RCA REVIEW

a technical journal

RADIO AND ELECTRONICS
RESEARCH • ENGINEERING

VOLUME VII SEPTEMBER 1946 NO. 3

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VOLUME VII — SEPTEMBER 1946 — NUMBER 3

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RCA REVIEW

INTRODUCTION

to

TECHNICAL PAPERS ON AIRBORNE TELEVISION

THIS issue of RCA REVIEW contains the first of a series of technical articles on **airborne television** — a system of sight transmission having momentous military and civilian applications. Prepared and written by scientists and engineers of Radio Corporation of America, they are presented to readers of RCA REVIEW as an historic record of pioneering and scientific progress.

The idea behind airborne television and its development originated in RCA more than twelve years ago. It was in the spring of 1934 that Dr. V. K. Zworykin formulated plans and submitted to me a memorandum suggesting the creation of such a system to serve as "electronic eyes" in guiding radio-controlled aerial torpedoes. At that early date, Dr. Zworykin foresaw the threat of Japan's "Kamikaze" or Suicide Corps, and sought to achieve by technological means what the Japanese hoped to attain by psychological training. I was so impressed that, accompanied by Dr. Zworykin, I went to Washington and presented his plans to the War and Navy Departments. Some time elapsed before the armed services became actively interested in airborne television, but our scientists, meanwhile, continued to experiment and pioneer with this revolutionary method of extending human sight. First Ray D. Kell and Waldemar Poch developed light-weight cameras and associated equipment. Then Henry Kozanouski joined in and produced research equipment which was field tested in an airplane. When the war emergency arrived, the entire organization was ready to meet the challenge.

Three airborne television systems — designated "Block", "Ring" and "Mimo" projects as security pseudonyms — evolved for secret wartime purposes. Television pick-up and transmitting equipment that once might have filled a large room was redesigned, modified and built to "suitcase" compactness for military uses in the Block system, which was employed effectively in the war by both the Army and Navy. The heavier, longer-range Ring system was developed during the final stages of the conflict by engineers of the National Broadcasting Company, Inc., in conjunction with the U. S. Navy. The Mimo equipment was the midget of the three systems, being even smaller than the Block apparatus. It was developed primarily for use in guided missiles where space was insufficient to accommodate the Block equipment.

The articles in RCA REVIEW will trace the development of the three airborne television systems and relate in technical terms how the special requirements were met for equipment that would operate satisfactorily under the unusual handicaps of aerial warfare. These reports will tell of the design of small antennas practicable for airplanes, the use of the airplane's power supply, and the overcoming of the problems of noise and vibration. Special emphasis will be given to the development of the now celebrated image orthicon tube. Accounts likewise will be printed of technical aspects in the development of other vital electronic tubes and equipment. The full text of Dr. Zworykin's original memorandum of 1934 is published in this issue.

Great praise is due the scientists and engineers whose research and pioneering, technical knowledge and ingenuity made possible airborne television as a successful weapon of war and opened the way for monumental progress in widening television's scope of service in peace.

DAVID SARNOFF, *President*
Radio Corporation of America

* * * * * * * *

The technical papers on airborne television referred to above are being included in this issue and that of December, 1946. It is not possible to follow a strictly chronological sequence since circumstances make it necessary to present the paper on the "Block" system in December, even though the development of this system preceded that of both the "Ring" and "Mimo." It is felt, however, that this will cause no confusion or difficulty.

Dr. Zworykin's 1934 memorandum is followed in this issue by the paper on the "Ring" system, and two papers on miniature airborne television—including the miniature image orthicon (Mimo) tube.

The December issue will include the paper on the "Block" system and a paper on television receivers.

The Manager, RCA REVIEW

FLYING TORPEDO WITH AN ELECTRