude and polarity to correct for small shading differences in the three camera tubes. The composite blanking and shading signals are applied to the cathode of the blanking mixer tubes. Linear clippers in the plate circuits of the blanking mixers clip off the bottom of the blanking pulses.

Following the blanking mixer in each channel is a nonlinear stage in which the transfer characteristic of the video signal is altered. The transfer characteristic is changed because the camera tube and the reproducing kinescope are nonlinear. When operated below the

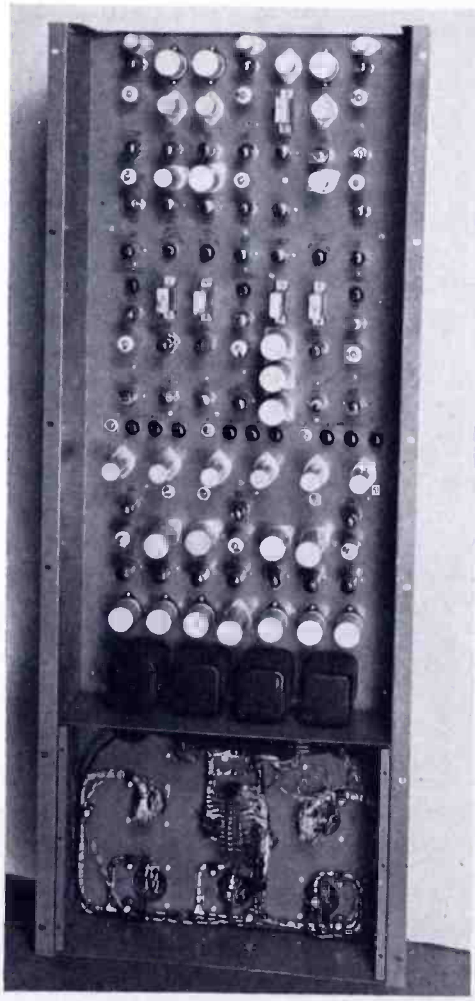

Fig. 9—Channel amplifier.

knee of its sensitivity curve, the type 5826 image orthicon has an average gamma of slightly less than unity. Present color kinescopes have an exponent of approximately 2.75.

Essential elements of the gamma stage are a constant voltage source and a nonlinear impedance in series with a current sampling

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resistor. The nonlinear impedance consists of four crystal diodes with separate bias controls. Setting of the bias voltage sets the level at which the diodes conduct, and thus establishes the shape of the transfer curve.

After being rooted in the gamma stages, the video signals are amplified and applied to the grids of the output tubes. Provision is made to feed both a program line and a monitor line from each channel of the channel amplifier.

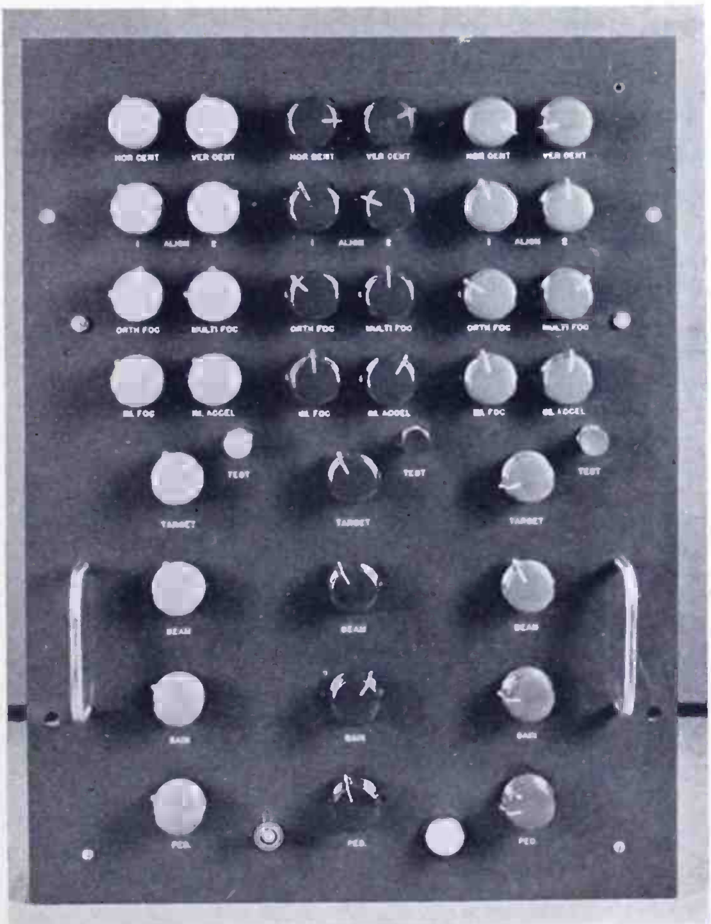

Fig. 10—Remote control panel.

Camera Remote Controls

Operating control functions for the camera and the channel amplifiers are performed at a remote control panel. The remote control panel is 13 inches wide and 18 inches high. It is designed for insertion in a standard console housing at the video operator's position. Controls are arranged in three vertical rows as illustrated in Figure 10.

Most of the controls are used to adjust operating voltages in the

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camera tubes. Those controls which apply to the camera are horizontal centering, vertical centering, beam alignment, orthicon focus, multiplier focus, image focus, image accelerator, target voltage, beam current, and multiplier gain. The push-button switches near the target control marked "Test" are used to set the target voltage. To make target voltage adjustment, one of the buttons is depressed, and the target voltage is adjusted for cutoff. When the button is released, the target voltage is placed two volts above cutoff automatically.

The pedestal controls at the bottom of each row are used to set the clipping level in the channel amplifiers. Two controls which do not

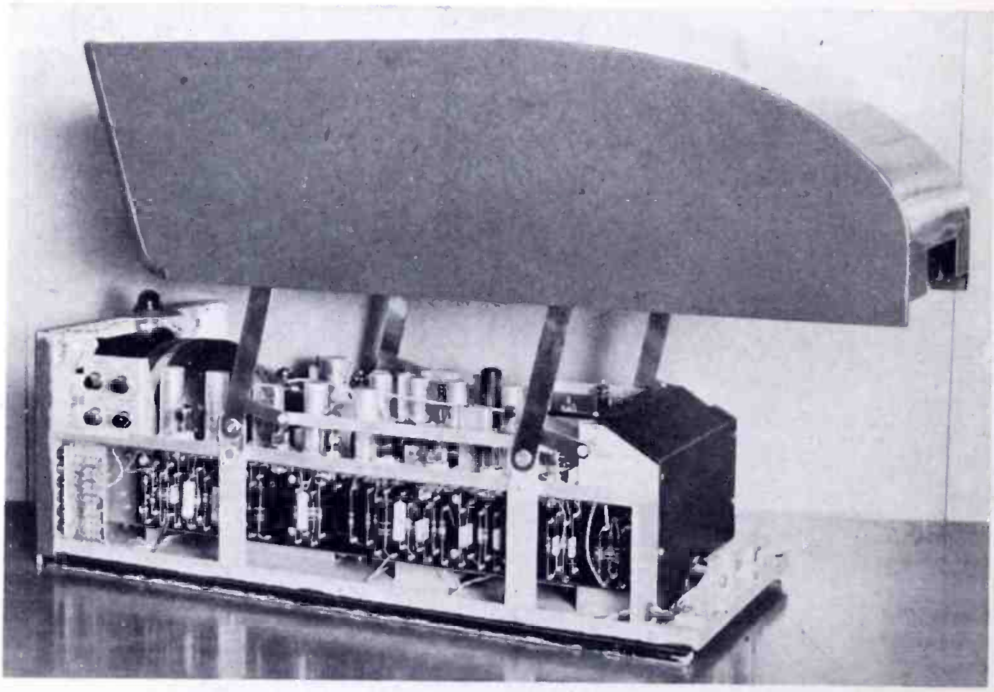

Fig. 11—Color camera view finder.

appear in the picture are over-all gain and over-all pedestal. These controls are used to change the gain and pedestal of all three video signals simultaneously.

Monitoring

In order to perform the various registration, focusing, and level setting functions thus far described, the camera and video operators must have a means for monitoring the video signals. The monitors required consist of an electronic view finder for the camera operator, a monochrome monitor, and a color monitor for the video operator.

Figure 11 is a photograph of the view finder with the cover raised

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to expose the components and circuit wiring. The view finder over-all is 30 inches long, 13 inches wide, and 10 inches high. The picture tube diameter is 7 inches. The view finder fulfills a twofold purpose. First, it provides a picture which enables the cameraman to follow the action and to check optical focus of the camera. Secondly, it provides a means for checking registration adjustments. Figure 12 is a view of the picture end of the view finder. By means of the six push buttons on the right-hand side, the cameraman can select any single channel for presentation on the kinescope, or he can select combinations of red

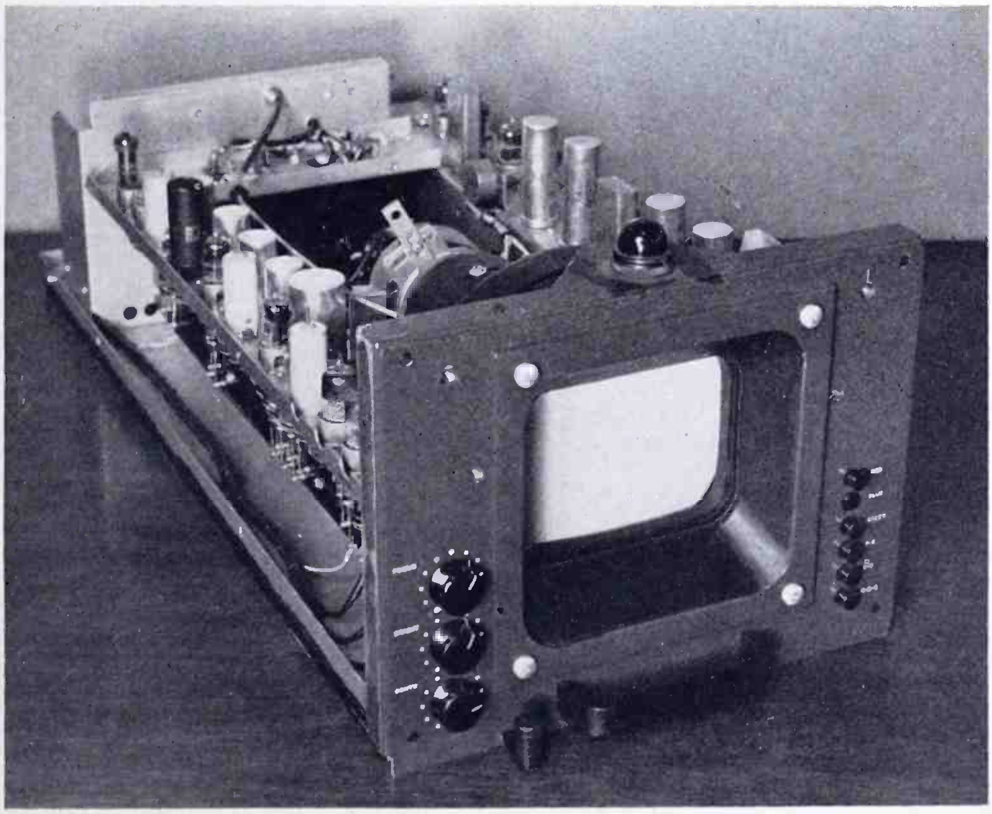

Fig. 12—Rear view of color camera view finder.

and green, blue and green, or red, blue, and green. During the registration procedure, the cameraman adjusts the green channel for normal scanning by means of the over-all scanning amplitude controls. Then he registers the red channel to the green channel. Next, he registers the blue channel to the green channel. By means of the push buttons he can select either the red channel or the blue channel pictures for superposition on the green channel picture. By observing the superimposed pictures, he can note the effect of moving the registration controls.

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One of the monitors required at the video operator's position is a standard monochrome monitor with slight modification of the cathode-ray-oscilloscope sweep circuits. Figure 13 shows a video operator's console arranged for two camera chains. A monochrome monitor is shown adjacent to each remote control panel. By means of this monitor, the video operator can observe picture quality and signal level for each color channel. In addition, he can check registration of the three color pictures.

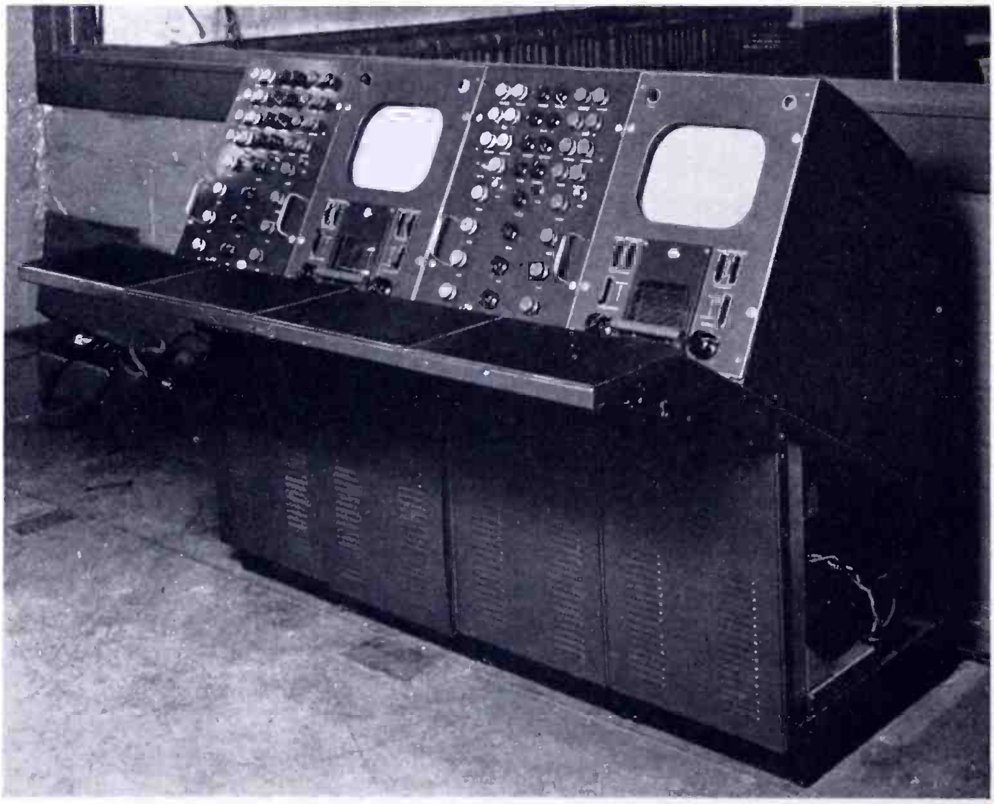

Fig. 13—Video operator's console.

An auxiliary keyer unit is housed in the bottom compartment of the console housing. The auxiliary keyer serves two functions. First, it mixes the three video signals in the same combinations that are available in the view finder. Thus the operator can observe the picture from any single channel or he can superimpose combinations of pictures for observing registry. Secondly, it keys the three video signals into the oscilloscope vertical sweep circuit so that three wave forms corresponding to red, blue, and green video signals are displayed on a single horizontal trace. The operator uses the oscilloscope information for setting levels and adjusting shading. The display sequence from left to right is maintained automatically in the order of red,

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blue, and green. Wave forms can be displayed at line frequency or field frequency.

In addition to the monochrome monitor, the video operator has available a color monitor which is used to observe the color fidelity of the camera chain. This monitor, which employs the 16-inch tri-color kinescope, is designed to use the camera signals directly without encoding or decoding operations.

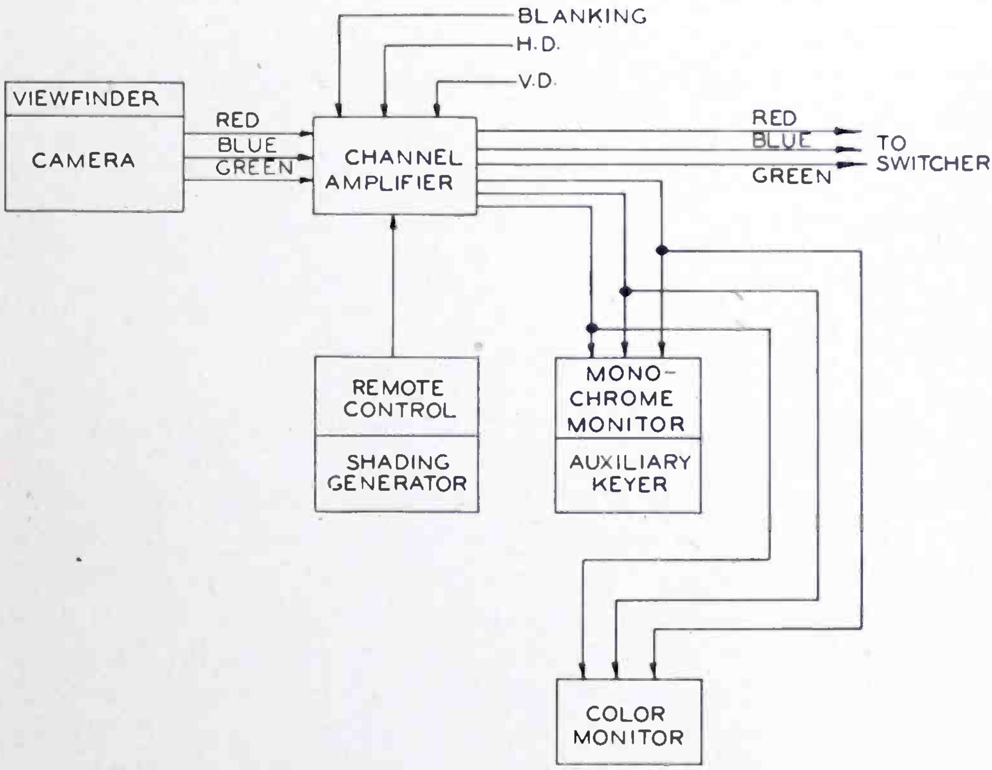

Fig. 14—Block diagram of color camera chain.

Conclusion

In conclusion, the block diagram in Figure 14 is presented to summarize the functions of the color camera chain. This diagram shows the origination of the primary color signals in the camera, and monitoring at the view finder. Signal shaping and level setting occurs in the channel amplifier. Output signals are monitored with the monochrome and color monitors. The video signals from the channel amplifiers are fed to the switching system and thence to the multiplexer.

Acknowledgment

R. C. Webb and the television research group of RCA Laboratories

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Division, Princeton, N. J. were instrumental in the development of the first RCA color television camera. A number of engineers contributed to the design of the commercial color camera chain. Misses G. L. Allee and M. E. Widdop, and Messers. G. L. Dimmick, L. T. Sachtleben, D. J. Parker, and E. Kornstein of the Advanced Development Group supplied solutions to the optical problems. Among those contributing to the over-all design of the camera chain were N. S. Bean, H. M. Potter, H. C. Shepard, D. L. Pierce, F. W. Millspaugh, I. Bosinoff, R. E. Bailey, J. W. Wentworth, F. Himelfarb, A. C. Luther, H. N. Kozanowski, and T. J. Shipferling of the Broadcast Studio Equipment Section and D. O. Hunter of RCA Laboratories Division.

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IMAGE ORTHICON COLOR TELEVISION CAMERA OPTICAL SYSTEM*†

By

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***Summary**—A relay lens system and dichroic-cross image divider is employed to provide three separated images for the respective image orthicon camera tubes. The green light is focussed directly on the light-sensitive surface of one image orthicon, the red and blue beams are reflected to their respective image orthicons by front-surface mirrors. Correction for the astigmatism introduced by the dichroic cross is made by means of two plates at right angles to each other mounted between the field lens and the relay lens system. The aperture of the optical system may be remotely controlled by a motor-driven iris located between the two halves of the relay lens system.*

Introduction

THE present color television camera employs three image orthicons which must be provided with images which are identical, except that each must be produced in a different primary color. The distance from the end of the lens mounts to the image plane in a standard television camera is about 1⅛ inches, and there is no simple way, in such a small space, to split this image three ways for distribution to the three image orthicons. It is, of course, very highly desirable to avoid the necessity of using a separate camera lens for each tube. This is because of the large number of separate adjustments that would be required, and also because separate lenses would not permit convenient turret mounting for quick changes of focal length. Others reasons such as cost are also factors in favor of using a single camera lens, but the turret mounting consideration is probably the most important.

It became apparent that the only practical way to gain adequate space for the beam splitter, or image divider, was to relay the image to a secondary plane at unit magnification. By this means, the working distance between the optical system and the image plane was effectively increased several inches, as compared to the 1⅛ inches between lens mount and primary image plane.

Figure 1 shows an assembled experimental relay system and color divider in approximately correct relation to the camera lens. Figure 2 shows the relay system and color divider disassembled.

* Decimal Classification: R583.12.

† The work described in this paper reflects developments prior to the middle of 1950.

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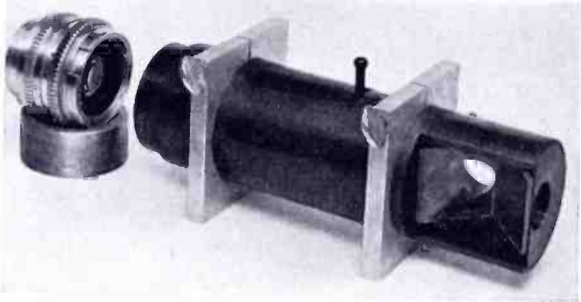

Fig. 1—Assembled experimental relay system and color divider in approximately correct relation to the camera lens.

The Present Image Orthicon Color Television Camera Optical System

Figure 3 shows a schematic of the optical system developed for the image orthicon color television camera. Light enters the usual television camera lens, A, which forms an image, in plane B, of the scene being televised. This image is re-imaged in plane D, by field lens C, without change of size. The relay lens system contains two lenses, G and H, of identical design and equal focal length, with their long conjugate sides turned toward each other. The plane D effectively contains the principal focal point of lens G, and the image of plane D appears at the corresponding principal focal point of lens H, located effectively at plane O. The magnification of this image is unity. Pairs of flat glass plates, or sandwiches, I, J, and K, constitute an image divider or dichroic cross. This structure permits the green image to be formed in plane O, but reflects the red image toward mirror M, and thence to plane N, while the blue image is reflected toward mirror L, and thence to plane P. The photosensitive surfaces of the three image orthicon tubes are located effectively in planes N, O, and P. The sandwiches, I, J, and K, introduce astigmatism into the images at N,

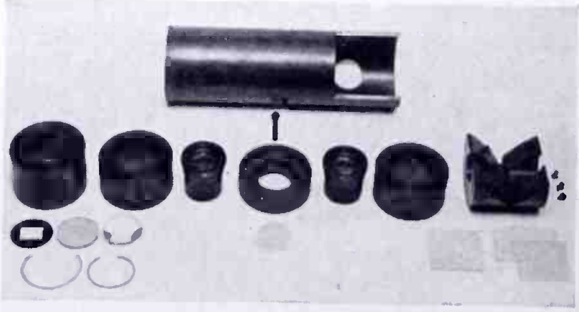

Fig. 2—Disassembled relay system and color divider.

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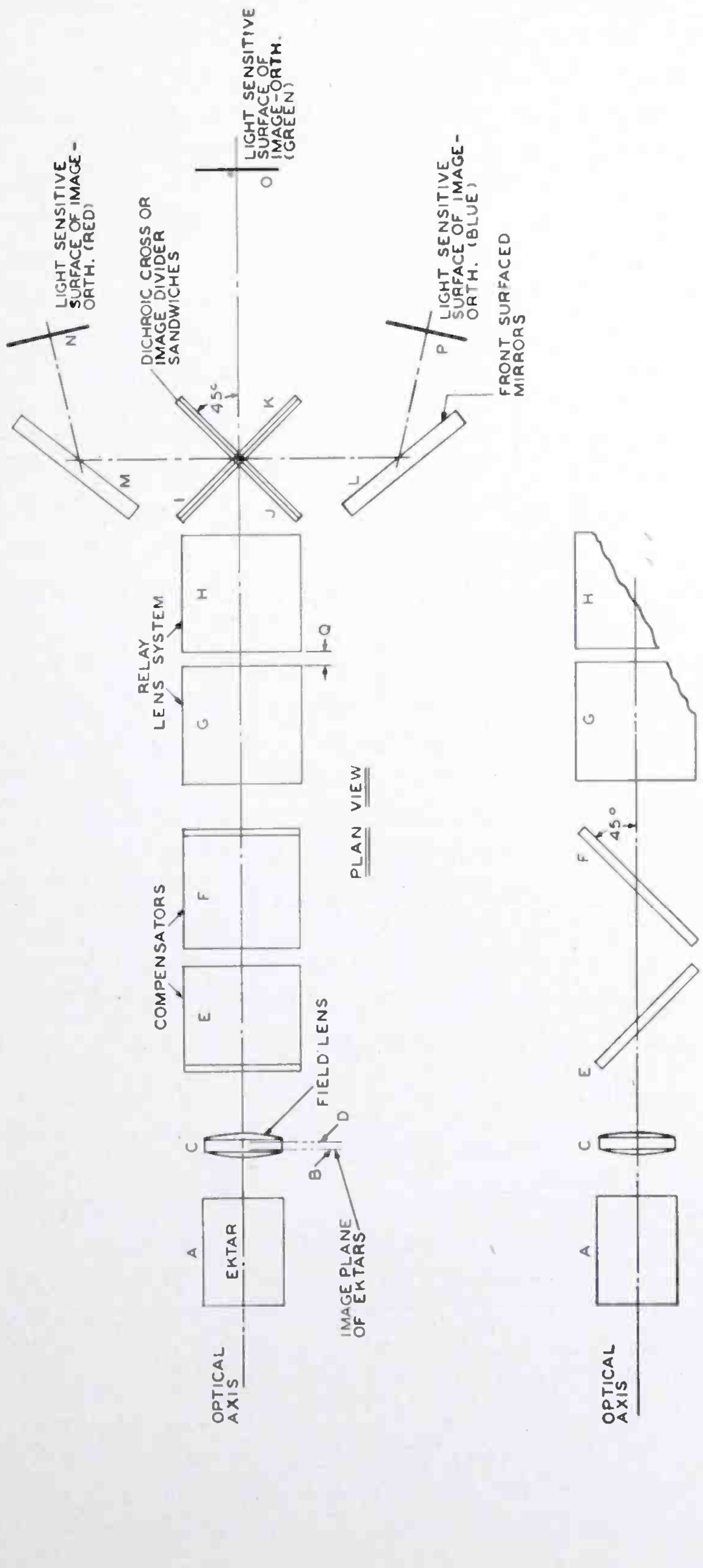

Fig. 3—Schematic of the optical system developed for the image orthicon television color camera.

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O, and P. The glass compensator plates E and F, introduce compensating astigmatism to offset that produced by the sandwiches.

When development work began on a production model of the image orthicon color camera, the importance of using the relay system had already been established, as noted above. One problem was to locate the best lens design for the relay system; another was how best to use the relay system in such a way as to minimize the over-all length as much as possible consistent with mounting the image orthicon tubes approximately parallel to each other. Other important problems were the design of the image divider and its mountings and adjustments, design of means for compensating the astigmatism arising in the image divider, and design of a suitable set of field lenses to be used with the usual series of camera lenses.

Relay Lens System

The most suitable lens design was found to be the Simpson Anastigmat 7½ inches equivalent focus, f/4.0. This lens has very good contrast and definition over the limited field of the image orthicon photocathode. The ratio of its working distance to focal length was large, about 0.86. This helped to minimize the focal length required, while keeping the distance from lens to image large enough to accommodate the image divider and the mirrors that are required to bring the image orthicons into approximate parallelism.

The lens was of triplet construction, especially designed for 2 × 2 inch slide projection, and consequently performed much better for the purpose than photographic lenses, such as the Tessar type, which normally cover a field diameter about equal to the focal length. The design was ordered to be made up in a focal length of 9½ inches.

Image Divider

Studies of various layouts indicated that the over-all length of the camera could be made less if the image divider were in the form of a cross instead of a "V". This involved a more elaborate mounting and adjustment means for the dichroic mirrors of the divider, but, because the length of the camera was already being increased considerably by the introduction of the relay system, any saving in length was considered worthwhile. The cross form of the divider had the disadvantage of an effective septum at its center which casts a shadow in the center of the image at small apertures, but this is located sufficiently close to the relay lens to cause no serious shadow at apertures as small as f/11.

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The mounting for the image-divider cross was developed in the form of a cube with one continuous arm of the cross (J of Figure 3) along one diagonal, and one discontinuous arm (I and K of Figure 3) along the other. The cube was divided into an upper and lower half, and each half was further divided along a diagonal. Each half of the cube was thus made to clamp one of the arms of the cross, and the complete assembly holds the two arms mutually perpendicular. The cube is open on four sides to admit light to the divider, and to permit its delivery to the three image orthicons. Screw-operated means were provided for adjusting the halves, I and K, of the discontinuous arm to perpendicularity with the continuous arm, J, and to parallelism and coplanarity with each other.

Each arm of the image-divider cross consists of a sandwich of two closely spaced glass plates. Each sandwich of the cross is suspended at three points. Either the surfaces of the glass plates from which it is assembled must be plane parallel to a high degree of accuracy, or else the plates must be selected to find combinations that minimize the effects of nonparallelism. One of these plates (closest to the relay lenses) carries a dichroic reflecting film structure on the surface closest to the second, or balancer, plate. The second plate is similar to the first, but is without the dichroic reflector. The function of the balancer plates is to make the cross a symmetrical optical structure which will introduce substantially the same amount of astigmatism into each of the three colored images which are reflected or transmitted by it. With the astigmatism of the three images equalized, any astigmatic correction which is applied before the light reaches the divider will apply equally to all the images. This simplifies the problem of correcting the astigmatism and avoids constructional complications.

Correction for Astigmatism

Correction for the astigmatism that results from the oblique position of the glass plates in the image divider was at first accomplished with a ⅛-diopter cylindrical lens, which was mounted between the relay lens system and the field lens. This was unsatisfactory because of imperfections in the lens and the difficulty of getting accurately made cylindrical lenses of such low power. The cylindrical lens was successfully replaced by a pair of oblique plates in the form of a "V" which intersect in a line at right angles to the optical axis and to the line in which the arms of the cross intersect. The "V" arrangement is necessary to preserve symmetry of the correcting effect above and below the optical axis, and to avoid displacement of the axis. A single

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oblique plate of double thickness would not be satisfactory in these respects. When each arm of the cross has the same thickness and obliquity as each side of the "V", astigmatism is eliminated for all points imaged by the relay system at unit magnification.

The effect of normal variations in plate thicknesses and focal lengths in the relay lenses is to reintroduce a small amount of astigmatism. This can be controlled and eliminated by moving the relay lenses to change magnification, or more easily, by varying the obliquity of the plates in the "V" to the optical axis. The astigmatism introduced by the cross is appreciable, for it amounts to 0.135 inch, and would produce serious image deterioration if uncorrected.

Field Lens

The field lens C (Figure 3) is located at the primary image formed by the Ektar or other camera lenses. Its function is to redirect all the light reaching the image from the camera lens, so that this light will enter the relay lens system and insure uniform illumination of the relayed image. The field lens does not change the size of the primary image. In general, the field lens must have a different amount of power for each camera lens, but studies have shown that the same field lens can, in some cases, be satisfactorily used with two or more camera lenses. In actual cameras, a series of nine different camera lenses, which range in focal length from 50 millimeters (1.97 inches) to 630.5 millimeters (25 inches), require only six different field lenses. All the field lenses are designed to be identical in thickness and location so as to avoid changes in the position of the primary image when lenses are changed.

Remote Control of the Aperture of the Optical System

The use of the color camera under outdoor lighting conditions and under variable studio lighting conditions necessitates a remote control of the aperture (level of image illumination) of the optical system. Previously, the speed of the system was regulated by adjusting, either remotely or directly, the iris diaphragms in each of the objective lenses on the turret. The nature of the relay lens system has made possible the use of one central aperture control to regulate the aperture of the optical system no matter which objective lens is used. An iris diaphragm is incorporated as part of the relay lens tube, with the iris diaphragm located in space Q (Figure 3) between the two relay lenses and so protected that the relay lenses cannot be slid into the iris mechanism. The iris itself is so thin that it does not materially reduce

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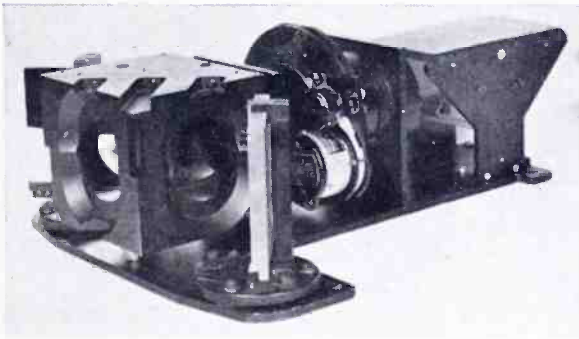

Fig. 4—Side view of completely assembled image dividing relay optical system.

the range of adjustment of the relay lenses. The iris diaphragm is driven by a 6-volt, direct-current motor which may be controlled from the video control room or any desired remote point, and is equipped with microswitches which limit the maximum and minimum diameters of the diaphragm. A potentiometer geared to the iris is used to operate a calibrated meter in the control room, or at any desired control point, where it indicates the aperture of the optical system.

Figures 4 and 5 show two views of the completely assembled system, with motor-driven central aperture control.

Acknowledgment

The authors wish to acknowledge the valuable contributions to the successful development of this optical system by J. P. Smith, G. L. Dimmick, J. E. Albright, J. D. Spradlin, A. C. Schroeder, F. C. Blancha, J. H. Roe, R. F. Leinhos, M. E. Widdop, and E. D. Goodale.

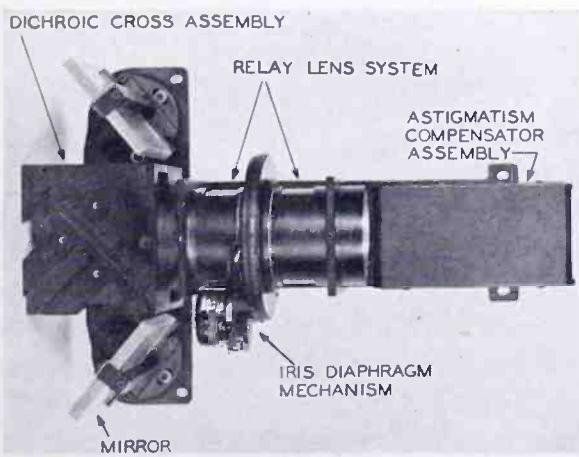

Fig. 5—Top view of completely assembled image dividing relay optical system.

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A BAND-PASS MECHANICAL FILTER FOR 100 KILOCYCLES*

By

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Summary—The detailed design and construction of a mechanical filter which should prove useful in many broadcast applications is presented. This filter has a pass band of 6 kilocycles centered at 100 kilocycles. The results obtained are compared with a similar crystal filter.

INTRODUCTION

THE use of mechanical filters for radio frequencies has been described by the author and his colleague in a previous article.[1] The detailed theory was developed and some illustrative examples of experimental filters were described.

Considerable development work in this field has been carried on since that time. Recently a program was started on the design of filters suitable for single-side-band radio telephony which would have a pass band in the vicinity of 100 kilocycles. This article describes a mechanical filter design which should prove useful in many broadcast applications.

THEORY OF MECHANICAL FILTERS

As is well known, a chain of cascaded, coupled, resonant circuits will produce a band-pass filtering action. A standard double-tuned intermediate-frequency transformer is an example. Where the number of resonant circuits is larger than two, considerable advantage results if the interior electrical circuits are replaced by acoustic or mechanical resonant circuits thus securing their advantages of small size, stability and inherent high Q.

In a typical case, the electrical resonant input circuit of the filter is coupled by magnetostriction to the first mechanical resonant circuit of the filter which is then in turn coupled mechanically to the next mechanical resonant circuit and so on to the last mechanical resonant circuit which is again coupled to the output electrical circuit by magnetostriction. The mechanical resonant circuits can be half-wave lengths of a suitable metal while the coupling between the mechanical

* Decimal Classification: R386.1.

[1] W. van B. Roberts and L. L. Burns, Jr., "Mechanical Filters for Radio Frequencies," *RCA Review*, Vol. X, pp. 348-365, September, 1949.

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resonant circuits can be quarter-wave lengths of the same metal but of a different diameter. This article describes the detailed construction and operation of a filter of this type. Figure 1 shows a comparison between the results obtained from this filter and a commercial single-side-band crystal filter.

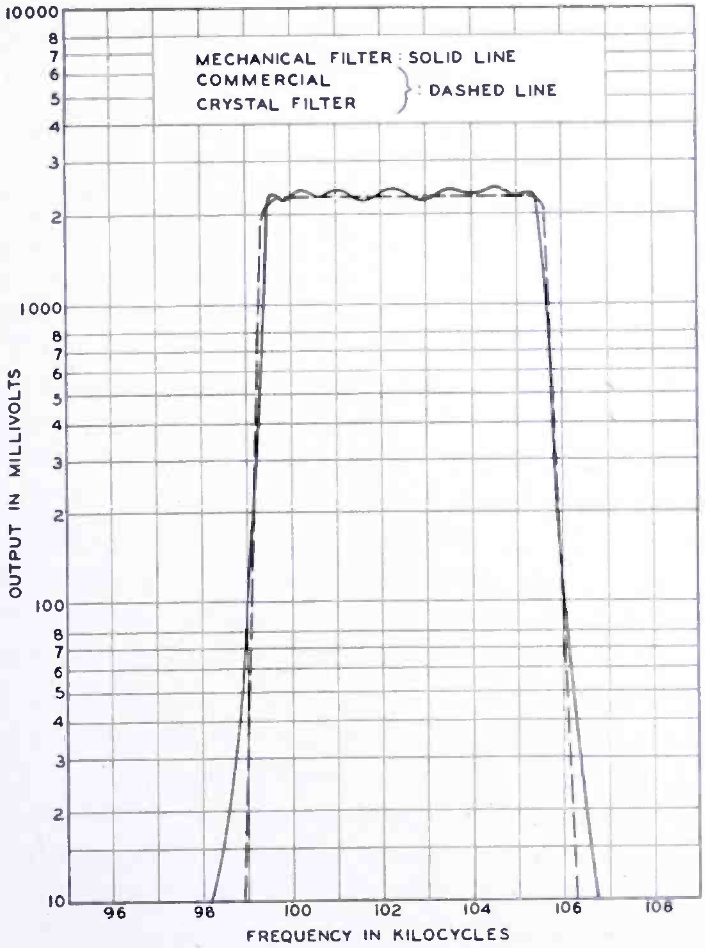

Fig. 1—Response curve of the single-side-band mechanical filter compared with an equivalent quartz-crystal filter.

CONSTRUCTION

Temperature stability was considered of prime importance and this immediately dictated the use of Ni-Span C or some similar constant modulus alloy for the filter construction. Ni-Span C has the added advantage of being magnetostrictive by virtue of its nickel content and thus does not require nickel plating for electrical excitation.

There are many forms which the actual mechanical filter can take but all of these may be divided into two classes: (1) mechanical resonators coupled by a heavy mass, known as slug type of construction, and (2) mechanical resonators coupled by a thin spring, known

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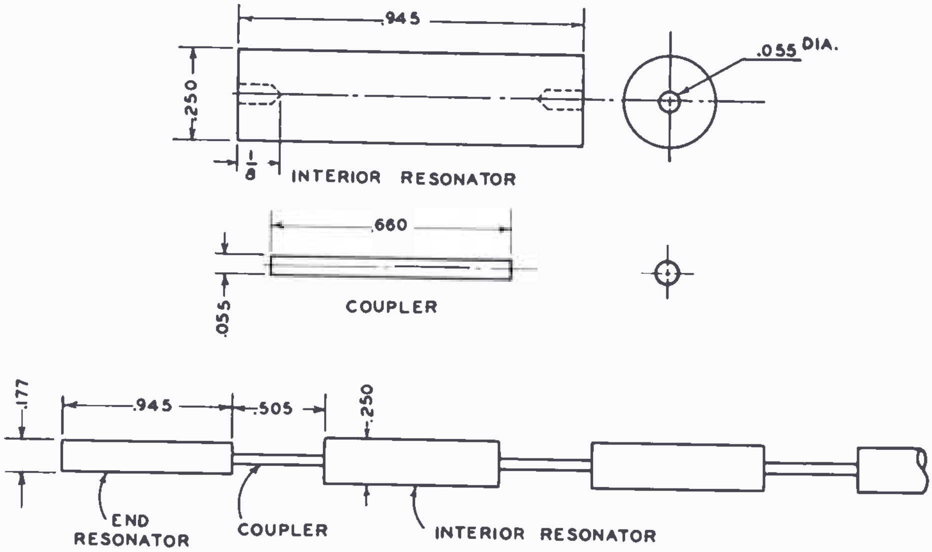

Fig. 2—Details of construction of the mechanical filter.

as neck type of construction.[1] The neck type of construction was chosen for this filter because the mechanical termination is much simplified. In the neck-type filter, an infinite line exactly like the neck provides a resistance termination that matches the iterative impedance of the filter at mid-band, as is evident from Equation (2) of Reference (1). If a slug-type filter is used, a single line acting as termination would have to be inconveniently small or else a more complicated termination would be needed. The filter consists of a series of 8 half-wave resonators coupled by thin necks as shown in Figure 2.

The actual dimensions of the resonators and coupling necks were determined by the design procedure indicated in the Appendix and are given by Figure 2. For convenience, steel couplers were used as the proper size Ni-Span C was not immediately available. The end resonators have half the impedance of the interior resonators in accordance with Campbell filter theory and are thus smaller in diameter as shown.

Before assembly, the resonant frequency of each resonator was checked in the bridge circuit of Figure 3. To use this bridge, the resonator under test is placed in one of the coils and an appropriate magnetic bias established with a permanent magnet. The two potentiometers are then adjusted for a minimum reading on the vacuum tube voltmeter M. Then as the signal generator is slowly tuned through the resonant frequency of the resonator, a sudden increase in

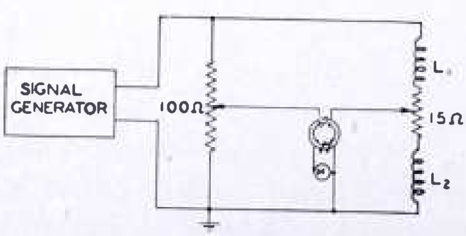

Fig. 3—Bridge circuit for checking the individual resonator responses.

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the meter reading will occur. By a process of selection, only resonators that were within 200 cycles per second of each other were used in the filter. Of course resonators that were too low in frequency could be raised by a slight trimming on the lathe but this was not found necessary.

During the actual assembly of the filter, close-fitting rings of 0.015-inch solder (Ag. 72 per cent, Cu. 28 per cent) were placed at each junction between a coupler and a resonator. The fit between the couplers and the resonators was almost a press fit and thus the entire filter was assembled before soldering. An oxygen-hydrogen flame was used to heat each resonator in turn to a cherry red until the solder flowed making a neat fillet at each junction. The oxide formed by the heat of soldering was removed by the gentle application of a buffing wheel. The over-all length of the unterminated filter measured 10⅜ inches.

The terminating resistors are in the form of lossy lines of the proper impedance. Each line consists of five feet of 0.050-inch copper wire which is coiled on a ⅞-inch form and then removed and dipped in self-vulcanizing liquid latex. Each line was given two coats of the rubber and then allowed to dry for 24 hours. The rubber provides the losses for the line as the copper itself is very low loss. Before attaching these lossy lines, a filter response curve was recorded to make sure the soldering process did not upset the tunings of the resonators. The symmetrical response shown by Figure 4 indicates proper tuning of all the elements. The lines were then soft soldered into the end resonators of the filter as is evident in Figures 5 and 7.

The chassis and mounting for the filter and its associated electrical components are shown in Figures 6 and 7. The chassis is approximately the size of a crystal filter that will do the same job. Particular care is necessary to isolate the input circuits from the output circuits as even a small amount of stray coupling will distort the response curve shape at high attenuations. Two entirely separate compartments are provided in the chassis by a dividing shield which has one small hole for the filter to pass through and another for the shielded power leads. A wiring diagram for the chassis is shown in Figure 8.

RESULTS AND DISCUSSION

Figures 9 and 10 show the response curves obtained. Figure 1 is a comparison between a three-section crystal filter and the mechanical filter. An interesting comparison between this mechanical filter and a standard high quality communications receiver is given by Figure 11.

The requirements for single-band use are generally given as 80

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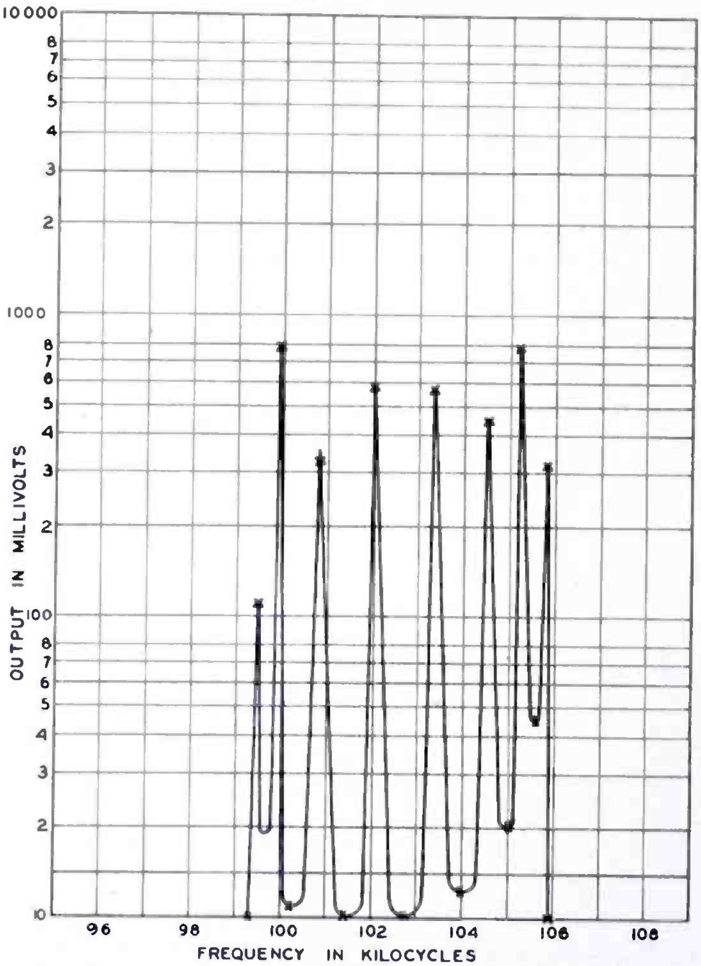

Fig. 4—Response curve of the unterminated mechanical filter.

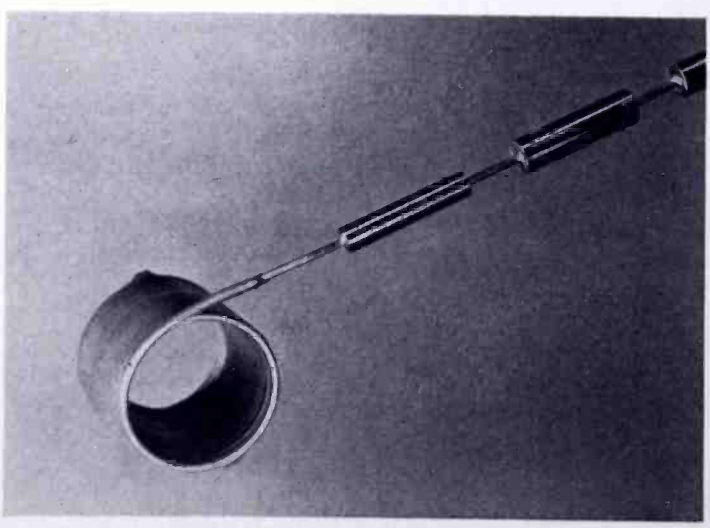

Fig. 5—Lossy line termination attached to one end of the filter.

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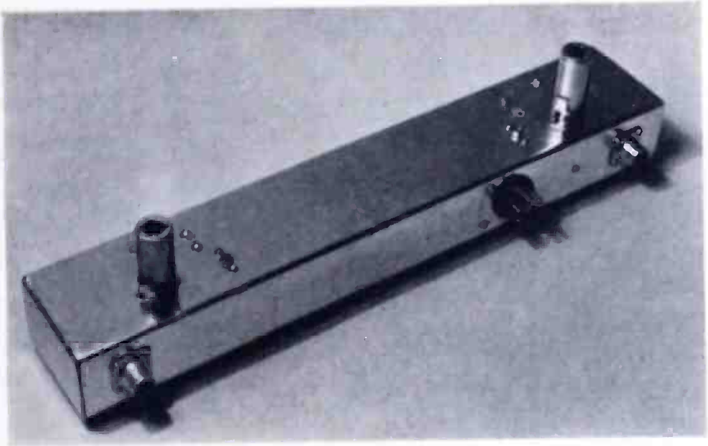

Fig. 6—Top view of mechanical filter chassis.

decibels attenuation, 1 kilocycle from the filter cutoff frequency. As the response curve indicates, this mechanical filter is only about half that good. There are seven sections in this mechanical filter and to double the attenuation would require double the number of sections. With fourteen sections, the mechanical filter would still compare favorably with the crystal filter, which has six double crystals in its three sections.

The ripple in the pass band of the mechanical filter is entirely satisfactory for the use intended. The curve of either Figure 9 or Figure 10 would be satisfactory. Single-sideband crystal filters generally have between 1 and 3 decibels ripple in their pass band although some are

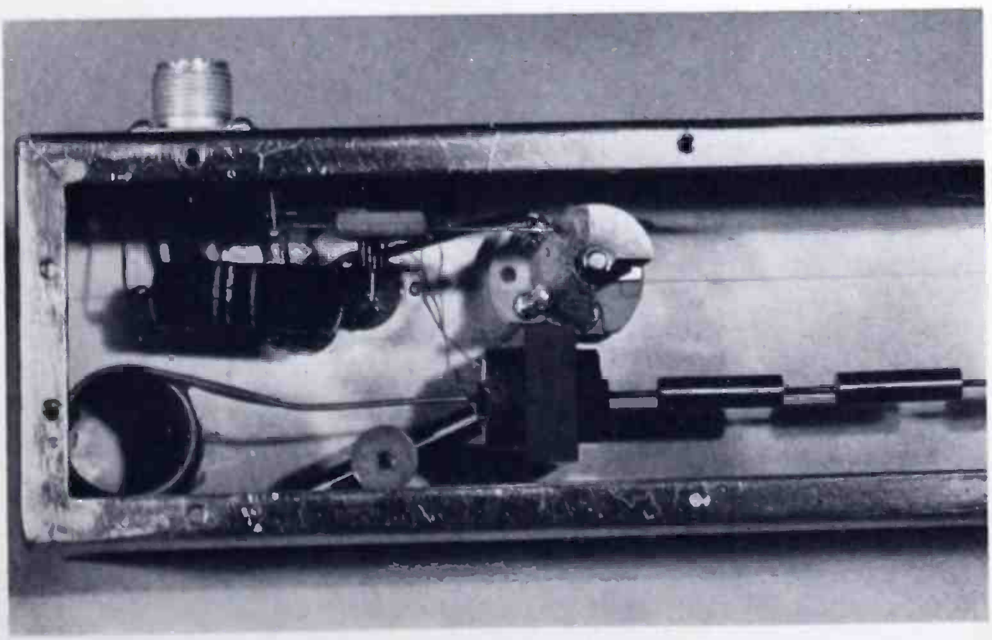

Fig. 7—Bottom view of chassis with cover removed showing wiring and biasing magnet.

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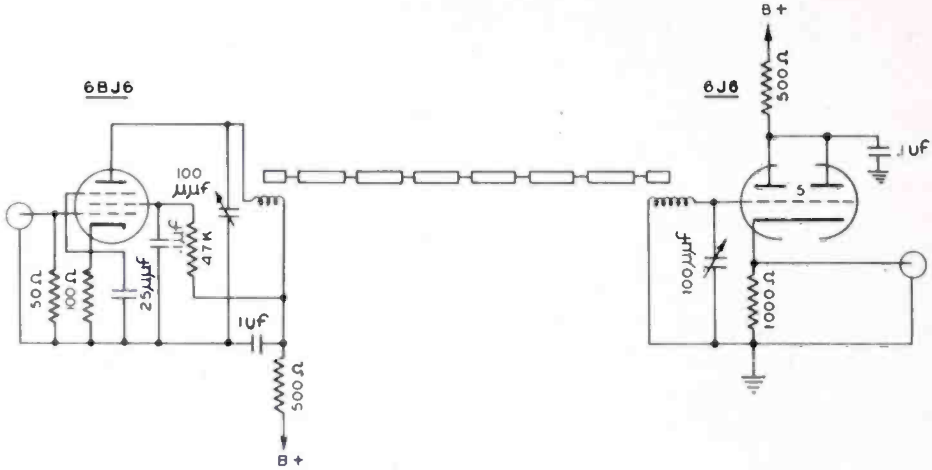

Fig. 8—Circuit diagram of complete filter unit.

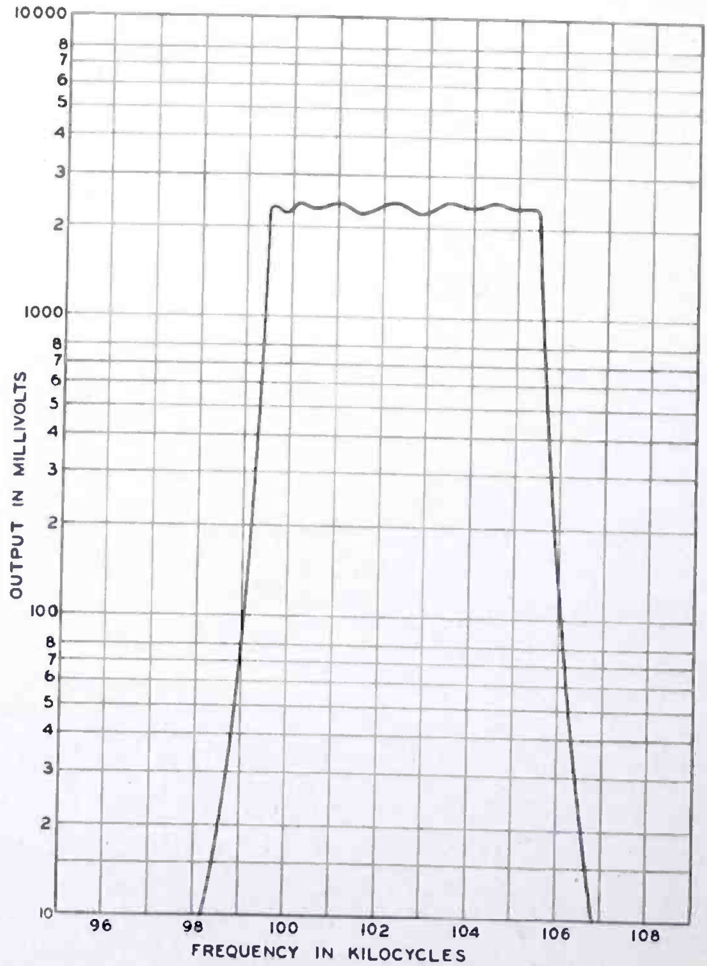

Fig. 9—Response curve of the mechanical filter with compromise terminations.

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better. The amount of ripple obtained in a filter such as this is governed to some extent by the choice of the terminating impedance. Figure 10 shows the response curve when the lossy lines at each end have characteristic impedances equal to the characteristic impedance of the coupling elements. As can be seen, reflections are nonexistent over the center portion of the band while relatively bad reflections occur at the edges. By using slightly lower impedance lossy lines at each end as compromise terminations, a lower average mismatch is obtained, resulting in smaller reflections. A compromise recommended by Guillemin[2]

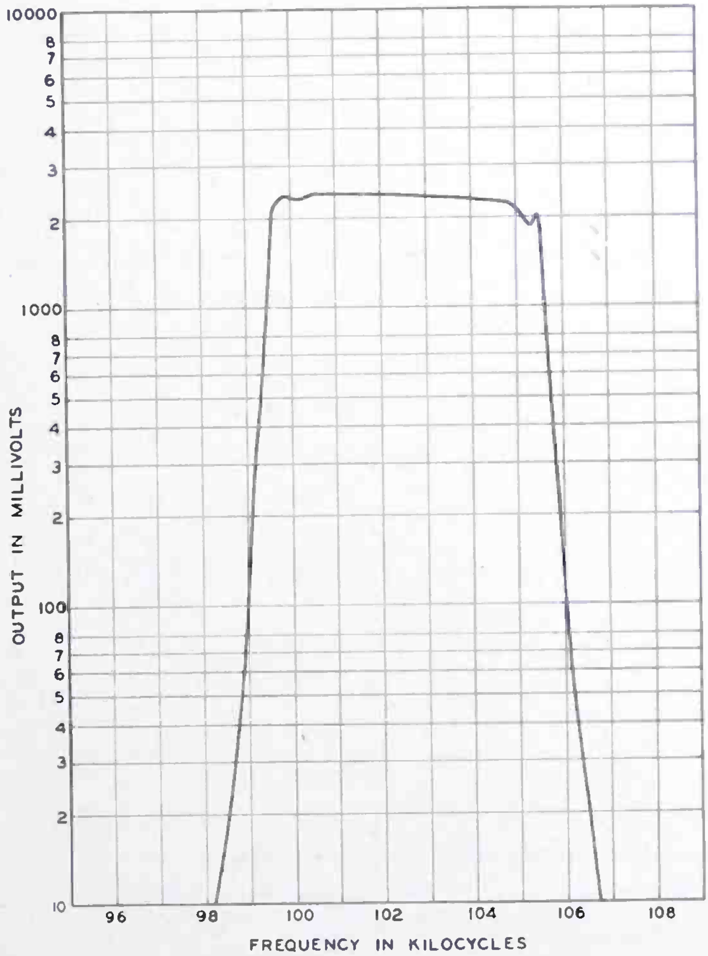

Fig. 10—Response curve of the mechanical filter with the theoretical terminations showing large variations at band edges.

is to make the terminations 60 per cent of the mid-band impedance, however, it has been found that 70 per cent gives slightly better results with this particular filter construction. The resulting response curve is shown in Figure 9.

[2] E. A. Guillemin, *Communication Networks*, Vol. II, p. 297, John Wiley and Sons, Inc., New York, N. Y., 1935.

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Perfectly flat response in the pass band could have been obtained by designing the various couplings between the resonators in accordance with established filter theory so as to obtain a "max flat" response.[3] Since the steepness of the cutoff slope would have necessarily been reduced, it was considered more desirable to accept the ripple inherent in the constant-k construction.

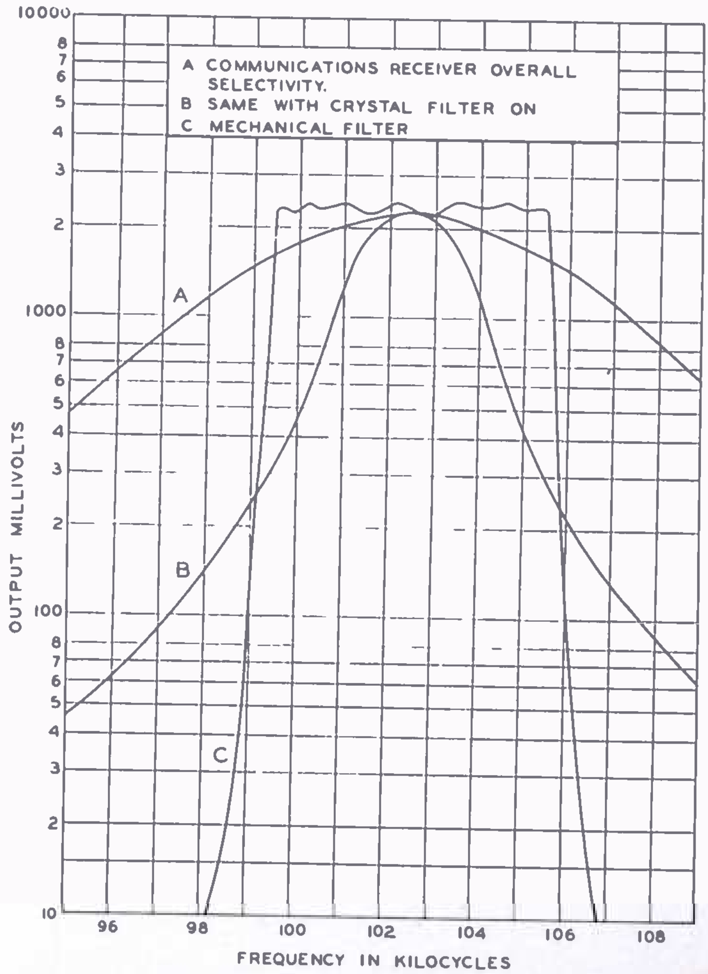

Fig. 11—Response curve of the mechanical filter compared with a standard communication receiver.

The rate of attenuation can be increased by increasing the number of sections as has been previously mentioned. It might be thought that another method of increasing the cutoff rate would be to design the filter couplings so as to obtain a Chebiskev polynomial type of response since it has been shown that this would be optimum for a coupled

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[3] Milton Dishal, "Design of Dissipative Band-Pass Filters Producing Desired Exact Amplitude-Frequency Characteristics," *Proc. I.R.E.*, Vol. 37, pp. 1050-1069, September, 1949.

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resonator type of filter.[4] However, a calculation according to the procedure of Dishal[3] gives 43.6 decibels attenuation 1 kilocycle from the edge of the pass band of a filter with similar ripple, while an inspection of Figure 9 gives 40 decibels attenuation 1 kilocycle from the upper edge of the pass band. Therefore, designing the filter to give a Chebiskev response would result in very little improvement, and the complexity of the design calculations would be increased many fold.

Apparently the only way of greatly increasing the rate of attenuation at the band edges without increasing the number of resonators is to incorporate some form of rejector arrangement so as to approach an m-derived type of response. This is easily done in the electrical drive and take-off circuits by simply placing high-Q magnetostrictive resonators of the correct frequencies in part of the two coils. Attaching the rejectors directly to the mechanical filter is more difficult and attempts thus far have not been too successful.

The insertion loss of the filter measured from the grid of the first tube to the grid of the second tube is about 8 decibels. By using an untuned line-matching transformer on the input to match the 50-ohm coaxial cable to the first grid, the unit insertion loss was reduced to zero; and by making the output tube a pentode and again using a transformer to match the line to the output tube, a gain of about 6 decibels was realized. Of course the mechanical filter itself still has the same loss. By using magnetostrictive ferrite for the input and output resonators, much higher efficiency can be obtained but some sacrifice in temperature stability would result. Piezoelectric barium titanate can also be used to provide efficient electrical-to-mechanical conversion at the input and output but again the temperature stability would be impaired.

The temperature stability of the filter can be made quite good over the range of −50°C to +80°C by the use of all Ni-Span C construction. As has been noted previously, however, steel couplers were used in the fabrication of this filter and as a result the heat treatment necessary to adjust the thermoelastic coefficient to zero was not carried out.

Two filters of the type described have been built and no trouble was experienced in reproducing the results. Either silver solder or soft solder was found satisfactory for joining the couplers to the resonators. A semipress fit between the parts was found desirable to minimize the detuning effect of the solder. The resonators used were 0.25 inch in diameter but this was an arbitrary choice and a smaller diameter

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[4] P. E. Richards, "Universal Optimum Response Curves for Arbitrarily Coupled Resonators," *Proc. I.R.E.*, Vol. 34, pp. 624-629, September, 1946.

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would work as well (of course, the couplers would have to be changed in proportion in order to keep the same band width).

CONCLUSION

Mechanical filters for 100 kilocycles having various band widths can be designed according to the procedure in the Appendix. The attenuation rate can be controlled by the number of sections in the filter. The ripple in the pass band can be reduced to a satisfactory value by proper termination of the filter using lossy acoustic transmission lines of the correct size. The insertion loss can be reduced by using magnetostrictive piezoelectric ferrite or barium titanate for the electrical to mechanical conversion with some compromise in stability. All Ni-Span C construction insures good temperature stability.

APPENDIX

Design Procedure for Mechanical Filters

The band width formula for a mechanical filter with half-wave resonators and quarter-wave coupling necks is given by Roberts and Burns[1] as:

$$B = \frac{4}{\pi} \phi\,(1 - \phi),$$

where B is the fractional band width given by $\dfrac{f_2 - f_1}{\sqrt{f_2 f_1}}$,

and $\phi = \dfrac{\text{(area of coupler) (intrinsic } Z \text{ of coupler)}}{\text{(area of resonator) (intrinsic } Z \text{ of resonator)}} = \dfrac{A_c Z_{IC}}{A_R Z_{IR}}$.

The intrinsic impedance of a material is given by

$$Z_I = \text{(Velocity) (Density)}$$

The above expression for the fractional band width can be solved for the diameter of the coupler:

$$D_c = \left[\frac{D_R^2\, Z_{IR}}{2 Z_{IC}} \left(1 - \sqrt{1 - \pi B}\right) \right]^{1/2}.$$

For the filter discussed in this report, $B = 0.06$ (i.e., 6 kilocycles wide, centered on 100 kilocycles),

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$D_R =$ diameter of resonator $= 0.25$ inch,

$Z_{IR} =$ intrinsic Z of Ni-Span C resonator $= 3.83 \times 10^6$,

$Z_{IC} =$ intrinsic Z of steel coupler $= 4.03 \times 10^6$.

The diameter of the required coupler then becomes 0.054 inch.

To terminate a Campbell filter properly, a half section must be used at each end. This requires end resonators of ½ the impedance of the interior resonators. Thus

$$\frac{\pi D_I^2}{(4)(2)} = \frac{\pi D_e^2}{4},$$

or

$$D_e = \frac{D_I}{\sqrt{2}} = \frac{0.25}{1.414} = 0.177 \text{ inch},$$

where $D_I =$ diameter of interior resonator,

$D_e =$ diameter of end resonator.

The length of the resonators is found from the relation

$$\lambda = \frac{v}{f},$$

where λ is the length of a full wave,

v is the velocity of sound, and

f is the frequency.

For half-wave resonators,

$$\frac{\lambda}{2} = \frac{v}{2f} = \frac{4.8 \times 10^5}{2 \times 100{,}000 \times 2.54} = 0.945 \text{ inch}.$$

Similarly, for the quarter-wave couplers,

$$\frac{\lambda}{4} = \frac{v}{4f} = \frac{5.13 \times 10^5}{4 \times 100{,}000 \times 2.54} = 0.505 \text{ inch}.$$

The couplers have to be made somewhat longer to allow for insertion into the resonators.

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The lossy lines for termination should have 70 per cent of the impedance of the couplers. Note that the lossy lines are copper wire while the couplers are steel.

$$\frac{\pi D_L^2 Z_{IL}}{4} = \frac{\pi D_c^2 Z_{IC} (70\%)}{4},$$

where D_L = diameter of the lossy line,

D_c = diameter of the coupler,

Z_{IL} = intrinsic impedance of line (copper), and

Z_{IC} = intrinsic impedance of coupler (steel).

Thus

$$D_L = \left[\frac{D_c^2 Z_{IC} (.7)}{Z_{IC}} \right]^{1/2}$$

$$D_L = \left[\frac{(.054)^2 (4.03) (10^6) (.7)}{(3.33) (10^6)} \right]^{1/2} = 0.050 \text{ inch.}$$

As stated in the text, the lines were made five feet long.

The location of the center of the pass band turns out to be slightly above 100 kilocycles. For an exact location of the pass band, some cut and try would be necessary.

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FREQUENCY CONTROL OF MODULATED MAGNETRONS BY RESONANT INJECTION SYSTEM*†

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Summary—*The output frequency of a magnetron oscillator may be synchronized by the resonant injection system to a crystal-controlled radio-frequency voltage. The new stabilization system suppresses the natural jitter, the pushing and moding, of an amplitude-modulated magnetron. The stabilized magnetron oscillator can be used as a transmitter tube to produce amplitude- or angular-modulated carriers.*

Introduction

The purpose of the investigations described here is to evaluate the merits of magnetron oscillators as transmitter tubes when they are frequency and phase controlled by injection locking to a standard frequency source. The magnetrons used in this work were normal multicavity magnetrons containing a cathode, a plate, and an output loop. Special attention was given to the production of amplitude modulated radio-frequency (r-f) carriers and also to the production of frequency- or phase-modulated carriers. The amplitude modulated carrier was produced by modulating the direct-current plate voltage of the magnetron. The angular-modulated magnetron carrier was produced by angular modulation of the standard frequency source. The investigations are not complete, but the results obtained are encouraging for the application of magnetrons to services where previously only triodes or tetrodes were considered as potential power tubes.

If the direct-current plate voltage of an unstabilized magnetron is modulated with a superimposed alternating voltage, varying output frequency will be observed. Continuous frequency changes are called "pushing" and discontinuous changes, "moding." Two systems, similar in operation, which eliminate these frequency changes will be discussed. The frequency-controlling ability of one of the systems, which was worked out in most of its details, is effective in suppressing the pushing and also the moding, when 100 per cent amplitude modulation is

* Decimal Classification: R355.912.1.

† Presented at the National Electronics Conference at Chicago, Ill., October 22-24, 1951.

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applied to the magnetron carrier by modulation of the plate, and even when the magnetron is heavily overmodulated.

To use a magnetron as an amplitude modulated r-f power source and to keep the carrier frequency constant by injection of a current from a standard frequency source was proposed by Irving Wolff in 1936.[1] This idea preceded by many years the necessity of using carrier frequencies higher than the practical upper frequency limit of high-power amplifier tubes then available. Furthermore, the magnetron has been developed into a reliable power tube only during the past ten years.

Interest in the phase control of microwave oscillators by injection of a locking current was stimulated by work done at the Massachusetts Institute of Technology and reported in 1947 by J. C. Slater[2] and in 1948 by E. E. David, Jr.[3] It was demonstrated that a klystron, at a frequency somewhat higher than 3,000 megacycles, can be phase locked to another microwave oscillator. In David's experimental system the power was injected into the oscillator by a directional coupler. This scheme, however, was not applicable for phase control of anode-modulated oscillators because a considerable part of the continuous-wave injection power was absorbed by the loading resistor of the controlled oscillator. Thus the maximum obtainable amplitude modulation factor would be rather limited in this system. Furthermore, the injection current flowed through an attenuator. Consequently, a relatively large amount of injection power was required.

Purpose of the Work

The present investigations were directed toward the problem of using ultra-high-frequency or microwave oscillators as r-f power generators to produce amplitude- and angular-modulated high-power carriers with a frequency and phase stability which meets practical transmitter requirements. Low injection power for stabilization is a prime requirement. The most attractive high-power generator is the magnetron, with a carrier-output to direct-current-input efficiency of about 60 per cent. In the course of plate modulation studies, J. S. Donal, Jr.* found that as long as the upper mode boundary is not reached, a good magnetron has, in general, only one critical moding region in the relevant current range. This region is near to cutoff. The experimental work on the frequency stabilizing system was done

[1] U. S. Patent 2,113,225.
[2] M.I.T. Report No. 35, "The Phasing of Magnetrons."
[3] M.I.T. Report No. 63, "Locking Phenomena in Microwave Oscillators."
* RCA Laboratories Division, Princeton, N. J.

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with developmental type A-128 magnetrons[4] operated up to one kilowatt level at carrier frequencies of 750 and 825 megacycles. The type A-128 magnetrons include an electron beam for frequency modulation purposes. The frequency modulator beam, however, was not used during these experiments. It is believed that the system can also be operated at higher power levels and at different frequency ranges.

The frequency deviation due to the pushing of an amplitude modulated unstabilized magnetron is substantially independent of the modulating frequency; thus it is similar to a frequency modulation process. Unstabilized pushing up to 1 per cent of the carrier frequency was observed during amplitude modulation, and several megacycles additional frequency change was observed when the amplitude modulation was increased through the low-level moding region, which must be done if 100 per cent amplitude modulation of the magnetron carrier is desired. Measurements have shown that, when the magnetron is stabilized, the remanent effect of the previously observed pushing depends on the amplitude modulating frequency and, consequently, it is similar to the character of a phase modulation of low argument. The argument decreases only at very high amplitude-modulation frequencies.

Resonant Injection System

One form of the resonant injection system is represented in Figure 1. A class C amplifier tube is placed in cavity "k". The grid of this tube is excited with a subharmonic of the output frequency. The amplifier tube in this case is a grounded-grid frequency doubler. The plate cavity of "k" is tuned to the magnetron frequency, f_m. In this circuit the r-f voltage of the magnetron is present between the plate and the grid of the class C doubler tube because the plate cavity of "k" is excited also with magnetron voltage. The plate-cathode circuit of the triode is only loosely coupled to the magnetron voltage. Consequently, the triode absorbs little power from the magnetron. The grid-cathode gap is the most delicate part of the injection amplifier tube and must be protected from overloading. The grid-exciting cavity is coupled parallel to this gap, as indicated in Figure 1. This cavity is tuned to $f_m/2$, which is one half the magnetron frequency, and consequently it has low reactance to the magnetron output frequency, f_m. Thus the magnetron output power cannot build up a high voltage between the grid and cathode, and the grid-cathode gap is, therefore, protected.

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[4] J. S. Donal, Jr., R. R. Bush, C. L. Cuccia and H. R. Hegbar, "A 1-Kilowatt Frequency-Modulated Magnetron for 900 Megacycles," *Proc. I.R.E.*, Vol. 35, pp. 664-669, July, 1947.

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The transmission lines "a" and "b" in Figure 1 have optimum lengths. Line section "a" should be chosen to transform the dynamic input impedance of the oscillating magnetron into an impedance which, at the low end of the amplitude modulation (AM) cycle, should be much smaller than the input impedance of the line section "d", seen from the junction point toward the load. The impedance of the section "d" toward the load is equal to the load resistance provided the "d" line section is matched. If the low input-impedance requirement for section "a" is satisfied, the injection current from line "b" at the low end of the amplitude modulation cycle is transmitted mainly to the magnetron, and the load receives only a small portion. The length of line "b" is determined by the requirement of the injection-voltage transformation and of the magnetron loading. Additional tuners on the transmission line may adjust the proper loading of the magnetron.

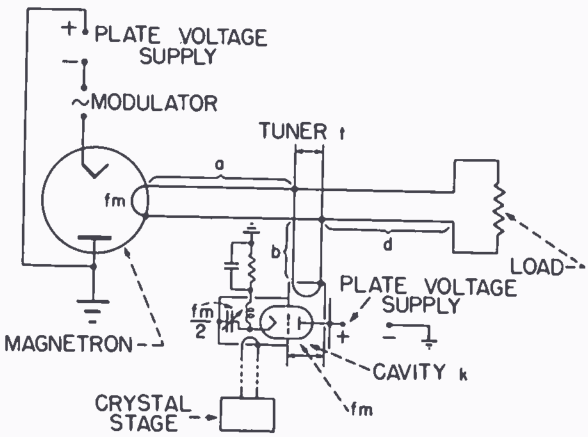

Fig. 1—Resonant injection system.

In the case of an amplitude modulated magnetron system, it is important that at the low end of the amplitude modulation cycle the amount of injection power which flows to the load, if any, should be extremely low because this injection power reduces the depth of modulation of the output carrier. A 95 per cent modulation in the load, computed from the peak carrier voltage, can be obtained in this system. In this case the magnetron is 100 per cent modulated. The remanent 5 per cent amplitude, which is due to the injection power in the load, represents only .25 per cent of the peak output power.

Power Requirement of the Injection Source

The above low power of .25 per cent of the peak power does not represent the entire required injection power. The condition can be analyzed by considering the standing-wave patterns in the transmission

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line. Line 1 of Figure 2 shows the standing-wave pattern of the injection voltage for the low-power end of the modulation cycle when the magnetron output is 100 per cent modulated, so that no magnetron current flows in the line. The junction of the main transmission line and the injection transmission line is indicated by "X" in Figure 2. At point "X", as a consequence of the previously described tuning condition, the injection has a low voltage, Δe_i, which is almost zero. The existence of an almost zero voltage plane of the injection standing wave, and the relative position of this plane with respect to the magnetron input, prove that the magnetron shows an almost pure reactance of low absolute value to the injection voltage at the low-power end of the AM cycle, where the magnetron is cut off. The reactance can be inductive or capacitive, depending on the setting of the internal

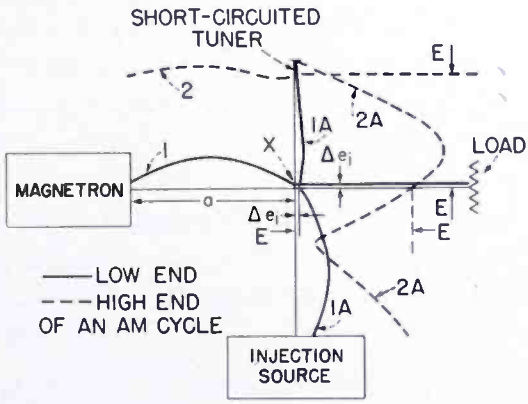

Fig. 2—VSWR in a resonant injection system.

magnetron tuner. The load, coupled into the system at point "X", absorbs only a very low amount of injection power at the low-power end of the modulation cycle. If the magnetron loop impedance changes, and the standing-wave pattern does not have an almost zero voltage plane at "X", a finite injection voltage appears on the transmission line which is terminated by the load. This happens at different output power levels; thus, the load absorbs more injection power during most of the AM cycle than it does at the low end of the cycle. The modulated output envelope, which is composed of the magnetron carrier and, at some levels, injection power, is almost perfectly linearly related to the voltage input to the modulator.

The injection source must also deliver power to cover the losses of the circulating high resonant injection current in the transmission line and in the cavities. The investigation of the requirement of the power capacity of the injection source is not yet complete. As a practical example, for one kilowatt of magnetron peak power, a grounded-grid triode, similar to the type 5588, in frequency-doubler

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service produces sufficient injection current to give satisfactory operation at carrier output frequencies below 1,000 megacycles.

Voltage-Standing-Wave Ratio of the Magnetron

Line 2A in Figure 2 represents, at the high end of the amplitude modulation cycle, the voltage standing wave produced in a short-circuited tuner and in the injection line terminated by a lossless injection source. The voltage-standing-wave pattern in line "a" is represented by nearly unity standing-wave ratio in Figure 2 by line 2. In a properly tuned system the voltage-standing-wave ratio (VSWR) is close to its minimum at the high-power end but it is not necessarily unity. However, the VSWR in line "a" is subject to changes during an amplitude modulation cycle. The VSWR increases as the power is lowered. The frequency and phase of the magnetron are determined by its own internal tuning and by the external impedance presented by all the circuit elements coupled to the transmission line. The presence of injection power in the load, and the variation of the same, change dynamically the impedance of the load seen from the magnetron, thus influencing the phase of the magnetron output. The injection current acts for the magnetron as an externally applied reactance. The effect of the reactances presented to the magnetron by the injection currents is a synchronized operation of the magnetron with the injection source.

If the free-running magnetron frequency is nearly equal to that of the injection source at the top of the amplitude modulation cycle, then the maximum frequency correction must be supplied at the low end of the cycle. At this point the externally applied dynamic susceptance due to the injection source must have its greatest value. The VSWR in the line outside the magnetron will be highest at the low end of the amplitude modulation cycle, as is the case in Figure 3. It should be noted that as the magnetron power is decreased toward the low end of the amplitude modulation cycle there is a decrease in the effective load resistance presented to the junction between the line and the magnetron loop. This junction is marked as plane L in Figure 3.

Limits of the Amplitude Modulation

Scope pictures of the demodulated carrier are reproduced in Figure 4. If the sine wave modulation, represented by Figure 4A, is increased up to the limit where the magnetron carrier is 100 per cent modulated, the detected envelope shows the form of Figure 4B. The remanent injection voltage amplitude, Δe_i, can be observed now on the scope. The magnetron starts and stops oscillating at each modulating cycle

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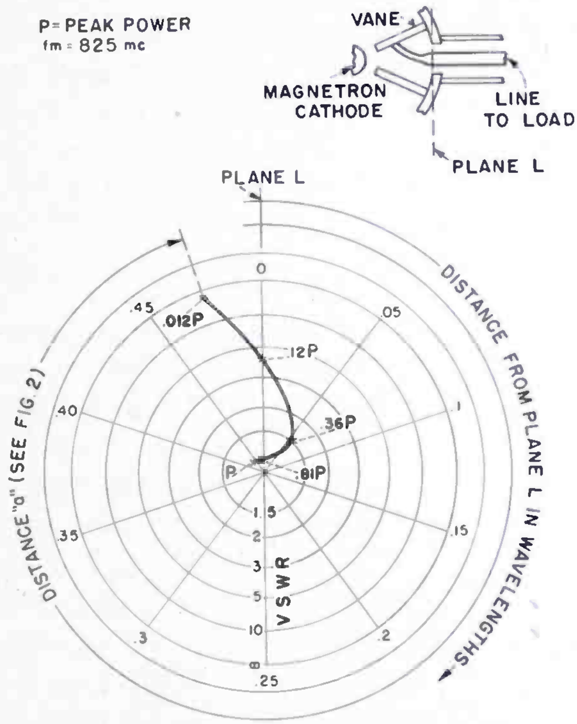

Fig. 3—VSWR and position of minimum during AM cycle.

without breaking out of synchronism. At different modulating frequencies up to 100 kilocycles, square-wave modulation was applied to the magnetron. The r-f envelope, detected by a diode, reproduced the square wave with low distortion (Figure 4C). Amplitude modulating frequencies up to several megacycles can be applied. The r-f band width which can be transmitted is about 2 per cent of the carrier frequency.

Angular-Modulated Magnetron Output Carrier

It was proven experimentally that if the injection power is frequency or phase modulated, the frequency of the magnetron output carrier follows the angular modulation with high fidelity at least up to several hundreds of kilocycles deviation. The magnetron carrier frequency deviation is increased between the angular modulated stage and the magnetron output. If the grid of the driver tube has, for

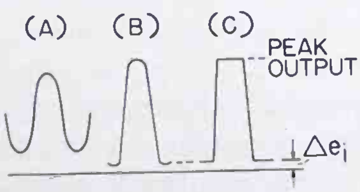

Fig. 4—Demodulated output envelopes.

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example, 100 kilocycles deviation, the magnetron carrier has 200 kilocycles deviation. This is natural in the previously discussed circuit. It is true also, however, in a different phase control scheme, where the control frequency is different from the magnetron output frequency. Such a circuit is described in the following section.

Synchronizing by a Subharmonic Frequency

Besides the previously described system, another synchronizing system was developed. In the system represented by Figure 1, the driving frequency of the injection source is a subharmonic of the magnetron output frequency. The plate cavity of "k", however, is tuned to the magnetron frequency, f_m, and the injection current has the same frequency. In the system represented by Figure 5, the plate

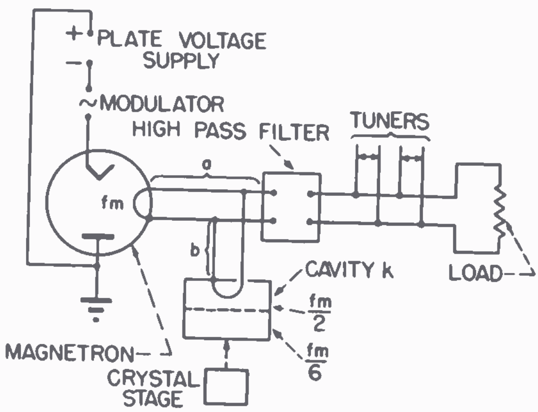

Fig. 5—Subharmonic resonant injection system.

cavity of "k" is tuned to a subharmonic of the output frequency, and the synchronizing current, which is injected into the magnetron cavities, is also a subharmonic of the magnetron frequency. A magnetron output frequency of 750 megacycles was used in the experiments and the subharmonic frequency was chosen as 375 megacycles. The magnetron was loaded by a dummy antenna which terminates the transmission line. The magnetron output loop with line sections "a" and "b" and cavity "k" was then tuned to 375 megacycles. The length of "a" is limited for 375 megacycles by a high-pass filter. Thus, the injection power does not flow toward the load. The high-pass filter had a simple construction. In some experiments an open-circuited 750-megacycle half-wave-length line was connected parallel to the main transmission line. This line element shows high impedance for the 750-megacycle magnetron frequency at the junction, but represents a quarter-wave-length open-circuited line, which produces a virtual short circuit for the 375-megacycle injection frequency. A class C

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amplifier tube placed in cavity "k" excites this resonant system with 375 megacycles. The grid circuit of the class C amplifier tube was driven by the sixth subharmonic of the magnetron output frequency. The magnetron cavity was tuned to 750 megacycles and, although it also forms part of a 375-megacycle tuned system, it oscillates only at 750 megacycles. The magnetron output carrier locks to the doubled control frequency.

The question may arise as to how the injected half-frequency voltage controls the magnetron output frequency. Cold test has shown that the magnetron vanes, where the output loop is coupled, were excited with the 375-megacycle voltage. Injection voltage of 6 per cent of the direct-current plate voltage was measured on the end of these vanes. Such an alternating-current voltage is sufficient to amplitude modulate the magnetron carrier 100 per cent if it is superimposed on the direct-current plate voltage. This, however, happens here only for some vanes. One kind of interaction may be due to the partial modulation of the plate voltage with the injection frequency. Another possible kind of interaction is a conversion process which produces the doubled injection frequency in the magnetron since the magnetron is a diode-type device. The doubled injection frequency is the magnetron output frequency, and the system may work as in the previous case.

The reactive elements, which are the line "b", the coupled cavity "k", and sometimes the high-pass filter, may, in certain combinations, introduce unwanted magnetron standing waves. This effect can be reduced satisfactorily by the stub tuners. These have no action on the tuned circuit of the synchronizing frequency if they are placed on the load side of the high-pass filter where no synchronizing frequency is present. The amplifier tube in cavity "k" cannot be damaged by the magnetron power because no high magnetron voltage can be built up in this cavity as it is tuned far away from the magnetron frequency.

General Requirements of Resonant Locking Circuits

The requirements of a practical resonant locking system can be summarized as follows:

1. A high circulating synchronizing current should be produced in the magnetron cavity to obtain stable phase locking. This requires a resonant tuning of the injection source, including the magnetron input element.
2. The synchronizing current (at least on the low-power end of the modulation) should be prevented from flowing to the load, in order to permit deep amplitude modulation and also to avoid loading of the injection source.

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3. The injection tube should be protected from the magnetron power with reactive and not with resistive circuit elements. In this manner the protective elements work practically without injection- and magnetron-power loss.

All these requirements are fulfilled in both circuits described. In Figure 1 the proper selection of the electrical lengths of the transmission line satisfies the second requirement. In the case of subharmonic synchronizing, as shown in Figure 5, a high-pass filter was added for the same purpose, but the high-pass filter could be omitted and the same effect could be obtained by proper selection of the line lengths if subharmonic synchronizing frequencies are used.

Summary of Results

Stabilization by the previously described systems produces a radical change in the characteristic behavior of the magnetron. Not only are the natural jitter and the pushing due to plate modulation substantially suppressed, but also the low-level moding disappears. A magnetron which, when uncontrolled, cannot be modulated to a power output below 100 watts with a given load due to low-level moding, will, in controlled condition, start dynamically and statically from no output. In controlled condition its power can be increased from cutoff to peak output without the production of any frequency other than that determined by the crystal. Of course, the side-band frequencies are also produced if the magnetron is modulated. The plate power efficiency at the peak of the modulation cycle is about 60 per cent. If the r-f output power is reduced, due to modulation, the plate power input is reduced also.

The crystal-controlled magnetron can be practically applied in a manner similar to a class C stage, even if electronically no analogy exists between them. These experiments demonstrated a way of obtaining high crystal-controlled transmitter power with good efficiency in the high-frequency regions where conventional amplifier tubes are limited in output power.

Acknowledgments

The author is indebted to Irving Wolff, Director of Research, RCA Laboratories Division, for many valuable discussions on the different aspects of the work. R. F. Schwartz cooperated with the author during the experiments and designed several parts of the experimental setup. Valuable discussions were held with J. S. Donal, Jr., D. S. Bond and

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L. S. Nergaard of RCA Laboratories Division on several occasions. A plate modulator of advanced design was built by K. K. N. Chang, and was used in the experiments. D. G. Moore, of RCA Laboratories Division, made several measurements on the system. D. E. Deuitch, J. J. Ayres, and E. M. Combellack, RCA Victor Division, contributed to different phases of the experimental work. A cavity design, developed by W. F. Fell, RCA Victor Division, was used in the experimental setup.

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A DEVELOPMENTAL PORTABLE TELEVISION PICKUP STATION*

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Summary—*Based on the Vidicon photoconductive pickup tube, a completely portable battery-operated television pickup unit has been designed and built. Popularly called "Walkie-Lookie," the unit consists of a 50-pound back pack and an 8-pound camera. The equipment includes a synchronizing generator and both video and sound channels operating on a common ultra-high-frequency carrier to link the unit with a base station over distances up to ½ mile. A receiver in the pack picks up aural instructions from the base and a reference frequency for synchronizing control. Self-contained, rechargeable batteries will operate the complete unit for one and one half hours.*

Introduction

COMPACT television equipment based on the Vidicon photoconductive pickup tube has been the subject of considerable work during the past few years.[1,2] All of the equipment thus far described has been of the closed-circuit type for industrial and educational purposes. There are many television applications, however, where complete portability of the pickup equipment with no cable connections to the control point would be desirable. It is the purpose of this paper to describe a completely portable battery-operated experimental equipment serving as a complete pickup station with synchronizing generator, video and sound channels and radio link to and from a control point.

The basic unit consists of a pack-carried control equipment containing all circuits for generating synchronizing frequencies for a standard 525-line, 30-frame interlaced picture; battery-operated power supply; deflecting circuits; video amplifier; sound pickup equipment; a 600-megacycle radio transmitter; and a radio receiver for receiving instructions and control information from the control point. A Vidicon

* Decimal Classification: R583.

[1] R. C. Webb and J. M. Morgan, "Simplified Television for Industry," *Electronics*, Vol. 24, p. 70, June, 1950.

[2] V. K. Zworykin and L. E. Flory, "Television in Medicine and Biology," *Elec. Eng.*, Vol. 71, p. 40, January, 1952.

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camera, including a kinescope monitor used as a view finder, is connected to this unit by cable.

A diagram of the entire system is shown in Figure 1. A transmitter at the control point serves to transmit instructions to the remote operator and also to transmit a control frequency as a reference for the remote synchronizing generator. The signal from the portable point is received here and processed for utilization as a complete video and sound signal.

Pack-Carried Unit

A block diagram of the portable equipment is shown in Figure 2. The Vidicon camera picks up the scene to be transmitted and converts it to a video signal. The signal then passes through a video amplifier

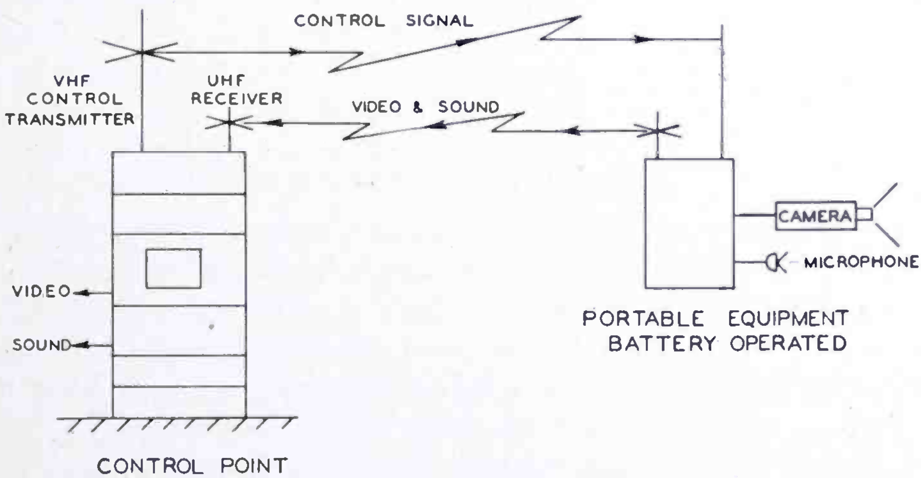

Fig. 1—Block diagram of system.

and modulator to the radio transmitter. The sound portion is picked up, amplified and combined with the video signal for transmission in a manner to be described later.

A synchronizing generator generates horizontal and vertical pulses in proper relation to produce a 525-line interlaced picture.

The radio receiver picks up audio instructions from the control point and, in addition, a 60-cycle sine wave. This frequency is compared to the field frequency from the sync generator and, by means of a phase detector and automatic frequency control (AFC) circuit, locks the remote sync generator with the 60-cycle frequency at the control transmitter.

A schematic diagram of the synchronizing generator in the portable equipment is shown in Figure 3. A blocking oscillator provides the basic frequency of 31,500 cycles or twice the scanning line frequency.

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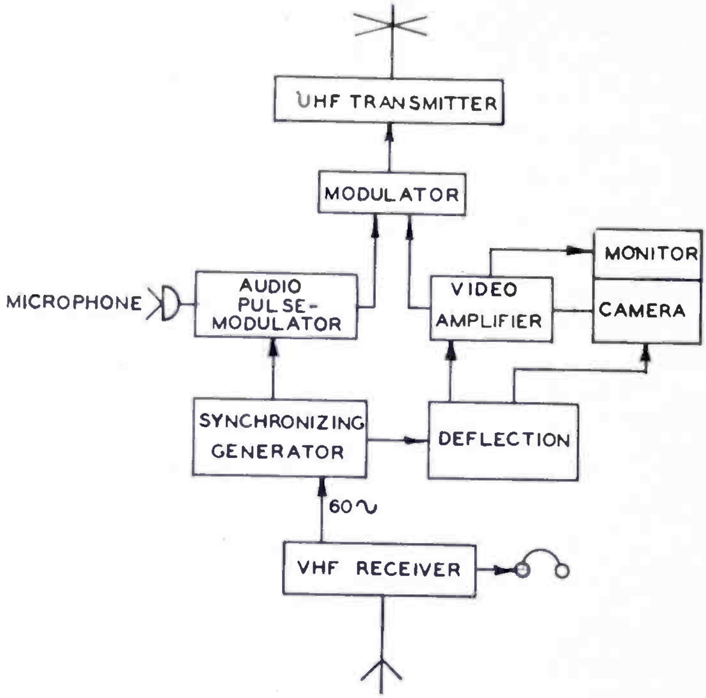

Fig. 2—Block diagram of portable equipment.

A second blocking oscillator operating as a counter divides this frequency by 15. Similar counters following this divide by 7 and 5 respectively. This counter chain dividing the basic frequency by 525 provides the field frequency of 60 cycles. This frequency is compared in a phase detector with the 60-cycle frequency received from the

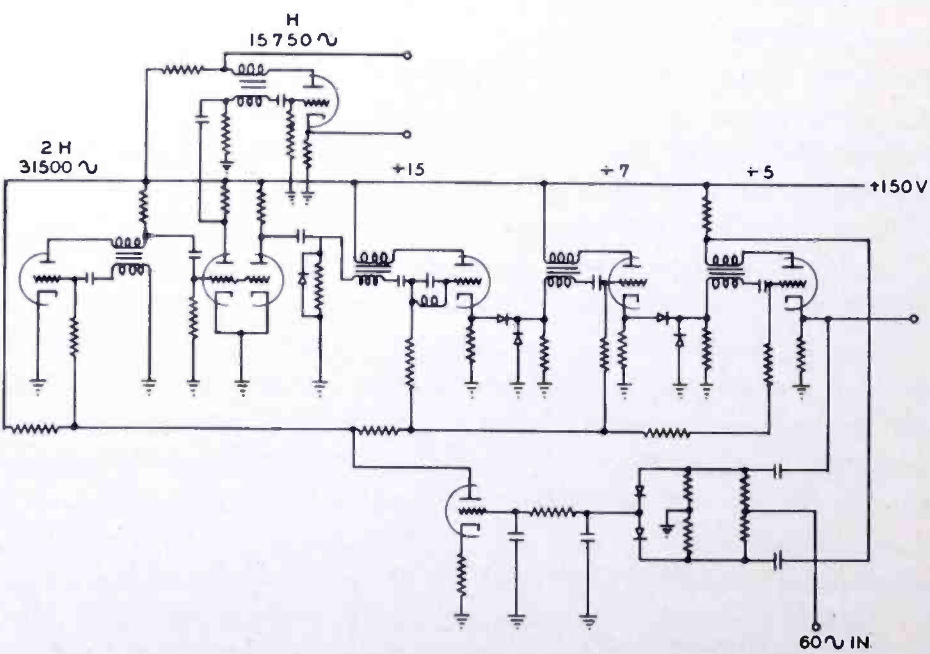

Fig. 3—Schematic diagram of synchronizing generator.

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control station. The direct-current voltage output of this detector is applied to the 31,500-cycle oscillator as an AFC voltage to maintain this oscillator at precisely the correct frequency. In addition, this voltage is applied to the grid circuits of the individual counters to cause a change in their natural period. This feature greatly increases the stability of the generator where operating locked to the reference frequency. By locking the generator in this manner to a frequency transmitted from the control point, its operation can be stabilized with respect to the local power-line frequency or any convenient 60-cycle source.

The transmitter operates at 593.96 megacycles and is crystal controlled with a third-overtone crystal oscillating at 49.496 megacycles. This frequency is tripled to 148.49 megacycles and then doubled twice to 593.96. The 148.49-megacycle frequency is used as the local oscillator frequency for the receiver in the pack. The two doublers and a final power amplifier make use of 5876 pencil triodes in grounded-grid coaxial line type tank circuits. Since the final amplifier is of the grounded-grid type, it is necessary to modulate both its plate circuit and that of its driver in order to obtain a high percentage of modulation. These plate circuits are both made a half wave length long so that they may be open circuited, thus minimizing the capacity to be driven by the modulator. A power output of 2 watts may be obtained from the final amplifier stage.

The video modulator posed somewhat of a problem since some 200 volts of video are needed and efficiency is of great importance to save power and weight. A "boot strap" modulator developed for the purpose is shown in Figure 4. The modulator acts as a series impedance in the transmitter plate supply. The driver tube is a pentode with the grid resistor R of the modulator acting as its load resistor. A video signal on the grid of the driver causes a signal to appear across R. This causes the current through the modulator to the transmitter to vary, thus modulating the transmitter output. A large voltage swing will appear at the cathode of the modulator and on the plate of the driver as well. Due to the pentode characteristic of the driver tube, however, this large plate voltage swing can be made to have negligible effect on the plate current of the driver. The effect is that of the driver tube working into a high apparent resistance. This circuit is quite efficient since the gain of both the driver and modulator are realized. Positive sync modulation is used, that is, the sync pulses are in the direction of increased carrier. Since a direct-current connection exists from the grid of the driver to the transmitter, black level is established by a clamp circuit on the grid of the driver.

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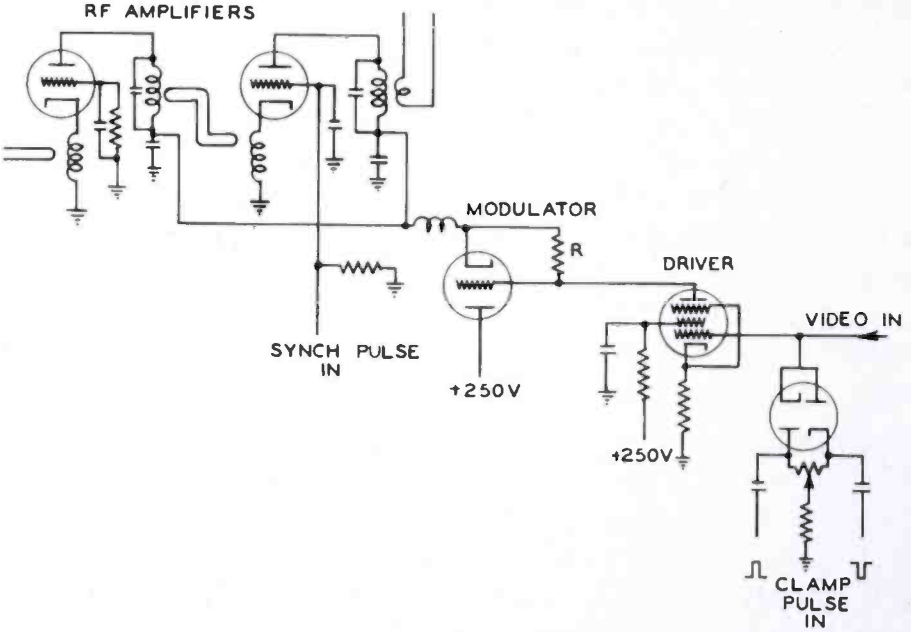

Fig. 4—Schematic diagram of bootstrap modulator.

Sound accompanying the picture is transmitted on the video carrier in an unconventional manner. Referring to the schematic in Figure 5, short pulses at horizontal line frequency are used to trigger a multivibrator which generates pulses of a length determined by its time constant. The length of these pulses is varied at an audio rate by applying the sound signal to a grid of the multivibrator. The result is a pulse, occurring at horizontal frequency, whose front edge is fixed but whose width varies with the sound modulation. This pulse is transmitted as a synchronizing pulse by applying it to the grid of the final r-f amplifier as can be seen on the schematic, Figure 4. In this

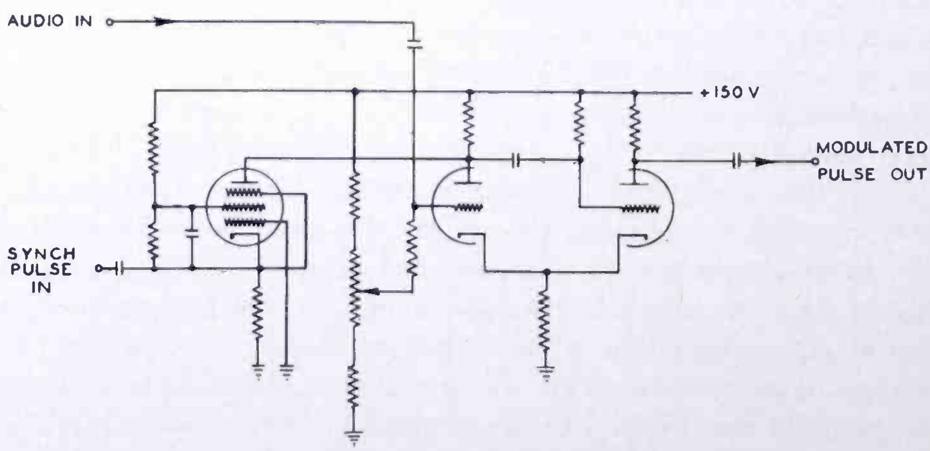

Fig. 5—Pulse duration modulator.

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way it is added in a direct-current manner to the video signal. An oscilloscope trace of the sync pulse with back edge modulation is shown in Figure 6. This shows the pulse in its proper position on the blanking pedestal of the video signal. The upper trace shows the unmodulated pulse while the lower one shows the pulse with full modulation at 60 cycles. To recover the sound information at the receiving point, the sync pulse, after separation from the video signal, is passed through a low-pass filter to remove the pulse repetition frequency. An upper frequency slightly less than one half the pulse repetition rate may be transmitted by this method. Using television standards this means an upper audio frequency of about 7000 cycles.

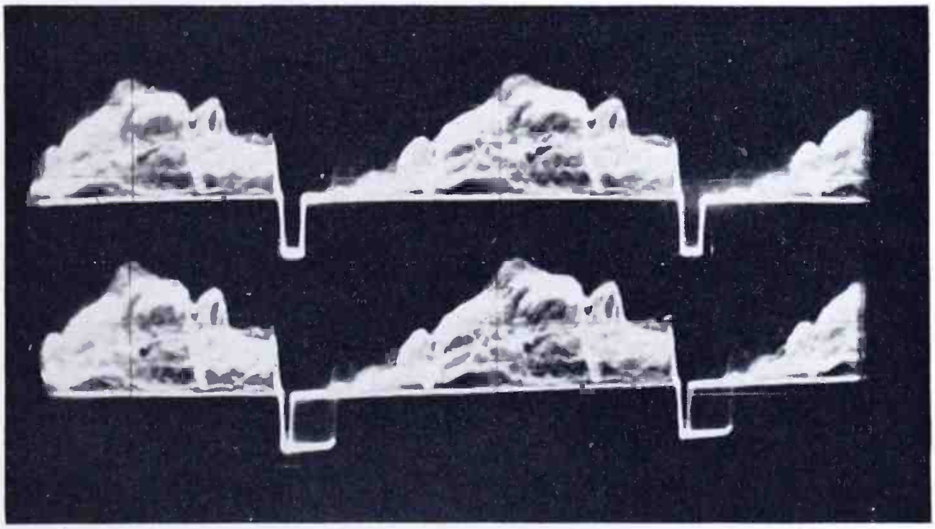

Fig. 6—Oscilloscope trace of sync pulse. Upper trace—unmodulated pulse; lower trace—full modulation at 60 cycles.

The receiver which picks up instructions and the control frequency is a rather conventional frequency modulation receiver designed for operation on the single frequency of 154.49 megacycles with 6 megacycles intermediate frequency. The local oscillator frequency is supplied by the transmitter oscillator. The output consists of a discriminator and high-pass circuit for voice and an amplitude modulation detector circuit peaked at 60 cycles to pass the control frequency.

Power for the unit is supplied by silver cell storage batteries of 60-ampere-hour capacity. By means of a dynamotor, voltages of 150 and 250 volts direct-current are supplied to the plate circuits. Power consumption is about equally divided among the two plate supplies and the heater circuits. Total power consumed is about 150 watts with an efficiency of around 60 per cent. The batteries supplied are sufficient to operate the pack for about one and one half hours on a single charge.

The camera designed for this equipment uses the C73162 Vidicon

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pickup tube described elsewhere.[3] A magnetic field for focusing the electron beam is provided by four alnico rods with soft iron end plates. A two-stage video amplifier in the camera builds the signal up to a level to be carried by cable to the pack unit. A special 1-inch diameter monitor tube in the camera permits the operator to monitor the video

Fig. 7—Portable unit in use.

signal being transmitted. Signal for the monitor is obtained from the cathode of the video modulator and operates a driver stage in the camera.

The pack, carrying batteries and all circuits except camera, may be back carried as shown in Figure 7. The camera may be held in the

[3] P. K. Weimer, S. V. Forgue and R. R. Goodrich, "The Vidicon Photoconductive Pickup Tube," *Electronics*, Vol. 24, p. 70, May, 1950.

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hand as shown or may be supported on a light tripod. The weight of the complete pack is 50 pounds and the camera about 8 pounds. The circuit side of the pack is seen in Figure 8. The miniaturized rack panel construction can here be seen. The tube side of the pack with bottom removed is shown in Figure 9. Batteries are contained in the removable bottom compartment and the dynamotor can be seen at the bottom of the pack. A closeup of the camera is shown in Figure 10 and the vidicon side with cover removed is seen in Figure 11. Here the alnico rods which provide the focusing field for the vidicon can be seen. The video amplifier is also visible. A small microphone and transformer are located at the rear. This permits the operator to carry on a com-

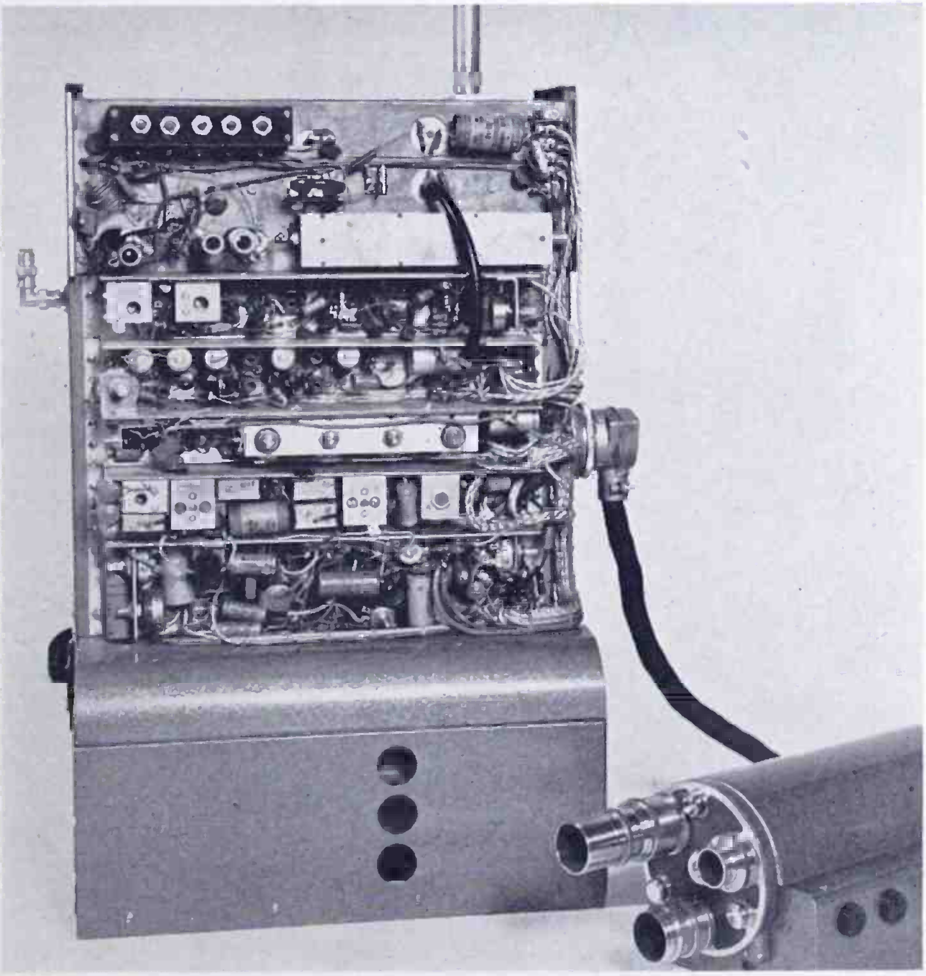

Fig. 8—Circuit side of pack.

mentary while using the view finding monitor. A cable-connected microphone may also be used if desired. A view of the monitor side of the camera is shown in Figure 12. Here the monitor tube, viewing eyepiece and driver amplifier can be seen.

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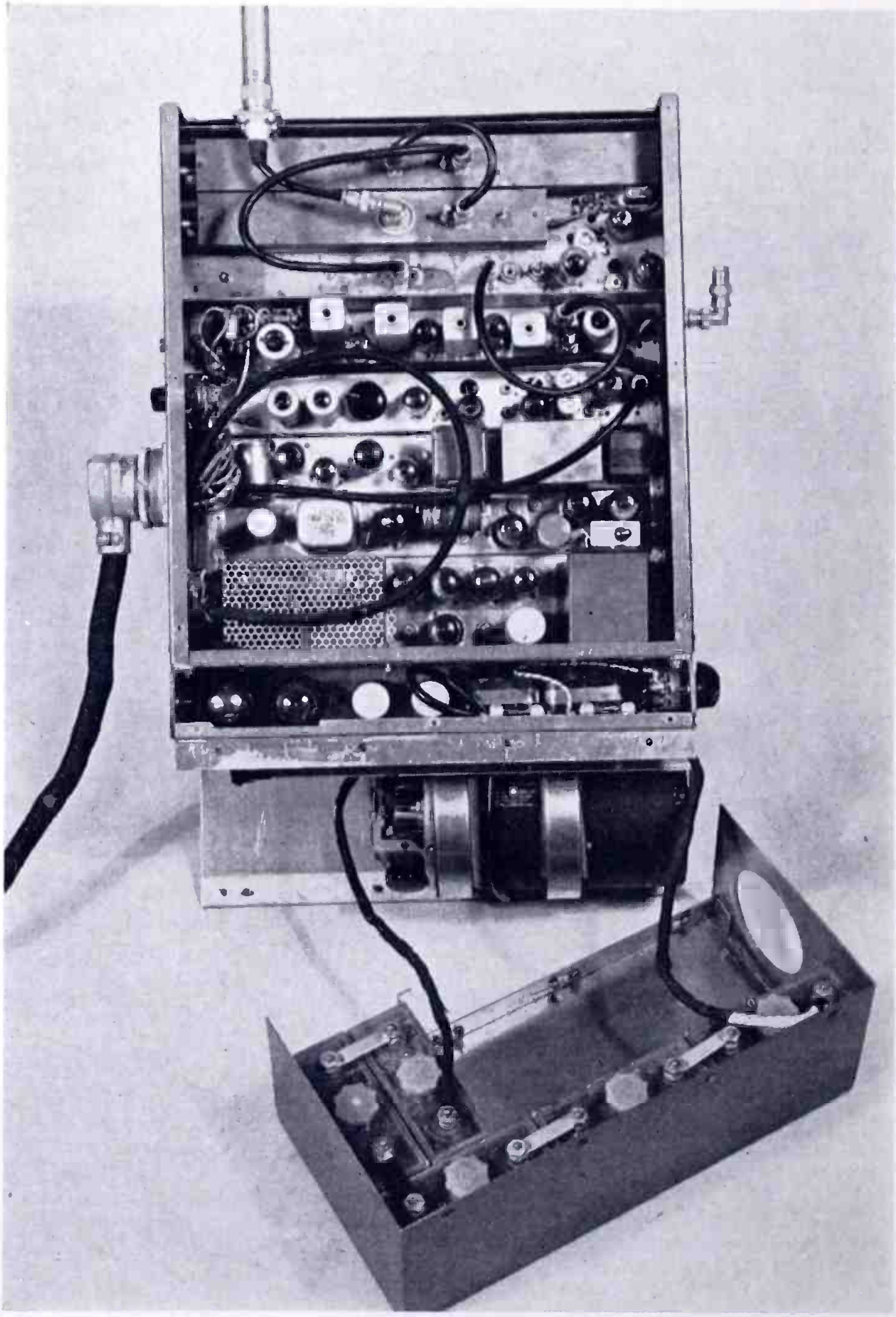

Fig. 9—Tube side of pack.

Control Equipment

A block diagram of the equipment at the control point is shown in Figure 13. Here the signal from the remote transmitter is received on a UHF television receiver. After the signal passes the second de-

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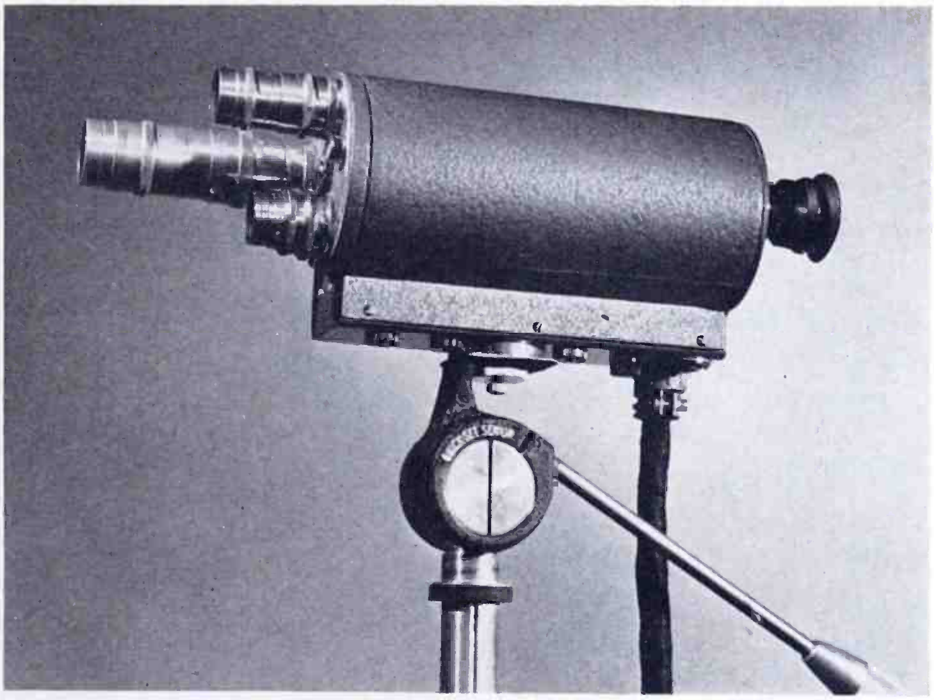

Fig. 10—Assembled camera.

tector it is passed through a synchronizing separator. This separator must be of a rather wider band width than normally used, in order to maintain the rise and fall of the horizontal sync pulses which carry the sound information. The video minus the sync pulse is recovered from one channel while the sync pulse carrying the sound on its trailing edge is recovered from the other. It should be pointed out that no vertical synchronizing is transmitted, so that no problem of separating vertical from horizontal pulses exists. The horizontal pulses are passed into the sound separator which integrates the pulses in a low-pass filter to recover the sound while the unmodulated leading edge is

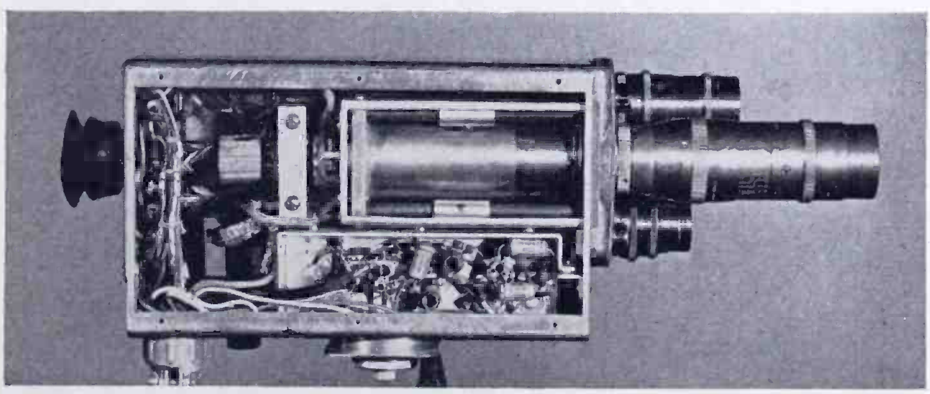

Fig. 11—Camera with side cover removed (Vidicon side).

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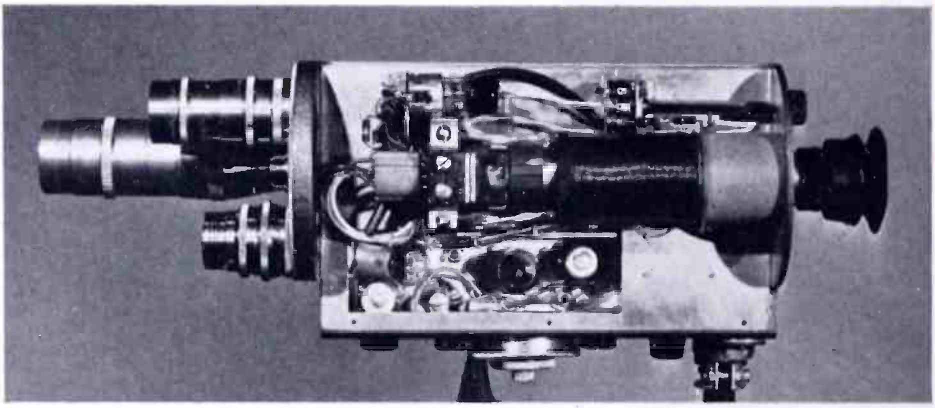

Fig. 12—Camera with side cover removed (monitor side).

recovered by differentiation and clipping in another channel. This signal from the leading edge is then used to lock the line frequency of another synchronizing generator. Horizontal and vertical pulses are supplied by this local generator and may then be shaped and processed as desired after which they may be mixed with the video signal to provide a composite video signal to any desired specifications. The

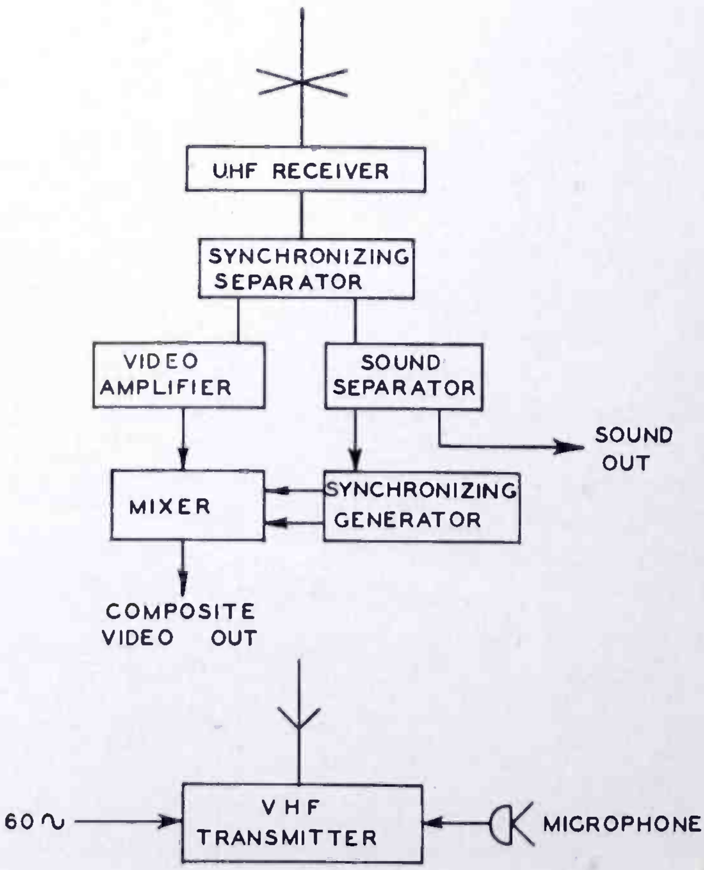

Fig. 13—Block diagram of control equipment.

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order transmitter is frequency modulated by voice for instructions and amplitude modulated by a 60-cycle reference frequency as described previously. A photograph of the equipment at the control station is shown in Figure 14.

In outdoor tests the equipment has given good performance over distances up to a quarter mile with simple antennas. Sufficient tests

Fig. 14—Control equipment.

have been made over a period of several months to indicate that this equipment will transmit a satisfactory picture with good reliability under conditions which might be encountered in practical use.

Acknowledgment

The authors wish to express their appreciation for the continued inspiration and encouragement of V. K. Zworykin, under whose direc-

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tion the work was done, and for the contribution of Lars Person, who was largely responsible for the sound modulator used. Thanks are also due to H. F. Olson and John Preston for the special microphones used, and to F. H. Nicoll for the special monitor tube. The pencil triode circuits used in the transmitter are from a design by G. M. Rose.

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DESIGN DATA FOR HORIZONTAL RHOMBIC ANTENNAS*

By

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Summary—*The practical difficulties of determining the complete radiation patterns for horizontal rhombic antennas at a number of working frequencies are discussed. A method of design is described which greatly reduces the labor of computation, using tables giving the spherical coordinates for all pattern lobes for a free-space rhombic radiator through those of the sixth order. With this data, the performance of a horizontal rhombic antenna over a range of working frequencies can be investigated with a minimum of engineering effort. Stereographic design charts of the type suggested by Donald Foster in 1937 are then introduced and described for computing the complete radiation pattern. Sets of these transparent charts for leg lengths from 2 to 7 wave lengths are described. These cover the usual practical range of design parameters and can be used for engineering design purposes.*

INTRODUCTION

THE horizontal rhombic antenna is used extensively throughout the world for high-frequency transmission and reception. It is structurally simple but its design is a relatively complicated procedure, due largely to the enormous labor of computation to determine its complete radiation pattern. Most engineering methods provide information on the main lobe of the pattern at one frequency. This information is insufficient because it omits consideration of other lobes that can be, and often are, very large and which greatly compromise its performance.

The popularity of the horizontal rhombic antenna is due to its relatively low cost, and to the fact that it is essentially aperiodic when matched in its characteristic impedance at the distant end. This permits it to be used for more than one operating frequency. However, there is no relation between its input impedance characteristics and its radiation characteristics, and only the radiation characteristics determine the useful range of operating frequencies for a horizontal rhombic antenna.

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* Decimal Classification: R325.5.

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In order to determine the significant radiation characteristics for a horizontal rhombic antenna over a band of frequencies, the designer must examine the orientations and amplitudes of several of the secondary radiation lobes as well as the main lobe at each operating frequency. Data and charts are presented here which enable the designer to perform the necessary computations with a minimum of effort. By means of the tables given, secondary lobes through those of the sixth order can be computed with adequate engineering accuracy. Higher order lobes of the complete pattern are usually negligible for ordinary practical purposes, assuming the antenna is properly built and properly terminated. By means of the stereographic charts, the essential geometric parameters and the resulting patterns for a horizontal rhombic antenna can be determined with ease.

The charts were prepared according to the method described by Foster[1] who explains their theory and construction. Tables II to VII were compiled by using large-scale charts.

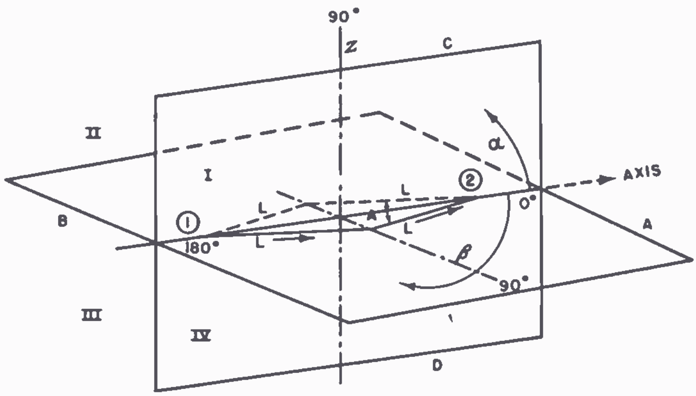

Fig. 1—Coordinate system for a rhombus in free space.

The Rhombic Element

Figure 1 represents the coordinate system for a rhombic element in free space. The rhombus lies in the plane A-B, and the normal plane C-D is the principal vertical plane along the axis, which is the intersection of the two planes. The rhombus has two controlling parameters; the leg length *L*, and the acute angle *A*. Pure unattenuated traveling waves are assumed to enter the system at the rear apex (1) and flow toward the front apex (2), where the matching impedance is located.

Radiation patterns for the rhombus are symmetrical in quadrants I and II, and likewise in quadrants IV and III. The angle α, ranging

[1] Donald Foster, "Radiation from Rhombic Antennas," *Proc. I.R.E.*, Vol. 25, p. 1327, October, 1937.

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from 0 to 90 degrees, always represents the angle of elevation with respect to the plane A-B. The angle β is an azimuth angle, ranging from 0 to 180 degrees, measured from the forward axis.

The radiation pattern for each leg is a function of its length in wave lengths. The radiation pattern for the rhombus is a composite of the patterns for the individual legs and the geometry of the rhombus.

The free-space radiation pattern for a single leg, which is a straight conductor guiding a unidirectional wave, consists of a number of cones of radiation centered on the conductor as an axis. There is a cone, or lobe, of radiation for each half-wave length of conductor length. Half of the lobes tilt forward in the direction of the wave movement in the conductor, and the other half tilt backward. Between these successive lobes of radiation there are conical zones of zero radiation. Table I gives the angles of maximums and zeros for straight conductors from 2 to 7 wave lengths long as a function of the angle to the conductor θ. There is always a zero in the direction of the conductor.

Table I also gives the amplitudes (E) of the successive lobes in terms of field strength relative to that of the first (principal) lobe. These relations are correct for each leg length, but not for comparison with the amplitudes of lobes for different leg lengths.

The composite free-space pattern for a traveling-wave rhombus is the result of interference between the patterns for the individual legs as a result of their spacial separations, and their mutual orientations. The multiplicity of lobes in the leg patterns causes a large number of lobes in the composite pattern, and interference effects in space give each lobe a different orientation in azimuth and elevation. When the rhombus is placed above a reflecting surface, such as the earth, interference with the image pattern further complicates and modifies the basic pattern. If arrays of horizontal rhombic elements are used, still higher orders of complication are introduced by additional interference effects. The complete solution of such patterns for practical antenna designs by conventional methods involves an enormous amount of skillful computation, and is seldom attempted.

Reference Data for Computing the Complete Free-Space Pattern of a Rhombus

The essential information on the complete pattern for a rhombic element can be limited to a determination of the coordinates and relative amplitudes of the main and the various secondary lobes. The

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Table I — Angles of Maximums and Zeros in the Free-Space Pattern for a Straight Wire With Traveling Waves

Order of Maximum or Zero	$L = 2\lambda$		$L = 3\lambda$		$L = 4\lambda$		$L = 5\lambda$		$L = 6\lambda$		$L = 7\lambda$	
	θ	E	θ	E	θ	E	θ	E	θ	E	θ	E
M-1	35.0	1.00	29.0	1.0	25.5	1.00	22.7	1.00	20.5	1.00	18.9	1.0
M-2	74.	0.426	58.	0.460	50.	0.479	45.	0.505	41.	0.520	37.	0.536
M-3	104.	0.252	80.	0.300	67.	0.340	60.	0.360	53.	0.383	49.	0.394
M-4	137.	0.127	99.	0.216	82.	0.251	73.	0.280	65.	0.305	59.	0.314
M-5			120.	0.153	97.	0.195	84.	0.228	75.	0.250	68.	0.264
M-6			147	0.076	112	0.149	96	0.182	85	0.207	76	0.226
M-7					129	0.107	108	0.148	94	0.175	86	0.190
M-8					151	0.058	120	0.118	106	0.146	94	0.165
M-9							134	0.086	116	0.121	102	0.145
M-10							153	0.050	127	0.097	111	0.124
M-11									139	0.066	120	0.103
M-12									155	0.044	130	0.083
M-13											141	0.063
M-14											157	0.037
0-0	0		0		0		0		0		0	
0-1	60		48		42		37		33		31	
0-2	90		70		59		52		47		44	
0-3	120		90		74		66		59		54	
0-4	180		110		90		78		70		63	
0-5			132		105		90		81		73	
0-6			180		121		102		90		81	
0-7					139		114		99		90	
0-8					180		127		110		98	
0-9							142		122		106	
0-10							180		147		116	
0-11									180		135	
0-12											148	
0-13												
0-14											180	

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shapes of the secondary lobes are not usually important for practical design purposes.

Tables II to VII list the azimuths (β) and elevations (α) of the principal and the secondary lobes in the complete radiation pattern for a rhombus in free space. They are for leg lengths from 2 to 7 wave lengths in steps of one wave length, and the acute angle (A) of the rhombus in steps of 5 degrees from 35 to 60 degrees. These limits embrace most of the values of practical interest. Intermediate data can be found by interpolation. The orientations listed have an accuracy of about 1 degree.

Table II — Orientation of Pattern Lobes for Free-Space Rhombus when $L = 2\lambda$ (in degrees)

For 2nd Side		Order of Maximums For 1st Side: 1		2		3		4	
		β	α	β	α	β	α	β	α
A = 71°	1	0	0	34	36	71	8	—	—
	2			0	70	88	64	108	24
	3					180	107	146	43
	4							180	155
A = 65°	1	0	16	38	36	—	—	—	—
	2			0	71	88	82	107	9
	3					180	107	142	43
	4							180	30
A = 60°	1	0	20	41	35	—	—	—	—
	2			0	72	88	59	—	—
	3					180	107	140	42
	4							180	33
A = 55°	1	0	24	43	33	—	—	—	—
	2			0	72	89	56	—	—
	3					180	107	138	41
	4							180	34
A = 50°	1	0	27	47	29	—	—	—	—
	2			0	72	89	52	—	—
	3					180	106	134	38
	4							180	37
A = 45°	1	0	28	50	24	—	—	—	—
	2			0	73	89	47	—	—
	3					180	106	131	35
	4							180	38
A = 40°	1	0	30	53	13	—	—	—	—
	2			0	73	89	40	—	—
	3					180	105	127	29
	4							180	39
A = 35°	1	0	32	—	—	—	—	—	—
	2			0	73	89	26	—	—
	3					180	105	124	19
	4							180	40

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The relative amplitudes of the lobes given in Table VIII are idealized values for unattenuated traveling waves in the system. In practice there is attenuation, and also some standing waves, which are unpredictable, and which modify the lobe amplitudes. However, the idealized data are the only firm values available for the study and appraisal of a design.

Each pattern lobe is caused by the coincidence of a maximum in the pattern for one pair of parallel legs with a maximum in the pattern for the other pair of parallel legs of the rhombus. For example, the peak of the lobe 3-4 occurs where the 3rd maximum (M-3) for one side coincides with the 4th maximum (M-4) for the other side. This occurs at some azimuth angle β and some elevation angle α that is not in the principal vertical plane. The coincidence of the 1st maximums for each side gives the main lobe (1-1), which has its peak in the principal vertical plane where $\beta = 0$. All intersections of lobes of equal order fall in the principal vertical plane, and it is only in this plane that the radiated fields are horizontally polarized. All intersections of lobes of unequal order occur outside of this plane, and the fields have both horizontally and vertically polarized components.

The tables of lobe orientations are used by choosing the order of maximum for one leg and the order of maximum for the second, for each value of A. The azimuth and elevation of the resulting lobes are then read from the table. Table VIII gives their relative field strengths with respect to the main lobe. The relative amplitudes are valueless if the rhombus parameters are such that the two first maximums do not coincide and therefore do not form the main lobe. Table VIII is to be used only when the main lobe exists and is fully formed.

In Tables II to VII the dashes put in place of a number indicate that the relevant first maximums do not intersect and that a resulting main lobe does not exist or is degenerate. Special caution should be exercised in those cases where the main lobe is shown not to exist, because then the main lobe has disintegrated to a mere vestigial form, or may be completely split by a zero on the principal plane at the lower angles. This indicates an impractical design that should always be avoided.

Table VIII shows that lobes due to intersections of maximums of order greater than the fifth are of vanishing importance. However, as a practical engineering fact, it is impossible to build and adjust a rhombic antenna that is completely free of reflections from side angles and terminal load, so there are always some standing waves. These standing waves greatly augment the smaller backward lobes. For this

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reason it is safer to assume that no lobe is smaller than 34 decibels below the amplitude of the main lobe (0.02) under the best practical conditions.

Table III — Orientation of Pattern Lobes for Free-Space Rhombus when $L = 3\lambda$ (in degrees)

For 2nd Side		Order of Maximums — For 1st Side: 1		2		3		4		5		6	
		β	α	β	α	β	α	β	α	β	α	β	α
A = 65°	1	—	—	22	27	46	26	—	—	—	—	—	—
	2			0	52	38	59	71	49	89	21	—	—
	3					0	78	89	73	107	49	—	—
	4							180	79	141	60	133	31
	5									180	53	158	32
	6											180	7
A = 60°	1	—	—	24	28	49	22	—	—	—	—	—	—
	2			0	53	41	58	73	46	90	0	—	—
	3					0	78	89	72	106	46	—	—
	4							180	79	137	59	130	27
	5									180	55	157	33
	6											180	15
A = 55°	1	0	9	27	29	52	17	—	—	—	—	—	—
	2			0	54	44	57	74	42	—	—	—	—
	3					0	78	89	69	104	42	—	—
	4							180	80	135	58	127	22
	5									180	56	154	33
	6											180	19
A = 50°	1	0	15	29	29	29	0	—	—	—	—	—	—
	2			0	55	47	57	86	36	—	—	—	—
	3					0	79	89	68	103	36	—	—
	4							180	80	132	57	125	14
	5									180	57	152	33
	6											180	22
A = 45°	1	0	19	32	27	—	—	—	—	—	—	—	—
	2			0	56	50	54	78	28	—	—	—	—
	3					0	79	89	65	102	28	—	—
	4							180	80	128	56	—	—
	5									180	57	148	33
	6											180	25
A = 40°	1	0	22	36	25	—	—	—	—	—	—	—	—
	2			0	57	54	52	79	5	—	—	—	—
	3					0	79	89	62	110	5	—	—
	4							180	80	125	53	—	—
	5									180	57	145	30
	6											180	27
A = 35°	1	0	23	40	20	—	—	—	—	—	—	—	—
	2			0	57	58	48	—	—	—	—	—	—
	3					0	80	89	58	—	—	—	—
	4							180	80	122	48	—	—
	5									180	58	142	27
	6											180	28

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Main Lobe Angles

Figure 2 shows how the elevation of the main lobe of a rhombus varies with leg length and the acute angle. There is a value of A where the two first maximums intersect in the plane of the rhombus

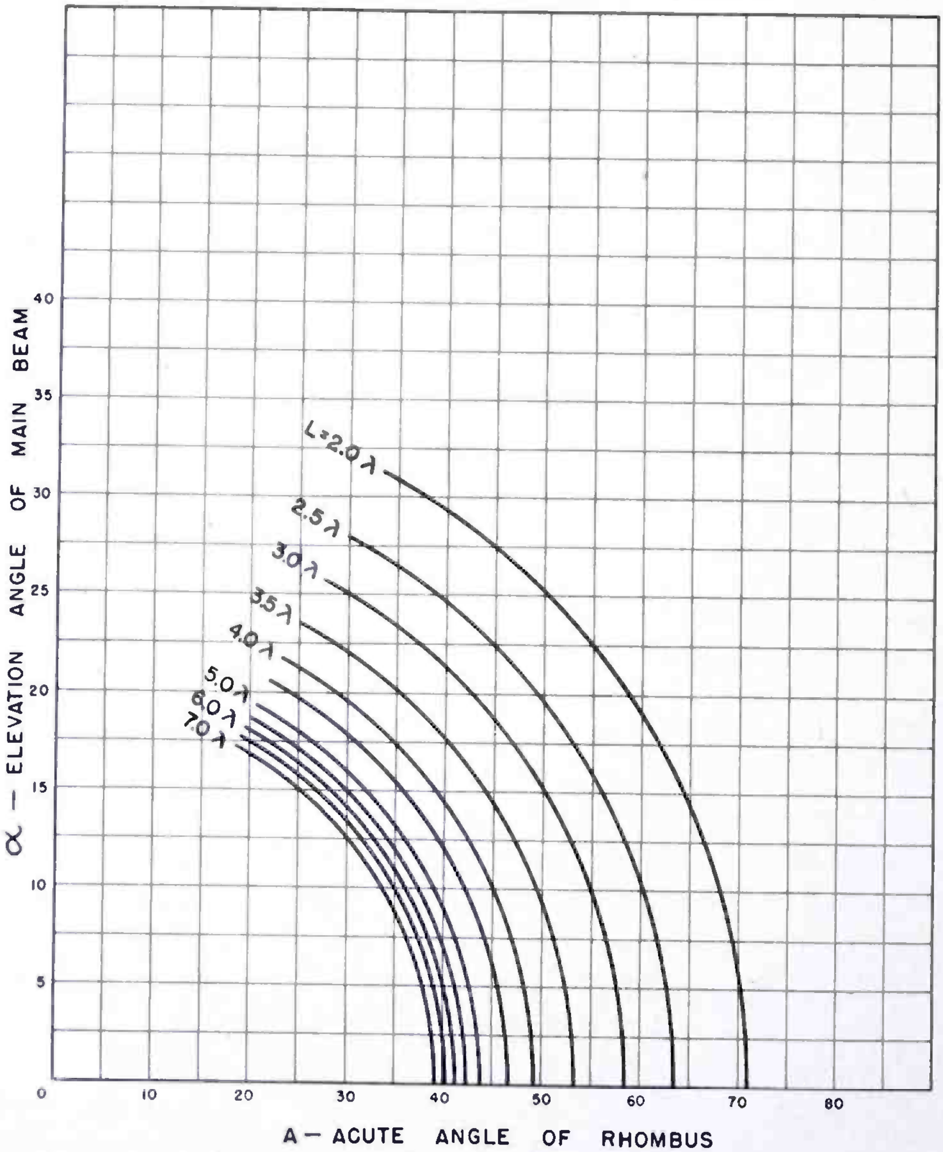

Fig. 2—Main-beam elevation with respect to the plane of a rhombus in free space.

where the main lobe has the coordinates $\alpha = 0$, $\beta = 0$. This value of A is exactly twice the angle θ for the first maximum for the single-leg pattern. When A exceeds this limiting value the main lobe disintegrates, and finally splits into two side lobes as A increases. This is what may happen when a given rhombus, designed for one frequency, is used at a much greater frequency.

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Special attention is directed to the very rapid variation of α with A for low main-lobe angles. When a low-angle lobe is desired, the value of A becomes very critical. This also implies that such an antenna would have almost no tolerance in the direction of higher frequencies, for which the electrical leg length of a fixed structure would be increasing, with the main beam tending to split.

Figure 2 also reveals the variation of the main lobe angle with

Table IV — Orientation of Pattern Lobes for Free-Space Rhombus when $L = 4\lambda$ (in degrees)

		Order of Maximums											
		For 1st Side											
For 2nd Side		1		2		3		4		5		6	
		β	α	β	α	β	α	β	α	β	α	β	α
A = 60°	1	—	—	17	21	35	24	52	11	—	—	—	—
	2			0	42	23	50	48	48	69	36	—	—
	3					0	63	40	67	74	58	90	41
	4							0	81	88	76	105	58
	5									180	82	140	68
	6											180	64
A = 55°	1	—	—	18	23	37	23	—	—	—	—	—	—
	2			0	44	25	50	51	46	71	30	—	—
	3					0	64	42	67	75	56	90	36
	4							0	81	88	74	104	56
	5									180	82	137	67
	6											180	65
A = 50°	1	—	—	21	24	41	19	—	—	—	—	—	—
	2			0	45	27	50	54	44	73	20	—	—
	3					0	64	45	66	77	52	90	27
	4							0	81	88	73	102	52
	5									180	82	134	66
	6											180	65
A = 45°	1	0	10	23	25	44	12	—	—	—	—	—	—
	2			0	46	30	50	57	40	—	—	—	—
	3					0	65	48	65	78	47	99	10
	4							0	81	89	70	101	47
	5									180	82	130	65
	6											180	66
A = 40°	1	0	14	26	24	—	—	—	—	—	—	—	—
	2			0	47	34	48	61	34	—	—	—	—
	3					0	65	52	63	80	41	—	—
	4							0	81	89	68	100	42
	5									180	82	127	64
	6											180	66
A = 35°	1	0	17	29	22	—	—	—	—	—	—	—	—
	2			0	48	37	47	64	24	—	—	—	—
	3					0	65	55	61	81	31	—	—
	4							0	81	89	64	98	33
	5									180	82	123	61
	6											180	66

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frequency for a structure of fixed size and acute angle. For constant A, the locus of variation with electrical leg length is a vertical line running across the various curves. This variation of lobe angle with frequency is an important factor in high-frequency applications, where a fixed structure designed for one optimum frequency is to be used over a range of frequencies.

Table V — Orientation of Pattern Lobes for Free-Space Rhombus when $L = 5\lambda$ (in degrees)

For 2nd Side		Order of Maximums For 1st Side: 1 β	1 α	2 β	2 α	3 β	3 α	4 β	4 α	5 β	5 α	6 β	6 α
A = 60°	1	—	—	13	15	27	22	42	19	53	0	—	—
	2			0	36	17	44	35	45	52	41	67	29
	3					0	54	24	59	49	58	69	50
	4							0	69	42	72	74	66
	5									0	84	90	78
	6											180	84
A = 55°	1	—	—	15	18	30	22	44	15	—	—	—	—
	2			0	38	18	44	38	45	54	38	69	22
	3					0	55	27	60	52	57	71	47
	4							0	70	45	72	76	64
	5									0	84	91	78
	6											180	84
A = 50°	1	—	—	16	20	32	22	48	0	—	—	—	—
	2			0	39	20	45	41	43	58	34	71	0
	3					0	56	28	60	54	55	73	43
	4							0	71	47	72	77	62
	5									0	84	91	77
	6											180	84
A = 45°	1	0	0	18	22	36	18	—	—	—	—	—	—
	2			0	41	22	45	44	41	61	27	—	—
	3					0	57	32	59	58	52	75	36
	4							0	71	50	70	78	58
	5									0	84	91	76
	6											180	84
A = 40°	1	0	10	21	22	39	12	—	—	—	—	—	—
	2			0	42	25	45	48	37	64	14	—	—
	3					0	57	35	58	61	48	77	25
	4							0	72	54	69	80	54
	5									0	84	90	74
	6											180	84
A = 35°	1	0	14	24	22	40	0	—	—	—	—	—	—
	2			0	42	28	44	52	32	—	—	—	—
	3					0	58	39	57	64	43	—	—
	4							0	72	58	67	82	48
	5									0	84	90	71
	6											180	84

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The Horizontal Rhombic Antenna

A rhombic element whose plane is parallel to ground is called a horizontal rhombic antenna. When the ground is perfectly conducting (as usually assumed for design purposes) it acts as a perfect mirror surface. The pattern for the horizontal rhombic antenna is then the rhombus pattern multiplied by a height factor introduced by the mirror image.

Table VI—Orientation of Pattern Lobes for Free-Space Rhombus When $L = 6\lambda$ (in degrees)

For 2nd Side		Order of Maximums — For 1st Side: 1		2		3		4		5		6	
		β	α	β	α	β	α	β	α	β	α	β	α
A = 60°	1	—	—	10	7	22	19	34	20	45	14	—	—
	2			0	28	13	37	27	40	41	39	55	32
	3					0	46	17	52	35	53	53	49
	4							0	61	23	65	50	63
	5									0	72	45	74
	6											0	85
A = 55°	1	—	—	11	13	25	20	37	18	47	0	—	—
	2			0	31	14	38	29	40	43	37	57	28
	3					0	47	19	52	37	52	56	47
	4							0	62	26	65	53	62
	5									0	73	46	64
	6											0	85
A = 50°	1	—	—	13	17	26	21	39	15	—	—	—	—
	2			0	33	15	39	32	40	47	15	60	21
	3					0	48	21	53	41	51	59	44
	4							0	62	28	65	56	60
	5									0	73	49	74
	6											0	85
A = 45°	1	—	—	14	19	28	20	43	6	—	—	—	—
	2			0	34	17	40	35	38	50	30	63	5
	3					0	49	23	53	44	50	62	40
	4							0	62	30	64	59	58
	5									0	73	52	72
	6											0	85
A = 40°	1	0	5	16	20	32	17	—	—	—	—	—	—
	2			0	36	20	40	39	36	54	23	—	—
	3					0	60	26	53	47	47	65	33
	4							0	63	34	64	63	55
	5									0	74	57	71
	6											0	85
A = 35°	1	0	11	18	21	35	10	—	—	—	—	—	—
	2			0	37	22	40	43	33	57	2	—	—
	3					0	51	29	52	51	44	67	22
	4							0	63	38	63	66	50
	5									0	74	60	69
	6											0	85

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Height factor $= f(\alpha) = \sin (H \sin \alpha)$, expressed in terms of relative field strengths. This factor is independent of azimuth. For each half wave length (180 degrees) in the height H there is a lobe in the height factor. When $H < 180°$, $f(\alpha)$ has but one lobe that varies in shape until, for H very small, it approaches a tangent sphere in shape. It is usually drawn in figures as a tangent circle. There are zeros between successive lobes in the height factor.

Table VII—Orientation of Pattern Lobes for Free-Space Rhombus When $L = 7\lambda$ (in degrees)

For 2nd Side		Order of Maximums — For 1st Side: 1		2		3		4		5		6	
		β	α	β	α	β	α	β	α	β	α	β	α
A = 60°	1	—	—	—	—	18	15	28	19	48	17	48	8
	2			0	23	10	32	21	37	33	37	45	35
	3					0	42	12	47	27	49	41	48
	4							0	54	16	58	34	59
	5									0	64	24	68
	6											0	75
A = 55°	1	—	—	10	7	20	18	31	19	42	14	—	—
	2			0	27	11	34	23	37	36	36	48	32
	3					0	43	14	47	29	49	44	47
	4							0	55	18	58	37	59
	5									0	65	27	68
	6											0	76
A = 50°	1	—	—	11	13	22	19	33	17	45	0	—	—
	2			0	29	13	36	26	37	39	35	51	27
	3					0	44	15	48	31	49	47	46
	4							0	56	20	59	41	58
	5									0	66	29	68
	6											0	76
A = 45°	1	—	—	12	16	24	19	37	13	—	—	—	—
	2			0	31	14	36	28	37	42	33	54	20
	3					0	45	17	49	34	48	50	43
	4							0	56	22	59	43	67
	5									0	66	32	68
	6											0	76
A = 40°	1	—	—	13	18	27	17	—	—	—	—	—	—
	2			0	32	16	37	32	36	47	27	57	0
	3					0	46	20	49	38	36	54	38
	4							0	57	24	59	48	55
	5									0	67	35	67
	6											0	76
A = 35°	1	0	8	16	19	31	14	—	—	—	—	—	—
	2			0	33	18	37	36	33	50	19	—	—
	3					0	47	22	49	42	44	57	32
	4							0	48	27	58	52	52
	5									0	67	40	66
	6											0	76

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Table VIII—Relative Field Strengths of Lobes in Radiation Pattern for Rhombus in Free Space

For 2nd Side	Order of Maximums For 1st Side 1	2	3	4	5	6
1	1.000					
2	0.544	0.26				
3	0.420	0.038	0.003			
4	0.354	0.007	0.00054	0.0001		
5	——	0.002	0.000156	0.000028	10^{-6}	
6	——	——				

There are an unlimited number of choices of the height of a rhombic antenna, each causing a different effect on the radiation pattern, so that there are no unique conditions that can be tabulated in the manner of the free-space rhombus pattern. It is therefore necessary to compute the effect of the height factor on the 3-dimensional pattern for each electrical height H.

Figure 3 shows the elevation angles of unity (maximums) and zeros in the height factor. When applied to a horizontal rhombic antenna, the best radiation efficiency is obtained when the first maximum in the height factor occurs at the same elevation angle as that of the main lobe in the rhombus pattern. It is most desirable that this angle should also be the optimum angle of propagation for the space radio path. However, for a fixed physical height, size, and shape of antenna, the variation of the angle of the first maximum in the height factor does not follow the variation in the angle of the free-space rhombus as frequency is varied, even though the directions of the variations are the same. The result is that the height-factor maximum does not track the rhombus maximum for any considerable change of frequency.

The height factor is always zero at $\alpha = 0$, so that any rhombus lobes occurring at $\alpha = 0$ are suppressed. Any rhombus lobes occurring at elevation angles corresponding to zeros in the height factor are also suppressed, or split into much smaller pairs of lobes. Any rhombus lobes occurring at elevation angles corresponding to maximums (relative value unity) in the height factor remain unchanged in amplitude or orientation. Other rhombus lobes occurring at elevation angles where the height factor has values anywhere between 1.0 and 0 are reduced to the value which is the product of the relative amplitudes of the rhombus lobe and the height factor at that elevation angle. The rhombus lobe amplitudes are read from Tables II to VII, and the value of $f(\alpha)$ at any angle is computed from the equation for the height factor.

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In dealing with only the peaks of the rhombus lobes, there often is a small error caused by a shift in the orientation and amplitude of a lobe where the actual pattern for the rhombus lobe is diminishing while the height factor is increasing with α, or vice versa. However, this is usually negligible as a design factor except when the main lobe is involved.

By this method, therefore, one can quickly determine all the essential values of a pattern for a horizontal rhombic antenna of chosen dimensions at any given frequency by working only with the peaks of the various lobes up through those of sixth order. By repeating this analysis for several different frequencies the performance over a band of frequencies can be evaluated.

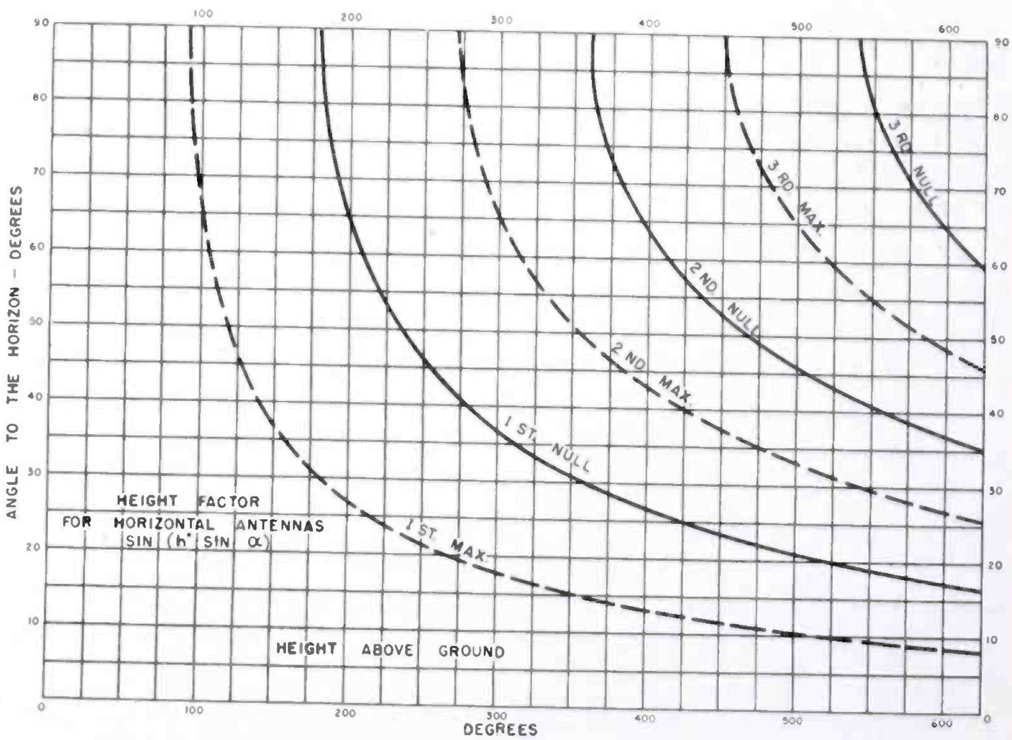

Fig. 3—Angles of maximums and zeros in the height factor for a horizontal antenna.

The principal fault with rhombic antennas, in common with all long-wire types, is that there are inevitably a multiplicity of secondary lobes. The best design is one where the desired main lobe is properly oriented for the propagation path and all other lobes reduced as far as possible. The largest lobes are seen from Table VIII to be those formed by the intersection of the first maximum for one leg pattern with the second and higher order maximums for the other leg pattern. In practical rhombic antennas the first maximum for one side never crosses maximums higher than the fourth for the other side.

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The largest secondary lobes are usually the pair 1-2. By proper choice of A, it is possible to have their elevation occur at an angle about twice that of the main lobe. This condition usually brings the next pair of side lobes (1-3) at or near zero elevation. By choosing a height H to bring the first maximum in the height factor at the elevation of the main lobe, the first zero in the height factor will be at or very near to the elevation of the 1-2 lobes, and they are suppressed quite completely. At the same time, the 1-3 lobes, at 0° elevation, are

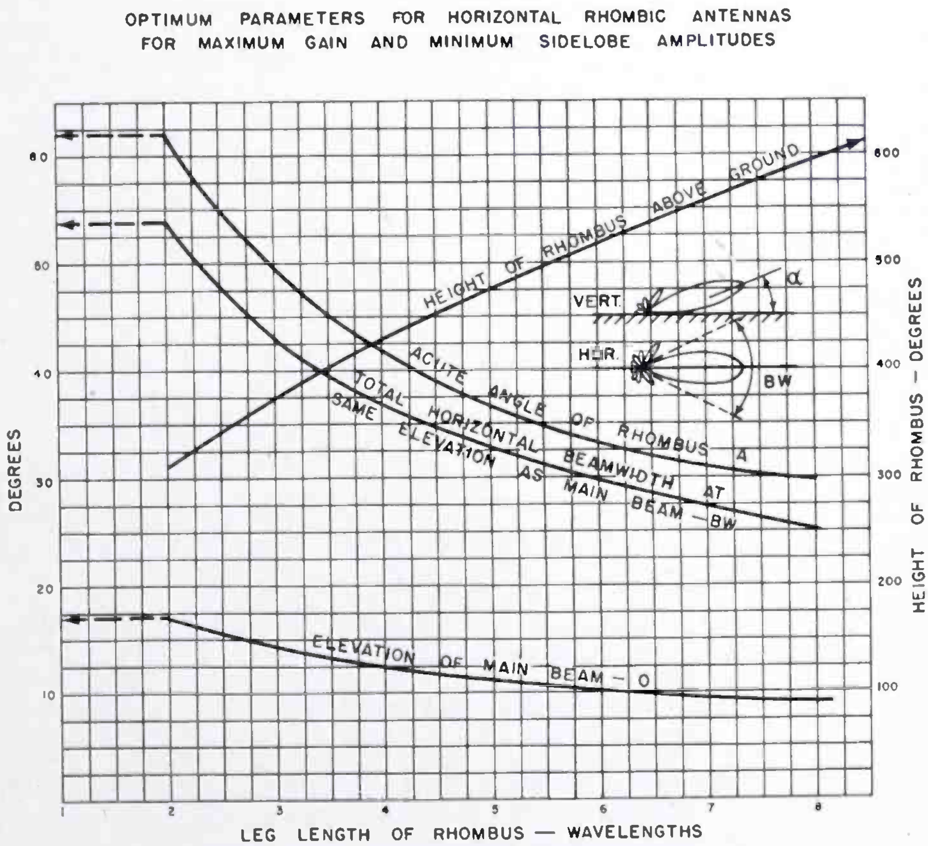

Fig. 4—Parameters and principal characteristics for horizontal rhombic antennas of optimum design.

suppressed by the zero in the height factor at this angle. With the first two dominant pairs of side lobes suppressed in this way, the resultant pattern for the horizontal rhombic antenna is the cleanest possible. The gain in the main beam is therefore at its maximum. This interesting case was found and explained by Foster. This particular condition prevails for one frequency only, or a very narrow band of frequencies near the optimum. The parameters for optimum designs of this type are shown in Figure 4. The word "optimum" in this regard pertains solely to the horizontal rhombic antenna as a

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radiator, and does not include any considerations of propagation requirements, or how well it would fit the requirements of any particular radio path. However, where the main lobe characteristics fit the propagation requirements, this optimum design is to be preferred.

SAMPLE CALCULATIONS

The application of this data for the design analysis of a horizontal rhombic antenna of one element will be made clear by the following examples.

Assume that a rhombic antenna is wanted that will have its main beam at an angle $\alpha = 12.5$ degrees at a specified frequency f_o. In order to take advantage of an optimum design at this frequency, Figure 4 is used and the following dimensions are read:

Leg length	$L = 4\lambda$
Acute angle	$A = 42$ degrees
Height	$H = 423$ degrees (1.18λ)
Total beam width	$BW = 37$ degrees between first zeros.

This optimum design is known to suppress lobes 1-2 and 1-3 at the frequency f_o, leaving vestigial lobes of a low order of amplitude that are relatively negligible.

The height factor for this array at f_o is

$$f(\alpha) = \sin (423 \sin \alpha).$$

There are maximums in this height factor at

$423 \sin \alpha = 90$ and 270 degrees, and zeros at
$423 \sin \alpha = 0$, 180 and 360 degrees.

These can be computed or read from Figure 3 which shows that two maximums occur at 12.5 and 39.5 degrees, and three zeros at 0, 25 and 57 degrees.

Table IV for $L = 4\lambda$ shows that one must interpolate between the values for $A = 40$ and $A = 45$ to find the coordinates of the various lobes of the 42-degree rhombus. The facts about lobes 1-1, 1-2 and 1-3 are already known sufficiently from the characteristics of the optimum design. There are no higher order lobes formed with M-1 for one side only. The next lobe of interest is 2-2, occurring at 46.5 degrees at zero

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azimuth. At this point the height factor lies between a maximum (39.5 degrees) and the next zero (57 degrees) so its value at 46.5 degrees is computed to obtain

$$\sin (423 \sin 46.5) = 0.788.$$

The relative amplitude for the lobe 2-2, from Table VIII is 0.26. With the height factor, this becomes $0.26 \times 0.788 = 0.20$.

In the same way the other lobes are examined, and one obtains: lobe 2-3, 0.023; lobe 2-4, 0.00049; lobe 3-3, 0.0014. Other lobes are smaller, and need not be studied. For engineering purposes it will be assumed that no lobe is less than 0.02 (—34 decibels).

The next step is to determine the high-frequency limit of this antenna. In order not to split the main beam, Figure 2 shows that when $A = 42$ degrees the greatest leg length that can be used is 5.5λ, at which length the main beam is at 3 degrees. At this corresponding frequency, the electrical height changes to 581 degrees. The first maximum for this height is at 8.5 degrees and the height factor at 3 degrees is 0.512. Since the height factor is increasing slowly between 3 and 8 degrees while the rhombus beam is decreasing rapidly in this range, one can estimate that their continuous product would give a maximum at about 4 degrees with a relative amplitude of about 0.75. The first zero in the height factor is at $\alpha = 17.5$ degrees. Interpolating between Tables V and VI, and between $A = 40$ and 45, shows the lobe 1-2 at $\alpha = 21$ degrees. The height factor at this angle is 0.515. The lobe 1-2 is 0.544, so their product is 0.28. After normalizing the main lobe, the ratio of lobe 1-2 changes from $0.28/0.75 = 0.374$, to 0.50 (—6 decibels). This is a large side lobe and one would consider it to be intolerable. Therefore the frequency ratio 5.5/4.0 is too high for this antenna. If the same examination of the 1-2 lobe for $A = 5\lambda$ is made, its value is of the order of 0.20 at $\alpha = 22$ degrees, $\beta = 19.5$ degrees. The lobe 1-3 is found to be larger and of the order of 0.30 at $\alpha = 14.5$ degrees, $\beta = 38$ degrees. These lobes are rather large, being down only about 14 and 10.5 decibels respectively. It is a matter of engineering judgment to decide if a frequency ratio of 5/4 is admissible. The side-lobe amplitudes are not large in terms of power leakage so the gain would not be greatly increased by reducing them. However, from an interference standpoint, the pattern for this frequency is not good.

When computations of this kind are made for horizontal rhombic antennas one is impressed by the rapid increase in the major side lobes as the frequency departs from that which gives optimum performance. This leads to the conclusion that the range of frequencies that should be used with a horizontal rhombic antenna is very restricted. By

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omitting to study the complete radiation pattern, the designer may fail to discover the shortcomings of an antenna which has low efficiency in the desired direction, and which causes unnecessary interference toward or from other directions. The purpose for which one uses a directive antenna is to give the best possible radiation intensity in the desired direction and to reduce radiation or pickup as much as possible in all other directions.

Further Remarks on Rhombic Antennas

The majority of rhombic antennas in service use heights less than those that provide the optimum design. This places the first maximum in the height factor at an angle that may be much higher than the main lobe elevation for the free-space rhombus. The combined effect is to raise the main lobe and to decrease its unnormalized value. This in turn tends to give all other lobes a relatively larger value, making the radiation efficiency lower, the gain lower, and the spurious radiation higher. Initial economy may well prove to be unwise, a fact that is not evident from a study of the main lobe only.

Since the values of the main lobe at angles off its maximum are not available in tables, it is necessary to compute the shape of the main beam in the vertical plane for the free-space rhombus. The pattern for the rhombus in the principal vertical plane C-D is ideally

$$f_r(\alpha) = N \frac{\sin^2 \left[180\, L \left(1 - \cos \dfrac{A}{2} \cos \alpha \right) \right]}{1 - \cos \dfrac{A}{2} \cos \alpha}$$

where N is a normalizing factor for the main lobe, and L is the leg length in wave lengths.

By using the appropriate pair of charts for a leg length L, and setting them at a selected acute angle A, the elevation of the first zero above the main beam can be measured. This equation can then be applied to compute the vertical shape of the main lobe and the relative field strength at any angle up to the first zero. Then, multiplying this series of values for the main lobe by the series of values for the height factor for the chosen height, the peak of the resulting main lobe for the horizontal rhombic antenna can be located exactly. With this pivotal information, one proceeds as before to compute the relative values of the important secondary lobes, finally determining their value relative to that of the main lobe.

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This operation is tedious and slow for exploratory computations. It usually suffices for preliminary studies to determine, from the charts, the angle of the main lobe and the first zero above it, and, using polar or Cartesian coordinates, to sketch a curve to fit the known maximum and zero angles. One accustomed to working with radiation patterns can judge typical shapes well enough for an approach. The resulting function is then used with the height factor to solve for the angle and the amplitude of the main lobe for the antenna, and the relative amplitudes of other lobes.

Assume that a rhombic antenna of leg length 375 feet, acute angle of 40 degrees and height 65 feet is to be analyzed for performance at 13 megacycles. $L = 5\lambda$ and $H = 0.866\lambda = 312$ degrees. From Table V, the rhombus main beam peaks at 10 degrees. From Figure 3 it is seen that the height factor is 1.0 at 17 degrees (1st max.). With the 5λ charts the first zero is found to be at 32 degrees. If the height factor is plotted in rectangular coordinates and a probable pattern sketched in that has its maximum (unity) at 10 degrees and a zero at 32 degrees, the resultant maximum obtained by multiplying the two functions should occur at approximately 14 degrees, with an amplitude of about 0.9. (By precise computation it is 0.925 at 14.3 degrees before normalizing.)

Proceeding as outlined before, this antenna has normalized values of the important secondary lobes, and their orientations, as follows:

Lobe	Relative Amplitude	α	β
1-1	1.00	14	0
1-2	0.54	21	21
1-3	0.39	12	39
2-2	0.14	42	0
2-3	0.028	45	25
All others	0.02 (allowed)	—	—

One sees that this antenna must have low gain because of the large secondary lobes, and that considerable power is radiated in undesired directions.

Rhombic Antenna Arrays

The ordinary single-element horizontal rhombic antenna may be regarded as a free-space array of two antiphased rhombic elements with parallel planes spaced twice the height above ground. In reality its pattern is eliminated in the lower half space by the ground. The

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principle is the same when rhombic elements are stacked into multiplane arrays, or variously disposed in a common plane.

Computation of such patterns is made relatively easy if one regards the geometric center of each rhombic element, real or image, as an isotropic point source of radiation and computes the space pattern resulting from this array of isotropic radiators, taking into account the amplitude and phase differences in their excitation. The pattern for an array of isotropic sources is then multiplied by the pattern for the rhombic element used, to give the pattern for the rhombic array. When the rhombic elements are all parallel to ground, the image currents are inverted, and this fact is recognized in assigning an inverted polarity to the isotropic images.

It is very evident that high-angle lobes can be reduced or suppressed by stacking rhombic elements one above the other to provide more destructive interference for the higher lobes than is provided by the height factor of the single-element horizontal rhombic antenna.

Destructive interference can be applied to important side lobes (usually those at the lower elevation angles around the main lobe) by coplanar rhombic elements spaced along a common major axis, or side by side along a common minor axis, or both. The elements may overlap or not, according to the choice of spacing parameters for their centers. Christiansen[2] has shown how such arrays of rhombic elements can provide relatively clean radiation patterns, comparable to broadside dipole arrays, but with the additional feature of aperiodicity, which is one of the most desired properties of rhombic antennas. In taking advantage of aperiodicity, a compromise choice is necessary to accommodate favorably a band of frequencies. The engineering of such arrays becomes a formidable task, although the method of computation given here minimizes the labor involved in computing the patterns.

Rhombic-Antenna Design Charts

Thirteen transparent charts for computing rhombic antenna patterns have been drawn up. There are pairs of charts for rhombus leg lengths of 2, 3, 4, 5, 6 and 7 wave lengths. Two such charts are reproduced in Figure 5.*

Each chart is a stereographic map of the radiation pattern for a straight wire in free space guiding a pure traveling wave. The arrow on the axis indicates the direction of the wave (current) flow. In

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[2] W. N. Christiansen, "Directional Patterns for Rhombic Antennae," *A.W.A. Tech. Rev.*, Vol. 7, p. 33, September, 1946.

* A complete set of 13 charts will be forwarded by RCA Review on request, free of charge.

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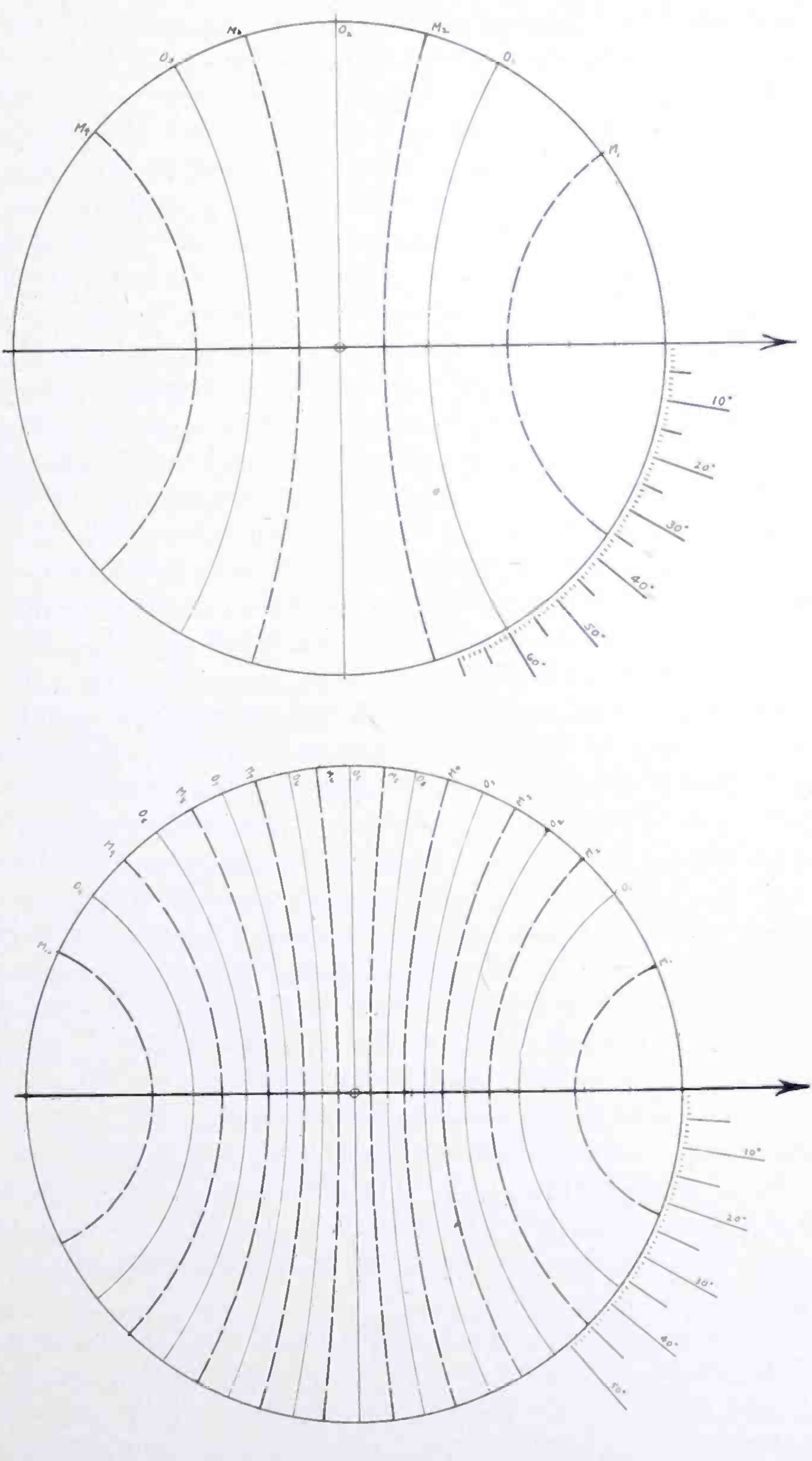

Fig. 5—Small-scale reproduction of stereographic patterns: above — for straight wire 2 wave lengths long; below — for straight wire 5 wave lengths long.

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stereographic projection, one looks down on the long wire and sees the enclosing hemisphere. The outer circle is the "horizon" in the plane of the wire, looking at it from the zenith. Each cone of radiation is a broken line, and each is numbered in sequence M1, M2, etc. starting with the main lobe nearest to the wire in the direction of current flow. Between successive lobes are cones representing the nulls, or directions of "zero" radiation. Actually, due to attenuation of current along the wire due to radiation and heat losses, these are minimums and not true zeros. They are numbered in sequence 01, 02, etc. starting with the zero between the first and second lobes. There is also a zero in the direction of the wire which can be called 00 if it requires identification.

Thus each chart is the radiation pattern for one leg of a rhombus. Since only the *angles* of maximums and zeros are shown, a chart also represents the maximum and zeros in the radiation pattern for two opposite parallel sides of a rhombus. Each chart has small cross lines on the axis which are in stereographic 10-degree intervals from 0 (the horizon circle) to 90 (the zenith and center). A circle drawn from the center represents an angle of constant elevation, or latitude, with respect to the horizon (equatorial) circle.

A separate chart is provided which is a stereographic hemisphere calibrated in latitude and longitude angles in 10-degree steps. Drawn to the same scale as the other charts, it is used as a cocentered overlay when one wishes to read the coordinates of any point of a pattern.

The radiation pattern for a rhombus in free space is obtained by setting two identical charts on the same centers with their axes at an angle that is the acute angle of the rhombus. The intersection of M1 on one chart with M1 of the other gives the maximum radiation lobe of the rhombic pattern, which lies in the principal vertical plane. There are other lobes of radiation where various orders of maximums for the two charts intersect, such as where M1 crosses M2.

There is a zero in the array pattern wherever there is a zero in the pattern for one leg. These zeros are lines (solid) associated with each chart. Zones between these zero lines are zones through which some radiation occurs, however small. The location of the null zones is a very important part of the design of the radiation patterns for practical use.

By changing the acute angle of the rhombus it can be seen that the angle of the main beam can be adjusted to occur at any desired angle with respect to the plane of the rhombus. If the angle is too large, the two M1's do not intersect at all and the beam either is not fully formed, or it is actually split into two symmetrical lobes, directed off the array axis. This often happens when a rhombic antenna de-

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signed for one frequency is operated at a much higher frequency. It is instructive to check this important fact in the following way: Set the two charts for a leg length of 2 wave lengths for an acute angle of 65 degrees and note the main beam at an angle of 17 degrees above the plane of the rhombus. This may be a very desirable pattern for a particular application where a vertical beam angle of 17 degrees is called for. If the antenna is constructed to give this pattern, how will it work for higher frequencies? This can be found by setting the pairs of charts for 3, 4, 5, etc. wave lengths successively at 65 degrees acute angle, and observing the results at frequencies where the leg lengths correspond to these electrical lengths. Take, for example, the frequency at which the length is 6 wave lengths. It will be seen that the two M1's do not meet at all (missing by 20 degrees) and there is a null at low angles in the pattern along the main axis. There is a secondary beam along the array axis at 26 degrees above the horizontal plane of the rhombus. A main beam therefore does not exist, the resulting pattern is very poor, most of the energy being radiated at angles where it can cause unnecessary interference.

Table VIII gave the mathematical relations of the amplitudes of the various lobes up through those of sixth order, in terms of relative field strength when used as a transmitting antenna, or antenna current for a receiving antenna, based on the assumption that all parts of the antenna are immersed in a field of uniform strength. The fact that this is not true in reality is the basis for diversity reception.

In order to study a particular rhombic antenna pattern, a print is made of the two relevant charts in a chosen angular relationship, using a dry process in which the paper does not shrink or stretch. The black-line printing processes are excellent for this reason. This gives a worksheet on which the various lobes and null zones are seen. On this worksheet, circles are drawn from the center at the elevation angles of maximums and nulls in the chosen height factor, using broken lines for the maximums. The print can then be marked with any notations necessary. The hemispheric coordinate chart may be used to measure any orientations desired.

The charts enable one to arrive at an antenna design for a particular frequency with a minimum of effort. They also facilitate the analysis of the performance of an existing antenna at various working frequencies by using the charts for other leg lengths set at the acute angle of the antenna. For leg lengths that are not an integral number of wave lengths, it is necessary to interpolate between the available charts, or, if necessary, to construct intermediate charts. Most engineering needs will be satisfied by those provided.

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Figure 6 is an example of a design worksheet for one set of conditions, illustrating the use of the charts and the application of height-factor information.

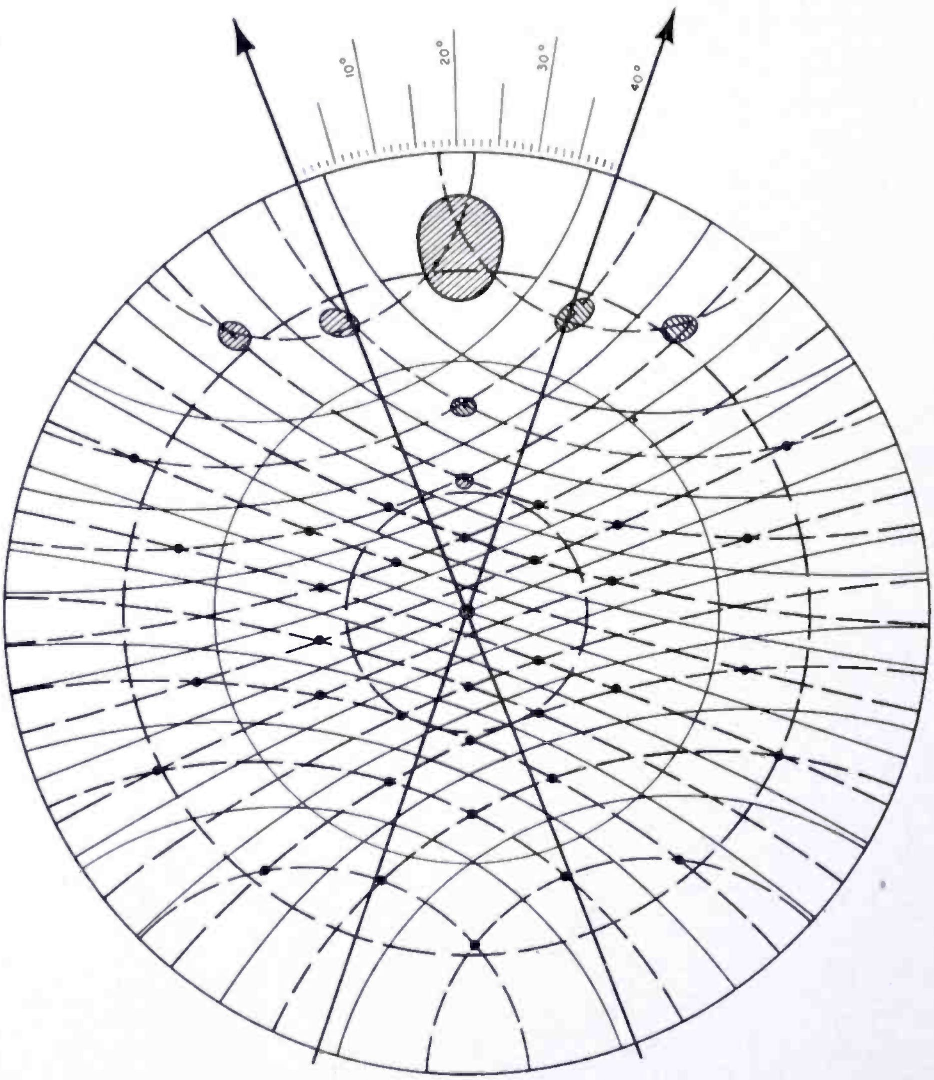

Fig. 6—Example of a stereographic map for a horizontal rhombic antenna where $L = 5\lambda$, $A = 40$ degrees and $H = 312$ degrees corresponding to the second example. The main beam and all other lobes are represented by shaded circles or dots. Broken lines represent maximums, and solid lines zeros.

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FREQUENCY STABILITY FOR TELEVISION OFFSET CARRIER OPERATION*

BY

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Summary—*This paper discusses the stability requirements which must be realized for successful offset carrier operation in the ultra-high-frequency television channels. It includes a discussion of the performance of representative stations and a description of the methods of construction and fabrication employed in a crystal unit which has been developed to provide extremely low drift over an extended period of time. The results of life tests conducted for a year of continuous operation indicate that precision in excess of that required can be realized and will permit offset carrier operation to be employed.*

INTRODUCTION

IN order to make efficient use of the available radio-frequency spectrum devoted to television broadcasting, it is necessary to permit use of the same channel by several stations. The minimum distance between stations operating on the same frequency has been established with the idea of affording protection to the service rendered by each station in its metropolitan area. Such planning is essential if the maximum service is to be afforded to the public without excessive interference. Unfortunately, the separation which must be employed in order to permit a reasonable number of individual stations to operate in the more populous areas of the country is not sufficient to prevent occasional interference from tropospheric propagation. Furthermore, receivers located beyond the metropolitan areas are not afforded the protection of a high ratio between the strengths of the desired and undesired signals, so that interference in such cases is almost certain to be present.

CARRIER SYNCHRONIZATION

The problem of reducing this cochannel interference has been a matter of major concern ever since the Federal Communications Commission hearings in the Fall of 1948. At that time RCA had been conducting tests on a system of synchronizing the carriers of two

* Decimal Classification: R214.211.

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stations, since the major difficulty was found to be due to the beat between the visual carriers which appeared as a series of horizontal bars, shifting in position as the difference between the two carriers varied. This carrier beat pattern has been referred to as the "venetian blind effect" because of the slat-like appearance on the receiver screen. The carrier synchronization approach was found to be definitely helpful; however, initial tests proved the offset-carrier approach to be markedly superior in almost every respect. Tests on carrier synchronization were then discontinued, and attention was centered on the offset-carrier method.

Offset Carrier System

It is evident that as the difference between the carriers increases, the pattern formed by the beats will be made up of more closely spaced bars. When this difference reaches half the line frequency, the pattern is very fine in structure and the alternate fields contain interfering pictures of opposite polarity which tend to cancel in the integrating process of the eye at normal viewing distances. To operate two stations under exactly this condition demands the same equipment required for synchronous carrier operation plus facilities for maintaining the exact carrier difference frequency.

During 1949 experiments conducted by the RCA Laboratories indicated that the relationship between the improvement in reception, stated in decibels, and the difference between the carrier frequencies, was approximately sinusoidal. A maximum is reached at a carrier difference of half line frequency while a minimum is reached at twice this difference. This data was published in the Spring of 1950.[1]

It will be appreciated that if three stations are to be operated in this manner, the improvement between one of the pairs of stations will be at a minimum because the carrier frequency difference between them will be exactly equal to the line frequency. By employing a separation somewhat greater than half line frequency, it was found that the improvement could be equally distributed. To accomplish this an offset frequency of 10.5 kilocycles is required.

This laboratory result was subjected to field tests during the Spring of 1949. The results were sufficiently encouraging so that in June of that year five stations, located in Boston, Schenectady, New York, Washington and Lancaster, began operating in this manner with substantial improvement in mutual protection.

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[1] RCA Laboratories Division, "A Study of Cochannel and Adjacent-Channel Interference of Television Signals," *RCA Review*, Vol. IX, pp. 99-120, March, 1950.

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Further extrapolation of the data taken during 1949 revealed that the carrier difference of 10.5 kilocycles could be varied over a limited range without appreciable reduction in the advantage gained by this method of operation. It has been estimated that a tolerance of plus or minus 2000 cycles can be applied to the carrier separation. In order to insure this tolerance in the separation between the carriers of two transmitters operating from their individual frequency standards, it is necessary that the tolerance applied to each carrier be half of this amount or plus or minus 1000 cycles. This tolerance is made up of the tolerance to be applied to the transmitter itself and the tolerance to be applied to the frequency monitor against which it is checked. Usually, the accuracy of the monitor is specified so that deviations from this source will not exceed one-half of the total permissible deviation. Thus an absolute accuracy of plus or minus 500 cycles should be realized in the station frequency monitor.

The tolerance proposed for the carriers of television transmitters by Radio Television Manufacturer's Association (RTMA) is 0.001 per cent. The maximum permissible deviation for low-band very-high-frequency (VHF) transmitters would occur on channel 6 and would amount to 832.5 cycles on the visual carrier. This performance is well within the capabilities of present transmitter operation. This is confirmed by the observed deviations of a number of stations operating in these channels. The departures as measured by reliable services did not exceed 500 cycles. The performance of television station WNBT over a period of several years is representative (Figure 1).

The same tolerance applied to the high-band VHF channels would result in maximum permissible departures of plus or minus 2112.5 cycles on the visual carrier of channel 13. This is approximately twice the tolerance established for successful offset carrier operation. It is, therefore, necessary to restrict the tolerances for channels 7 to 13 to limits of 0.0005 per cent for station operation and 0.00025 per cent for the station monitor. In actual operation the desired tolerance has been maintained by frequent calibration and adjustment of the local monitor against a reliable frequency standard such as the government-operated radio station WWV.

The most exacting requirements are encountered when offset carrier operation is to be employed in the ultra-high-frequency (UHF) channels. The required precision for the visual carrier of the highest channel is plus or minus 0.000113 per cent. This represents a stability in the order of 1 part per million for the station carrier and a frequency monitor tolerance of only 0.00005 per cent.

Where comparison with a precise frequency standard is possible,

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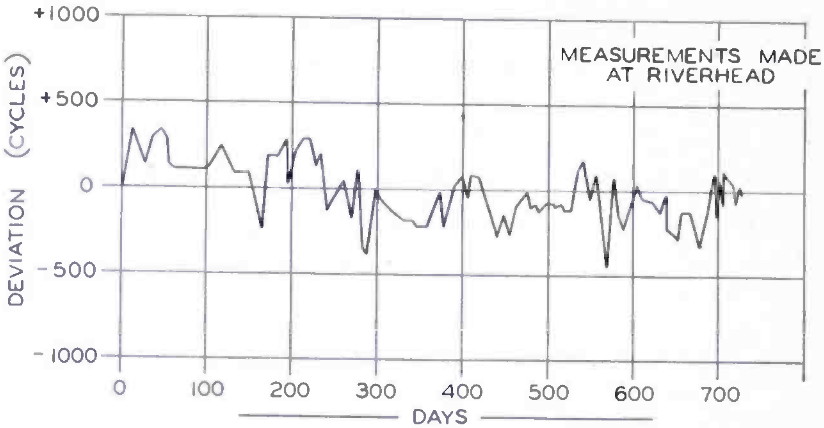

Fig. 1—Visual carrier stability, station WNBT, channel 4 (67.25 megacycles): August 12, 1948 to August 4, 1950.

the desired stability can be realized by careful operation and frequent readjustment. In the case of station KC2XAK the deviations as measured by Riverhead[2] are shown in Figure 2. It will be noted that after the first few weeks of operation the deviations of the visual carrier seldom exceed the limit of 1000 cycles.

While satisfactory stability of the local monitor can be achieved by frequent recalibration against a primary standard, it is necessary to achieve greater reliability and precision in the station monitor in order to permit offset carrier operation to be accomplished in areas where a primary standard is not readily available. The accuracy required is of such a high order that single checks against a stable reference such as WWV are inadequate. This is due to the variation in the frequency of the received carrier caused by the Doppler effect

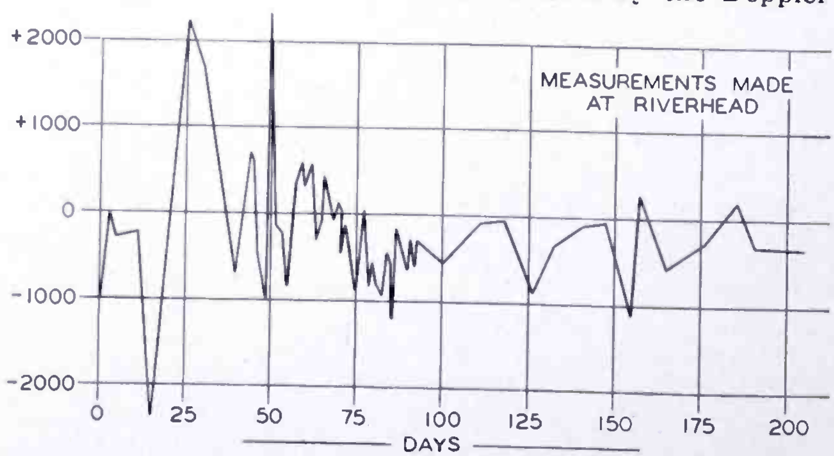

Fig. 2—Visual carrier stability, station KC2XAK, channel 24 (530.25 megacycles): January 17 to August 11, 1950.

[2] R. F. Guy, "Investigation of Ultra-High-Frequency Television Transmission and Reception in the Bridgeport, Connecticut Area," *RCA Review*, Vol. XII, p. 98, March, 1951.

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in transmission and reflection from the ionized layers of air in the upper atmosphere. Analysis of records kept at Camden, New Jersey, over a period of three years indicates that such deviations may, at times, approach 2.5 parts in ten million in a single day. This is half of the tolerance which is permissible in the station monitor. Therefore, precise calibration of the absolute frequency of the station monitor requires that readings be made over a reasonable period of time in order to allow an accurate average to be obtained.

Recognizing the importance of offset carrier operation to the eventual success of UHF television service, RCA embarked on a program aimed at the development of stable crystal oscillators which would require recalibration only at relatively infrequent intervals. The desired degree of frequency stability indicated above was more than twenty times any previous requirement. In fact, only a year or so ago it was almost unheard of to specify any definite limit of frequency deviation as a function of time for any type of commercial crystal unit. Frequency variations due to extended exposure to elevated temperatures, or even to normal room ambient, have been recognized for several years. However, very little prior effort has been devoted to the problem of reducing this type of aging effect to a practical minimum. Any logical attempt to accomplish this must approach the problem by an analysis of factors which could cause a deviation in frequency, starting with possible physical or chemical changes within the body of the quartz plate itself.

Natural crystalline quartz is not perfect, and may contain a small percentage of impurities. Since this foreign matter may be in the form of a gas, a liquid or a solid, it has unstable properties according to the nature of the impurity. The most effective treatment found to stabilize this possible source of trouble, is to subject the quartz plates to a high temperature bake at 500°C to 525°C. Many tests during the past year have shown that a half-hour baking cycle results in a measurable decrease in effective resistance, adequate proof of an unloading effect or liberation of entrapped substance. For maximum effectiveness, this treatment must be applied immediately before coating the quartz plate surfaces with metallic films, which may be used as electrodes, or before mounting it between separate electrodes in an air-tight envelope, which is hermetically sealed and evacuated promptly. Otherwise atmospheric contamination will attack the quartz plate and again introduce foreign matter and consequent instability.

Finished quartz plates are fashioned from rock crystals by cutting with diamond charged saw blades, grinding on diamond wheels and by lapping with abrasives. All three operations introduce superficial

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fractures and strains, thus disturbing the natural molecular and atomic structure near the boundary surfaces. The penetration of these stresses depends upon the hardness and size of the abrading particles, and upon the pressure applied. Normal crystal lapping techniques require that a fine grade of abrasive, such as an optical emery, be employed in the finishing touches which reduce the crystal thickness to the exact dimension desired for a specified frequency. Even when this precaution is exercised, there are minute cracks, pits and fissures in the lapped surfaces, as well as strained areas immediately beneath these surfaces. If effective preventative action is not taken, atmospheric moisture will collect in these surface faults and the force of capillary attraction will cause further surface cracking to the extent that small particles of quartz will be liberated from the main body.

To overcome these two conditions of broken surface quartz and superficial strains, two processes may be employed to provide maximum stability. First, the damaged quartz surfaces can be removed by dissolution in hydrofluoric acid or ammonium bifluoride. This etching is continued for several minutes until the crystal thickness is reduced by a very small amount, but readily measurable by increase in crystal frequency. Excessive etching is carefully avoided because the acid does not attack quartz equally in all directions, and the facial contour as produced by the lapping operation must not be measurably upset. While this etching operation has been proved to be very beneficial, it is not a 100 per cent cure for surface damage. Second, the strained areas just beneath the quartz surface may be largely neutralized by an annealing cycle. This comprises a short bake at 525°C followed by a gradual controlled cooling in a 24-hour period. Comparison of aging effects of units with and without this treatment, clearly indicate that this annealing operation is an important step towards achieving maximum frequency stability.

To permit use of a quartz crystal as a frequency controlling element in an electronic oscillator, it must be provided with conducting electrodes. The great majority of modern crystals are coated with two metallic films, one on each major surface, evaporated directly onto the quartz faces. Because of this intimate contact, the metal film actually vibrates with the quartz, when the latter is suitably energized. Since the mass of the plating offers inertia, the natural period of quartz vibration is retarded slightly by the presence of the electrode platings, and any change in the mass or physical properties of these platings will reflect a corresponding change in frequency of oscillation. To avoid this type of frequency instability, the preferred construction is to omit the normal platings on the crystal faces and to energize the

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quartz plate through metallic films spaced away from the crystal surfaces by a very small distance, such as 0.0005 inch. This construction (shown in Figure 3) introduces an air gap on either side of the crystal, and for maximum stability these gaps must not change. The essential constancy may be obtained by employing two recessed quartz discs of the same size as the oscillator plate, each disc having a circular gold-plated area on its inner face, to act as an electrode. Fabricating these electrode discs from oriented quartz ensures substantially constant air gaps, since the lands which determine the gaps are of the same material, and hence of the same hardness, as the oscillator plate itself. Furthermore, as the 3-piece assembly is subjected to temperature vari-

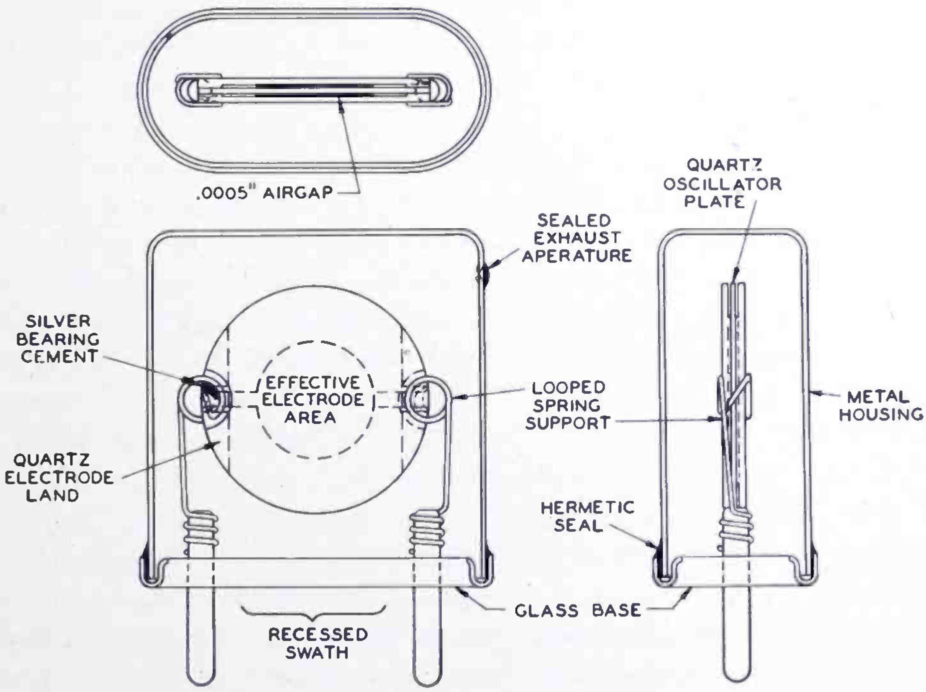

Fig. 3—Basic construction of type VC-1-F crystal unit.

ations, the individual pieces move together as an integral unit because they have the same coefficient of expansion. This avoids any rubbing action between electrode discs and oscillator plate, which otherwise would eventually cause a decrease in airgap and a resulting negative deviation in frequency. This 3-piece construction, then, greatly minimizes the effects of any physical or chemical changes which may take place in the electrode metallic films.

Pursuing this pattern of examining potential sources of aging effects from the quartz plate outward, the next consideration may well be that of the crystal supporting members. Thus far in the theoretical design, an unplated, heat-treated, etched crystal with two plated quartz

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electrodes, one against either crystal face have been considered. These must be secured in position and the 3-piece assembly suitably supported in a holder which lends itself to hermetic sealing. This support is obtained by inserting diametrically opposite edge areas of the 3-piece "sandwich" between adjacent turns of two looped spring wires, the lower ends of which are coiled around the upper ends of the two holder contacting pins to which they are secured with high melting point solder. These two supports are 0.009-inch diameter music wire, having excellent spring properties, but like all other metals they are subject to fatigue by continued high frequency vibration. However, tests have shown that the frequency deviation due to aging is substantially at the same rate whether or not the crystal is energized during the aging period. Therefore, one may rule out changes in the physical structure of the supporting wires as having any important effect on aging characteristics.

When inserting the 3-piece crystal-electrode assembly in the spring loops, a silver bearing cement is applied to join each loop with the outer plating on each quartz electrode. This cement is cured by a baking cycle, which evaporates the solvents, leaving a hard, conductive bond. No real evidence has been found to indicate that these two cemented joints contribute in any way to aging effects. However, it is conceivable that minute particles may become dislodged or evaporated from the cement and become deposited on the surfaces of the oscillator quartz plate to produce a slight loading effect, and thus a decrease in frequency. To avoid this possibility so far as possible, the volume of cement employed is reduced to an essential minimum, and then thoroughly cured.

Since frequency deviations due to aging are normally negative, particular attention is given to any construction or process which might contribute to crystal loading. In the holder soldering operation, when the cover is secured to the metal rim of the glass base, there is a probability of solder flux vapor becoming trapped within the crystal cavity. To minimize this danger, the cover is perforated and the internal gas evacuated while being heated in a vacuum oven. The interior is then flushed with dry nitrogen and finally sealed while charged with nitrogen to atmospheric pressure. Although this does remove much of the moisture and impurities, without question some residue of contamination remains within the sealed chamber, either in the gas itself or occluded to the solid inner surfaces. It is probable that these impurities and residual moisture account for the major portion of the frequency aging in a negative direction.

Careful application of the foregoing considerations contribute

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materially to the frequency stability of crystal controlled oscillator circuits. However, there are at least five other important factors which must be incorporated to achieve minimum aging. The quartz oscillator should be excited at an overtone mode rather than at its fundamental, it must be maintained at a very constant temperature, overexcitation must be avoided, all heater and oscillator voltages must be held constant by effective regulation and the oscillator components must be of top quality to avoid changes in load capacitance as seen by the crystal unit.

The essential features of the theoretical minimum aging design were incorporated in a metal enclosed unit, designated Type VC-1-F. This unit employs an AT-cut third-overtone quartz plate oriented at $+35°29' \pm 1'$ from the optical axis of a natural crystal.[3] Use of an overtone mode of thickness shear vibration decreases aging effects of the type which may be caused by surface changes. This is because a fundamental mode crystal has two surfaces for one half-wave vibration, while a third-overtone crystal has two surfaces for three half waves.[4] Thus the effect of any surface change is appreciably reduced when an overtone mode is employed. This reasoning indicates that a 5th or 7th overtone might be still more desirable. However, at this writing, procurement of overtone units above the 3rd mode is difficult, and disproportionately expensive.

It is well known that any change in temperature normally causes an appreciable change in crystal unit frequency. This particular problem involves but one type of quartz plate, an AT-cut, 3rd overtone, which reverses direction of frequency change twice when its temperature is varied widely, such as from $-55°C$ to $+90°C$. By careful orientation from the mother crystal, one of these reversals can be positioned at a convenient temperature, such as at 75°C, to facilitate artificial temperature stabilization by use of a suitable oven. This oven, in the developed design, is energized directly from any 115-volt, a-c or d-c source, through a precision type bimetallic thermostat. Although the Edison type S1-1 thermostats employed have a sensitivity of 1°C, a temperature variation of that magnitude cannot be tolerated. To achieve the optimum stability, the hermetically sealed VC-1-F crystal unit already described is placed within a heavy walled brass cylinder which is mounted inside the 14-watt oven heater and insulated from it. Furthermore, glass wool is packed loosely in all air pockets to decrease heat transfer by convection. This construction provides a

[3] W. P. Mason, "Zero Temperature Coefficient Quartz Crystals for Very High Temperatures," *Bell Sys. Tech. Jour.*, Vol. 30, pp. 366-380, April, 1951.
[4] Commentary by W. P. Mason, *Trans. A.I.E.E.*, Vol. 57, pp. 105-106, February, 1938.

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sufficient mass of metal around the crystal to act as an effective thermal flywheel, maintaining its temperature constant to a small fraction of a degree centigrade. Thus another factor tending to cause frequency instability was brought under adequate control.

The constancy of crystal temperature may be upset not only by external influences, but also by heat generated within the crystal body itself. Quartz is an excellent insulator, but when provided with conducting electrodes it permits a flow of alternating current in the same manner as a capacitor. However, it does offer a resistance to that flow and internal heating results, approximately equal to the product of that resistance and the square of the current. If this heat is not limited to a very low level by preventing excessive voltage between the electrodes, the temperature stability provided by the oven will be disturbed and frequency variation will be experienced. Hence, the oscillator circuits in which these crystal units are employed, have been

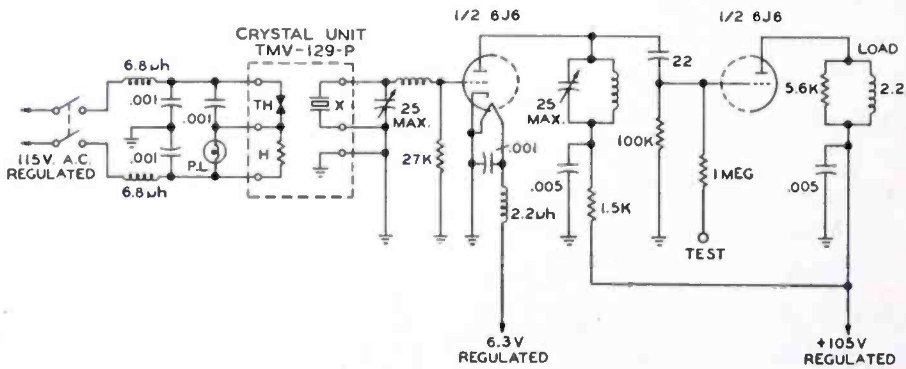

Fig. 4—Typical oscillator circuit.

designed carefully to provide sufficient excitation to produce stable operation and a useful output, but also to avoid any possibility of excessive crystal current. A schematic diagram of a typical oscillator used in these tests is shown in Figure 4.

For this application, all factors which might cause frequency deviation either during short intervals of time or for much longer periods of weeks and months are of concern. It has been shown that variations in crystal unit excitation can disturb the quartz plate temperature, and similarly, changes in the oven heater voltage can upset normal conditions of stabilization. This heater is provided with an effective compensator and a precision thermostat, but if the supply voltage is allowed to change suddenly the rhythmical on and off cycling is disturbed and a measurable temperature variation may result. For these reason, both the d-c and a-c voltages must be effectively regulated if maximum frequency stability is to be achieved.

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A final factor which may cause frequency change as a function of time, is that of aging effects in the oscillator tube and circuit components. Any changes in these parts which result in a variation of the load capacitance, as seen by the crystal unit, will reflect a corresponding change in frequency. The most common disturbance of this type is encountered whenever the crystal oscillator tube is replaced, since the interelectrode capacitances of the new tube will not be identical with the old. Other circuit components may age sufficiently to alter the load capacitance, and causes of this type are very difficult to counteract. Normal practice dictates the use of a small trimmer

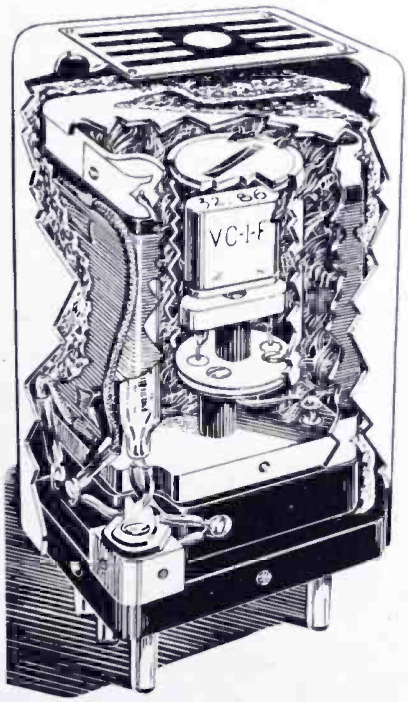

Fig. 5—Sectional view of final crystal unit showing 3rd-overtone crystal (VC-1-F) within its tubular metal housing centrally located in the heater compartment. Housing and heater are loosely packed with glass wool. Heater is covered with asbestos wrapping. The assembly fits a standard 6-prong socket.

capacitor, either in parallel with the crystal or so arranged that it provides a corrective action, employed to make compensating adjustments at periodic intervals.

The new type TMV-129-P crystal unit developed during this investigation is illustrated in Figure 5. It includes all of these features of construction and the treatments which have been shown to contribute to maximum frequency stability. Fifteen such units were fabricated, provided with 3rd-overtone VC-1-F crystal units between 25 and 35 megacycles, and placed on continuous life test. For this purpose,

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banks of oscillators were constructed, provided with regulated a-c and d-c supplies and operated day and night for nearly a full year. The frequency of each crystal unit was measured very accurately, first at frequent intervals of several readings per week, and later only a few times per month. The individual characteristics of five typical units are shown in Figure 6. A brief study of these curves, based on the most critical UHF monitor requirement of ±.00005 per cent maximum permissible deviation in 30 days, shows that all units were well within the tolerance. One unit drifted out negatively on the 63rd day, and a second unit on the 99th day. The other three units, however, never exceeded the permissible limits even after eleven months, and from

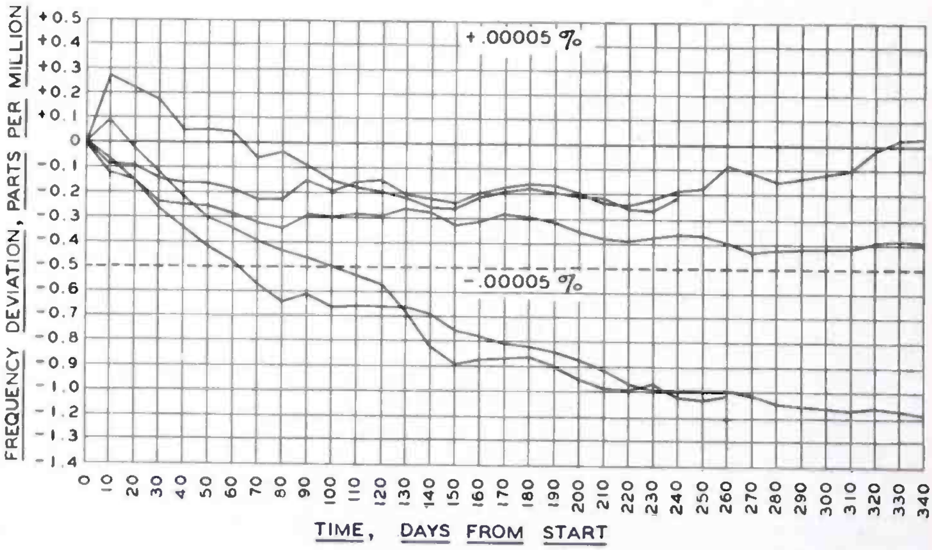

Fig. 6—Aging characteristics of five typical crystal units.

the trend shown by their aging curves might have remained well within the critical limits for more than twice that length of time.

Such excellent freedom from serious aging effects is not to be expected in every unit produced. However, careful fabrication of the crystals and proper assembly can be expected to produce units of this type which will be more than adequate to provide the frequency stability required for offset carrier operation. It is, therefore, concluded that such operation is practical even at the highest channel in the UHF spectrum by employing crystal units similar to the Type TMV-129-P in low-drive, voltage-stabilized circuits.

Acknowledgments

The authors wish to acknowledge the contributions of E. M. Brown, L. L. Dimmick and P. D. Gerber to the successful conclusion of these investigations.

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THE NBC NEW YORK COLOR TELEVISION FIELD TEST STUDIO*

By

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Summary—*Studio 3H in Radio City New York has been converted for use as a color television studio. The studio was used in field testing the RCA color television system. At a later date the installation was modified, and field tests using NTSC standards were conducted. Equipment and operation of the studio are described.*

Introduction

AFTER a period of nearly two years of intensive operational experience in field testing the RCA Color Television system in the Washington studio installation, it was decided to continue the activity in the NBC studios in New York. For this purpose, apparatus for a complete studio was jointly planned by engineers of RCA and NBC. The equipment was developed and built by the RCA Victor Division. The specifications for the apparatus were based upon experience from the Washington field testing and upon plans which envisaged expansion to include additional studio setups for enlarged scope of operation.

Planning

At the outset it was recognized that full advantage should be taken of the experience gained over the years in monochrome television operation. At the same time, however, the fundamental layout and design had to be such that it would promote the development of those new program and operating techniques which would be needed with the addition to television of the very important dimension of color. The design, therefore, was intended to be sufficiently rigid to permit a daily routine of program schedules while being flexible enough to facilitate any circuit or basic system modifications which might become advisable. A versatile design of this type would provide the advantages of facilities permitting regular daily use, but still being capable of easy changes for experimental purposes.

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* Decimal Classification: R.583.3.

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Figure 1 shows the basic block diagram of the color television system. It will be seen that the plan does not vary widely in its fundamentals from that used in present day monochrome plants. Chief differences lie in the switching system, where three channels are switched simultaneously for each camera, and in the multiplexer which accepts the three outputs of the switching system and combines them to form a single composite color output signal with subcarrier.

It was thought that the greatest efficiency would be achieved by subdividing the over-all design into a number of separate, functional units. Each unit would then be assigned its relative degree of importance and position in the over-all plan and design, and would be built in accordance with it.

Selection of Studio

For a number of reasons it was desirable to locate the color studio in Radio City in New York where it would be conveniently accessible to development laboratories, program production facilities, and executive offices. Studio 3H in Radio City was selected for the conversion to color television. Designed in 1933 as a radio broadcast studio, it measures 50 feet in length, 30 feet in width, and 18 feet in height. The control booth is located at one end of the studio at a level slightly above the studio level. The installation of monochrome television equipment in 1935[1] required so much additional space that a separate video control booth was constructed on the fourth floor over the original audio booth. 3H was selected as the first Radio City color television studio because, having been previously used for monochrome television, it was equipped with many of the services that would be required for color operations. In addition to this there was some space adjacent to the fourth floor booth which could easily be converted to an equipment room. Previous use of the studio for monochrome television had required the installation of supplementary air conditioning and power supply facilities. Some additional revisions in these services were necessary with the conversion to color on account of the additional equipment installed.

Lighting

Overhead power distribution for lighting in the studio was provided by installation of five ducts running lengthwise, with outlets on three-foot centers. The individual fixtures are suspended from an overhead

[1] R. E. Shelby and R. M. Morris, "Television Studio Design," *RCA Review* Vol. II, p. 14, July, 1937.

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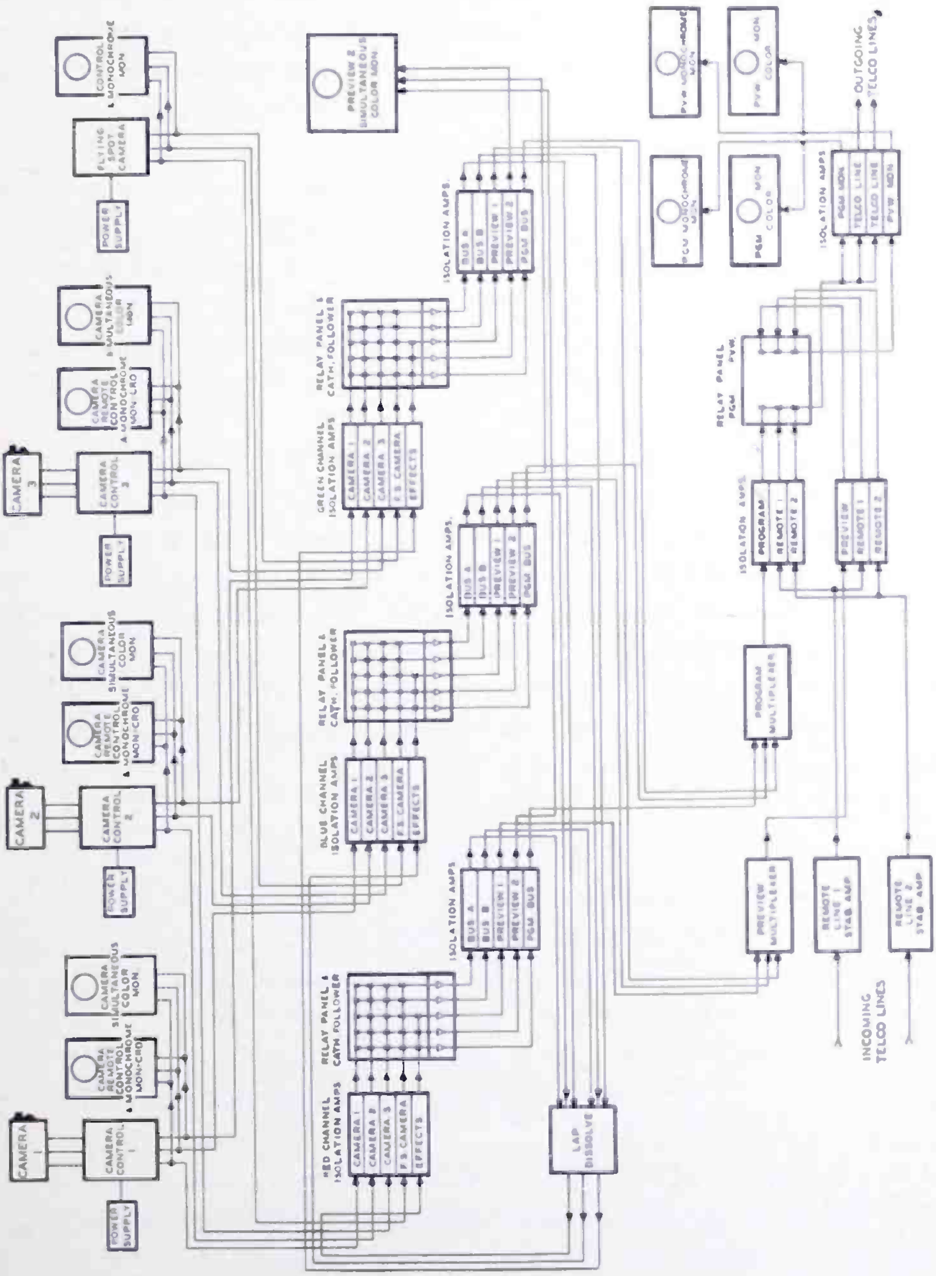

Fig. 1—Block diagram of switching system.

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pipe grid, either by means of adjustable pantographs or by fixed-length rods. An ample number of power receptacles are also provided along the walls to accommodate any lighting fixtures of the portable floor-stand type which might be required to achieve low-angle lighting effects. Each lighting circuit is equipped with circuit breaker control, and additional master breakers are available for controlling lights in groups. Dimmer control is provided for maximum potential flexibility in lighting control and to determine the value of dimmer controls in color television operation. The lighting power feeders are separate from technical equipment power feeders in accordance with usual television studio design practice. The total lighting power available to the studio is in excess of 100 kilowatts and is supplied to the studio over a direct four-wire three-phase system. Thus far, the lighting levels for color television have been somewhat higher than those generally used with monochrome operation.

Experiments in color television lighting have proven that production sets with the same degree of complexity as those utilized in monochrome television can be satisfactorily handled. Figure 2 indicates the lighting plan utilized on a color production set. At present, incandescent lamps are used for lighting in this studio during all field test transmissions. Standard voltage, long-life bulbs are used and are operated at approximately 2900 degrees Kelvin. The fixtures are conventional units and are used interchangeably with the monochrome studios in Radio City.

Air Conditioning

The air conditioning system supplies the studio with 5500 cubic feet per minute of conditioned air cooled to 55 degrees Fahrenheit. This is sufficient to maintain an ambient temperature of 78 degrees Fahrenheit within the studio with all equipment operating and with 45 kilowatts of light in use. This amount of power is more than adequate to produce proper lighting levels for two average stage sets.

Camera Equipment

The design of the video system provided for 3 studio cameras for live pickup and one flying spot scanner for transparencies. Thus far only two of the studio cameras have been installed. The cameras are equipped with electronic viewfinders (monochrome), lens turrets, and the standard-type intercommunication system. A detailed account of the color camera design is given in an accompanying paper.[2]

[2] J. D. Spradlin, "The RCA Color Television Camera Chain," *RCA Review*, Vol. XIII, p. 11, March, 1952.

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Following the general concept of monochrome operations, one of the studio cameras is mounted on a conventional crane-type dolly and the other on a standard studio pedestal. The transmission of film programs in color has been accomplished by the use of the rear projection screen method employing a studio camera focused on the projected image on a translucent screen.

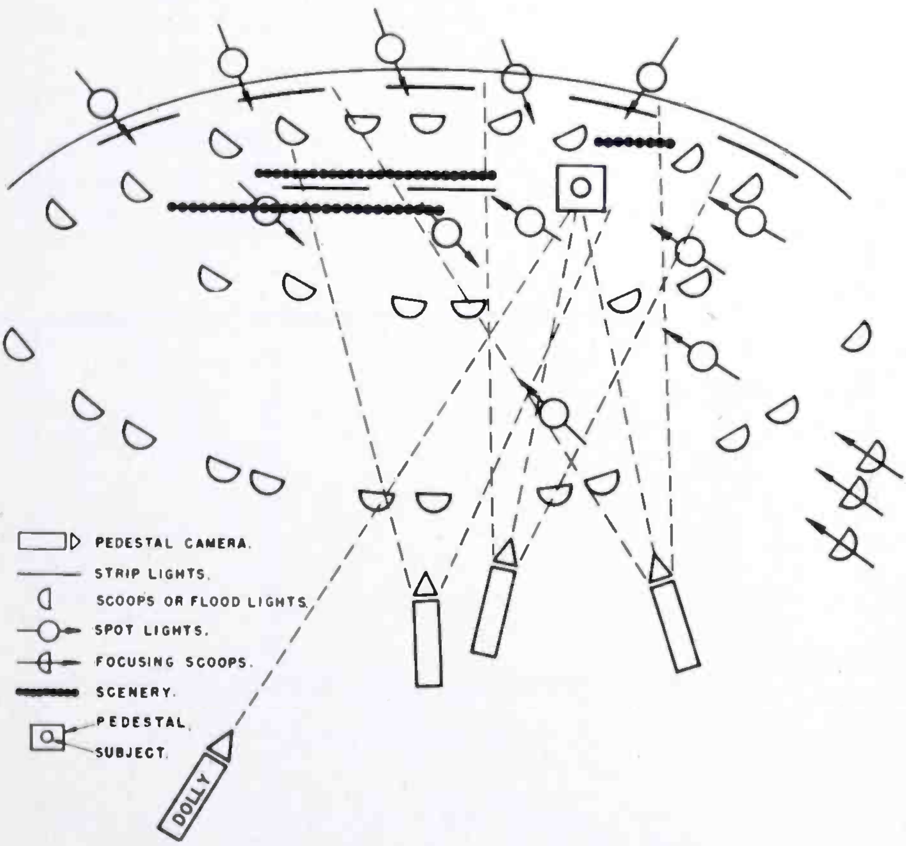

Fig. 2—Diagram of set lighting plan.

Intercommunication System

The studio is equipped with the standard-type intercommunication system used in all of the newer NBC television installations. With this system the technical director and the program director are able to talk to studio personnel during the rehearsal by means of loud-speakers. During periods of program transmission, communication with floor personnel is by means of headphones and small "pocket ear"[3] radio receivers.

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[3] J. L. Hathaway and W. Hotine, "The Pocket Ear," *RCA Review*, Vol. VIII, p. 139, March, 1947.

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Control Booth

The control booth is divided into two separate units according to function — an audio booth and a video booth.

Audio Booth

Figure 3 is a third-floor plan of the studio and the audio control booth. The audio control booth is equipped with a studio-type console containing an eight-position split mixer with the conventional echo chamber, monitoring, and outgoing line controls. It is also provided with complete jack field facilities to permit patching of 16 microphone inputs, turntables, remote lines, and all component equipments associated with the console system. Microphone preamplifiers and monitoring amplifiers for studio and control booth speakers are a part of the control booth assembly. Program and preview video monitors are provided so that the audio control engineer may more closely follow camera action in the studio. Intercommunication is provided with the video booth and microphone boom operator.

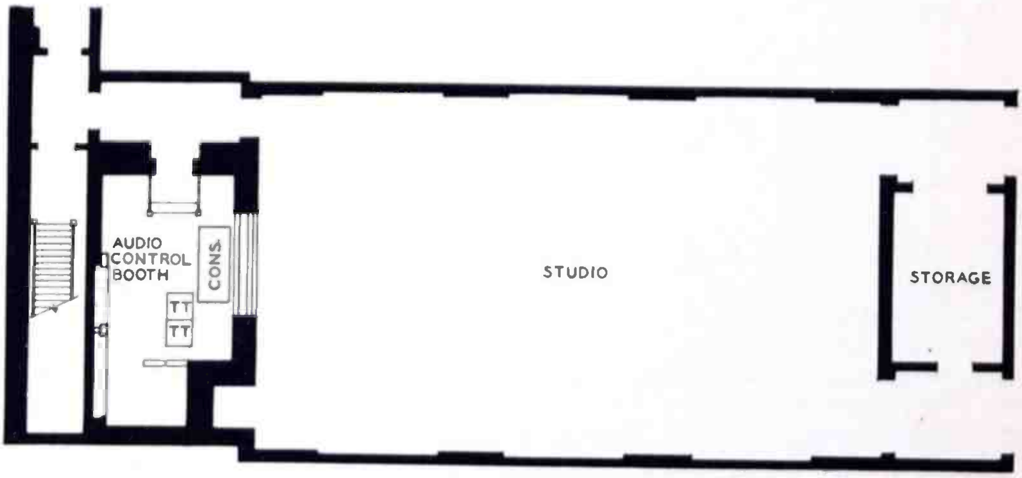

Fig. 3—Third floor plan of studio and audio booth.

Video Booth

The over-all circuit plan of the video booth follows rather closely the general plan of a typical monochrome booth. However, since the color operation is not at present an integral part of the monochrome operation in Radio City, the video booth contains much additional equipment, such as complete patching and processing facilities for all incoming and outgoing video lines as well as control and patching facilities for all house monitoring and other miscellaneous video circuits. Figure 4 is the fourth-floor plan of the studio showing the

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video booth, equipment room, and space for future equipment expansion. This arrangement provides a complete unit of color television operations and functions as a full-scale working model from which information and experience will be gained for guidance in the future planning of multistudio color television plants.

Physically, the video control booth is basically a two-level design and is rectangular in shape measuring 18 feet in width and 30 feet in length. The equipment is arranged according to function in five basic groups: monitors, technical and program directors' console, video

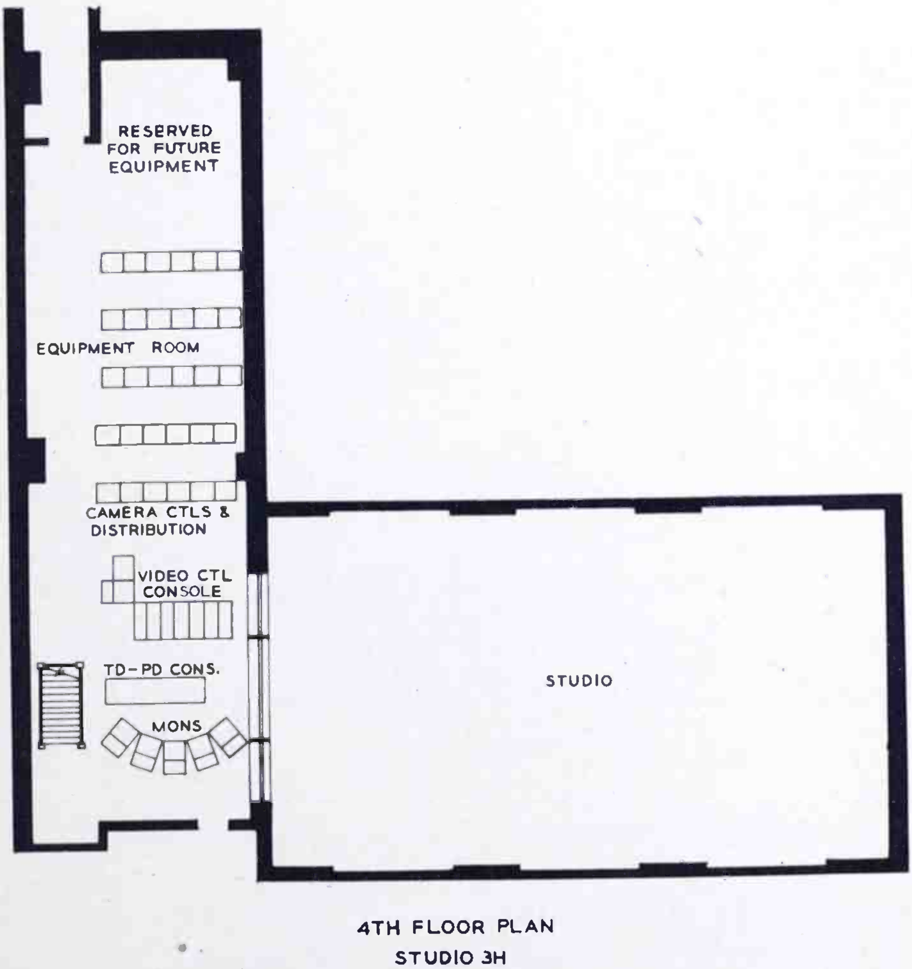

Fig. 4—Fourth floor plan of studio, video booth, and equipment room.

control console, flying spot scanner, and rack-mounted camera control units with associated patching and distribution facilities.

Generally it has been the accepted practice in video control booth design to locate camera controls and switching equipment in operating consoles so that the program director, technical director, and video engineer have unobstructed views of the studio from their normal

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operating positions. Ordinarily this condition is achieved by arranging the control booth so that the equipment is in stepped rows parallel to the control booth window. For the design of the color video control booth it was decided to deviate from this practice by rotating the equipment plan of the booth 90 degrees, still retaining an unobstructed view of the studio with the distinct advantage of always viewing monitors against a dark background. Figures 5, 6, 7, and 8 are views showing the arrangement of control booth equipment. The major equipment groups are:

Fig. 5—Photograph of arrangement of monitors with technical and program directors' console.

First: A total of 6 monitors, including 2 simultaneous color camera monitors plus a spare rack position for the third camera monitor, 2 three-gun kinescope color monitors for program and preview, and 2 monochrome monitors also for program and preview.

Second: Program and technical directors' console.

Third: Video engineer's console with individual camera control auxiliaries.

Fourth: Rack-type camera control units with associated jack fields for circuit patching and distribution.

Fifth: Flying spot scanner and switchable simultaneous color monitor.

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Fig. 6—Photograph of video control console.

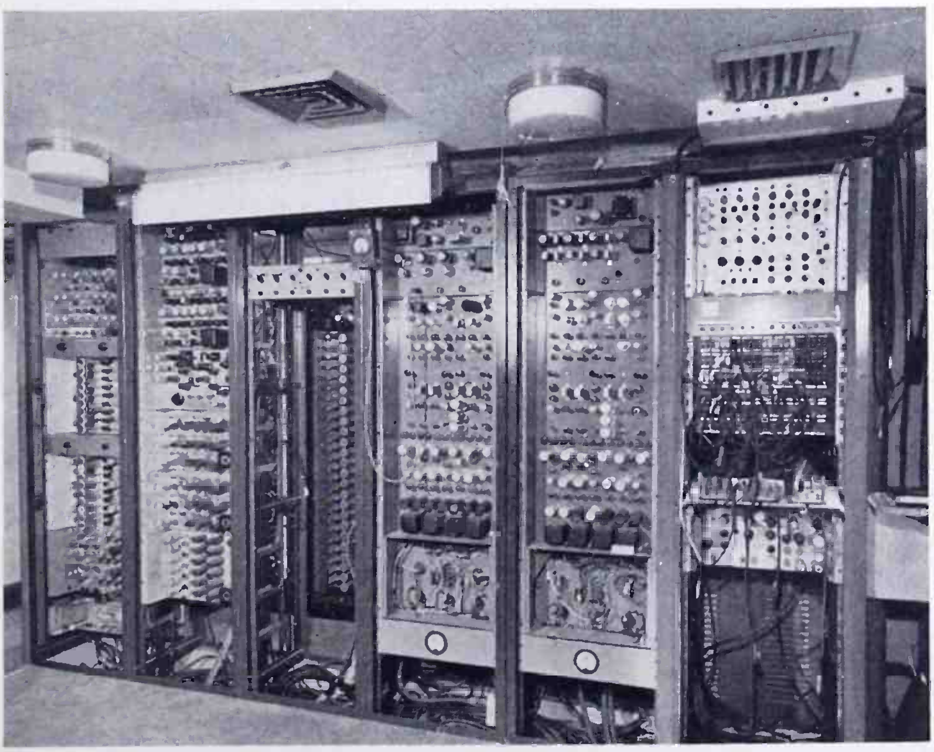

Fig. 7—Photograph of rack mounted camera control units and circuit patching rack.

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The control booth floor level was raised at the point of the video control console to permit viewing of the color monitors from the video control position. This arrangement has proved satisfactory.

The normal camera switching and picture processing controls, such as lap dissolve, are located on the technical director's console. (Lap dissolve has been found to be feasible and desirable with this system of color television.)

The physical arrangement of the studio color camera chain differs from the conventional monochrome chain in that two console sections

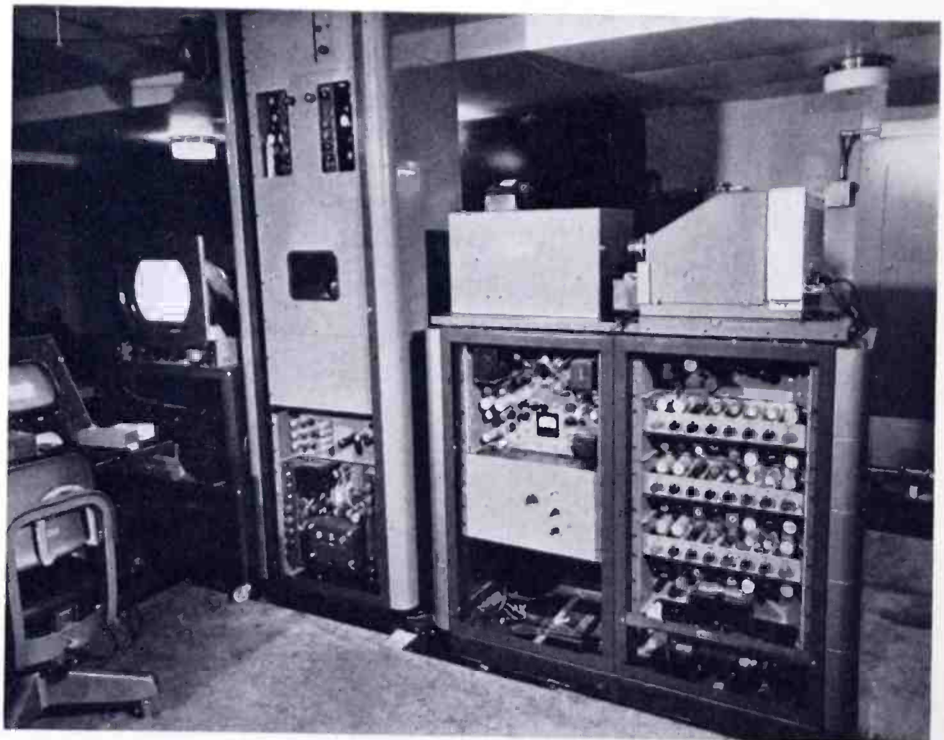

Fig. 8—Photograph of flying spot camera and switchable simultaneous monitor.

and one equipment rack in addition to the power supply racks are required for each camera. The first console section contains all the normal controls for each of the three color channels (red, green and blue) and the second a TM-5A monochrome monitor with cathode-ray oscilloscope which is provided with suitable switching so that signal amplitudes of the color channels may be displayed individually or in groups as determined by the video engineer. The basic camera control unit comprises several rack-type equipments mounted on a standard rack. The major portion of the controls on the rack units do not require adjustment during normal operations. However, those controls, such as pedestal and gain, which do require operational adjustments have been extended to the video engineer's console.

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Equipment Room

This portion of the studio was constructed in accordance with the over-all plan for a centralized equipment room and is located adjacent to the video control booth as shown in Figure 4. Physically, the equipment room is an extension of the video control booth; however, its function is entirely separate. In the 3H installation these two functions were combined in one space to permit further study on centralized equipment room design in anticipation of large multistudio-type color television plants. The equipment room contains equipment such as synchronizing generators, distribution amplifiers, stabilizing amplifiers, power supplies, switching panels and all of the so-called fixed-adjustment-type equipment. It was planned that the 3H color studio installation would simulate a large color plant, with studios displaced considerable distances from the central equipment room. This condition may be achieved for experimental studies by the insertion of extra lengths of cable, thus increasing the electrical separation of the video control booth from the equipment room.

Switching System

The plan of the camera switching system is on a tri-color basis, that is red, green, and blue channels are distributed individually from the cameras to isolation amplifiers, thence through three standard monochrome relay switching panels, and are combined after processing in the multiplexer. Video signals from remote sources such as mobile field unit or network connection are inserted in the switching system at a point following the multiplexing function. The block diagram of Figure 1 shows the switching system and indicates in skeleton form the circuits and components for a complete 4-camera switching system with monitoring, lap dissolve, and facilities for incoming remote and outgoing telephone lines. Monitoring of the individual camera chain is accomplished by means of the three-tube simultaneous-type monitor. Monitoring in all other parts of the video circuit is by means of the RCA three-gun color kinescope units.[4]

Operations

The operation of a color television studio encompasses all of the routines normally included in the operation of a monochrome studio plus a few which are peculiar to the color television studio. These

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[4] H. B. Law, "A Three-Gun Shadow-Mask Color Kinescope," *Proc. I.R.E.*, Vol. 39, p. 1186, October, 1951.

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latter routines are those associated with the colorimetry of the system and with the multiplexing of the additional information.

The cameras in Studio 3H use the optical beam splitting system described in an accompanying paper.[5] In so far as the optical system is concerned, there are few routine operational requirements beyond keeping the camera optical system clean and protected, since the coating on the dichroic mirrors, the color temperature of the studio lighting, the spectral response of the image orthicons and the response of the phosphors in the tri-color kinescope are all integrated into the over-all colorimetry of the system, and all are assumed to remain constant under normal conditions. Gelatin filters used to supplement the dichroic mirrors in providing the spectral transmission characteristics of the three color channels of the camera must be renewed periodically.

Image orthicons vary somewhat in absolute sensitivity (microamperes per lumen from the photocathode) and in the amount of light input required to reach the knee of the light input versus electric output characteristic. Some means of equalizing these sensitivity and saturation point variations must be provided. This requirement is made more positive by the fact that light transmission through the three optical paths to the image orthicons is not equal. The equalization is accomplished by the use of neutral density gelatin filters placed in the optical paths to the individual image orthicons. Those channels which reach saturation at lower light levels are attenuated until all three channels reach the knees of their respective characteristics simultaneously. Operationally, this is adjusted by televising a step wedge pattern illuminated with a standard light level. The resultant signals from the three color channels are viewed simultaneously on a cathode-ray oscilloscope, while an iris in the common optical path is alternately stopped down and opened up sufficiently to cause all image orthicons to operate above and below the knee of their respective characteristics. Neutral density gelatin filters are inserted in the individual optical paths as required until the best adjustment for tracking at the knee is obtained. The optical iris, the studio illumination, and the electrical outputs from the camera must be in an operational relationship after the insertion of the neutral density gelatin filters. That is, there must be a reasonable margin available for control settings, and light levels must be within permissible limits.

Image orthicons must be matched somewhat more critically for color television than for monochrome operation. The spurious signal

[5] G. L. Allee, E. Kornstein, D. J. Parker and L. T. Sachtleben, "Image Orthicon Color Television Camera Optical System," *RCA Review*, Vol. XIII, p. 27, March, 1952.

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(shading) output of each image orthicon must be within limits that will permit nearly complete cancellation by the shading correction circuits provided in the equipment. The requirements just described, namely the matching of image orthicons for shading and sensitivity characteristics, comprise two of the four duties which must be performed by the video control operator with more exactness in alignment than is normally exercised in monochrome operations.

The third task, while not unknown to monochrome operation, assumes a high degree of importance in the color operation and must be carried out with exactness. This is the adjustment of the transfer characteristic or "gamma" correction circuits. These correction circuits, as described in reference (1), are incorporated in each camera control unit and must be adjusted accurately against the prescribed correction. The care with which transfer characteristic correction adjustments are made will have an important bearing on the ability to match camera outputs with respect to color fidelity.

The adjustment of gamma correction is accomplished by driving the correction unit with a step wedge test voltage repeated at line frequency. This step wedge test signal is derived from a step wedge signal generator, an electronic device which produces a step voltage having increments that vary exponentially with time, as indicated in Figure 9. The exponential envelope curve for the step wedge generator is selected in consideration of several factors, including the transfer characteristics of the tri-color kinescope, the image orthicon, and other elements of the system, and it is assumed that the desired over-all characteristic for the system is linear for normal scenes. The following paragraph illustrates the method currently utilized in selecting the proper envelope curve for the step wedge generator for adjusting the transfer characteristic correction circuits.

Assume that the tri-color kinescope has a transfer characteristic which approximates a second-power exponential curve, thus requiring a one-half-power exponential curve for correction. Further assume that the transfer characteristic of the image orthicon is best represented by a 0.7-power exponential curve. If C is the power of the exponential curve or transfer characteristic required to linearize the over-all system, then

$$0.7 \times C = 0.5,$$

$$C = \frac{0.5}{0.7} \approx 0.7.$$

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This relation states that an additional correction of 0.7 is required to linearize a system where the assumptions of 0.7 and 2.0 have been made for the image orthicon and the tri-color kinescope transfer characteristics respectively. Taken by itself, the correction circuits adjusted to provide a transfer characteristic represented by a 0.7-power exponential curve will linearize a transfer characteristic represented by a 1/0.7-power exponential curve, or a transfer characteristic represented by a 1.4-power exponential curve. Hence, the power of the exponential curve selected from the step wedge generator should be 1.4 and the correction circuits should be adjusted to linearize the steps (Figure 10) as viewed on a cathode-ray oscilloscope connected to the output of the correction circuits.

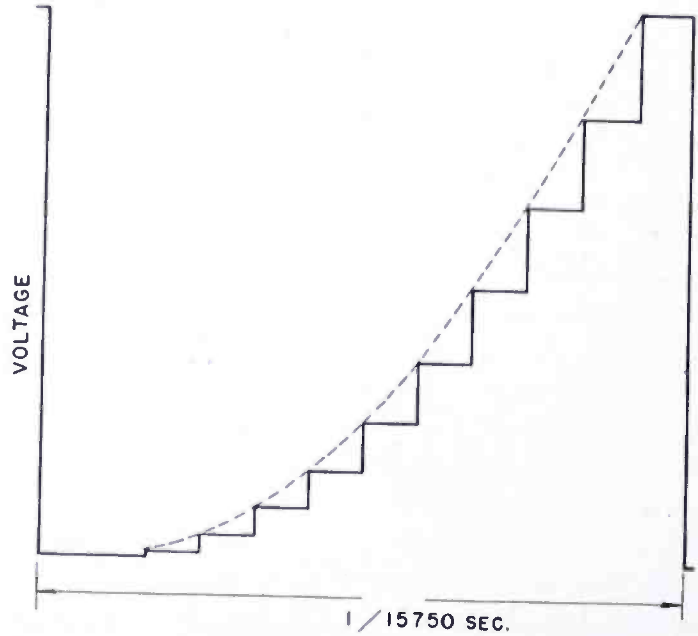

Fig. 9—Second-power exponential step wedge test voltage.

Use of the test voltage of Figure 9 and the adjustment of the correction unit to provide the output of Figure 10 would linearize a system with a transfer characteristic represented by a second-power exponential curve.

The fourth adjustment which requires greater attention than its monochrome counterpart is the setting up of registration in the cameras. The adjustment is a refinement of the distribution check normally made in monochrome cameras. Rough registration is automatic inasmuch as the three camera scanning yokes are driven from a common source. Precise registration is obtained by adjustment of the width, height, centering, and skew controls on the individual channels. Operationally, this is accomplished by televising a pattern of lines creating

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approximately 1-inch squares across an 18 × 24-inch area. The cameraman sets the above-mentioned controls while the video control engineer views the result on a monochrome monitor that permits viewing of individual channel outputs or any combination of the three channel outputs.

There are also the previously mentioned operating adjustments which have no parallel in monochrome operation. One such operation is the setting of a proper color temperature on the color monitors. One way to accomplish this is by the use of a photometer comprising a photocell meter unit with provision for inserting gelatin filters over the photocell. Relative readings of the meter with the three filters

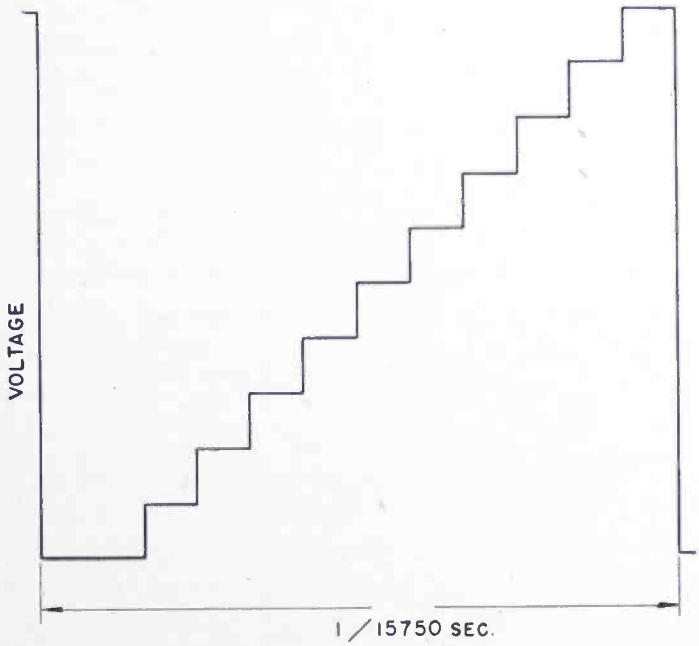

Fig. 10—Linearized step wedge test voltage after passing through the transfer characteristic correction circuits.

(red, blue, and green) in place (one at a time) are established by taking readings against the white of a color monitor when that white has been set to match a standard approximating illuminant C* (6800° K). Once the three relative readings are established for the photometer, it is possible to set the backgrounds of all monitors alike.

Another operation having no counterpart in monochrome operation is the adjustment of the multiplexer. This unit can be adjusted

* This refers to the National Television System Committee Color Field Test Specification which requires that the color signal be so proportioned that when the color subcarrier vanishes, the chromaticity reproduced corresponds to I.C.I. system of specifications illuminant C ($x = 0.310$, $y = 0.316$).

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to a standard with exactness by the use of a synthetic signal — one that is relatively free of the residual imperfections found in the output of even the best camera. It is therefore a reference in the over-all system, and other components of the system should not be misadjusted to compensate for maladjustment or deficiencies of the

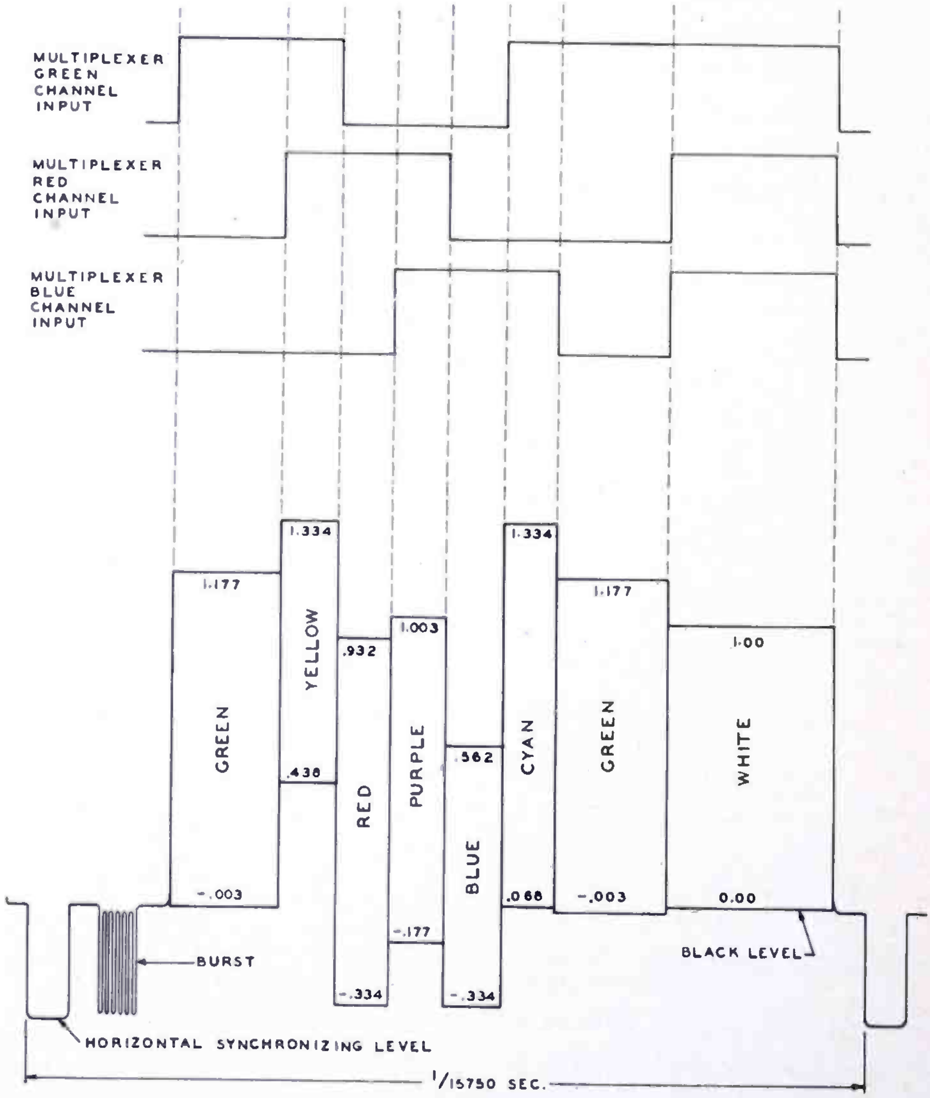

Fig. 11—(A) Inputs to the multiplexer from the synthetic color bar generator (above) and (B) resultant output signal from multiplexer (below).

multiplexer. The synthetic signal source employed in the present operations is a color bar test signal generator which produces the test signal shown in Figure 11A. With the signal from this generator, the multiplexer can be set with exactness by making prescribed inputs to the multiplexer deliver a calculated pattern as viewed on a cathode-ray oscilloscope connected to the output. In Studio 3H, the synthetic color bar generator delivers equal signals to each of the three inputs

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of the multiplexer. The time sequence of the signals applied to the three inputs of the multiplexer is as indicated in Figure 11A. The resultant signal on the output of the multiplexer when adjusted to the National Television System Committee (NTSC) field test standards[6] is as indicated in Figure 11B.

FIELD-TEST OPERATION

This studio and associated facilities have been in continual use since April, 1951 for purposes of the development of operating, lighting, and programming techniques, as well as over-all systems development and testing of the RCA color television system.

Many hours of field test transmissions have been made. Three sets of showings during the course of these field tests were presented during the months of July, September and October for the press, public and other interested groups. Each of these consisted of three showings a day for periods of one, two and three weeks, and included in addition to the studio portion, a short act from a remote point in the vicinity of New York. The remote pickup was accomplished by the use of a mobile unit which carried a duplicate of the studio cameras previously mentioned, working in conjunction with standard monochrome portable-type power supplies and sync generator. The signal was transmitted to the studio by means of standard 7000-megacycle link equipment.

These presentations were broadcast in New York on channel 4 (KE2XJV) from the Empire State Building whenever that transmitter was available for color experimental operation. Other points to which the color signals were fed during part or all of the periods mentioned included a viewing room adjacent to the studio, the Johnny Victor and Center Theatres in Radio City, and the Colonial Theatre on Broadway at 63rd Street, where the picture was viewed on a theatre-size screen by means of RCA color television projection equipment. The signals also were transmitted to the NBC studios in Washington, D. C., over both 2.7-megacycle coaxial cable and regular microwave facilities of the American Telephone and Telegraph Company, and portions of the field tests were also broadcast in Washington through the NBC experimental station KG2XDE, operating on channel 4.

Early in November, the studio and remote facilities were modified to operate in accordance with the Field Test Standards adopted by the National Television System Committee.[6] These modifications in-

[6] "Specifications for Color Field Test," *Electronics*, Vol. 25, p. 126, January, 1952.

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volved a change in the subcarrier frequency from 3.58 to 3.89 megacycles, and a change from symmetrical equal amplitude multiplexing to asymmetrical multiplexing. Field test transmissions using the NTSC signals were broadcast 5 days per week throughout the month of December and on a varying schedule during January and February. The field testing of the RCA color television system using the NTSC signal standards will continue.

ACKNOWLEDGMENTS

It is not feasible to indicate separately the contributions of the many individuals in the RCA and NBC organizations who have been active in the Color Television Systems Development project. The authors are pleased to present, in their behalf, this account of a portion of the project.

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RCA TECHNICAL PAPERS†

Fourth Quarter, 1951

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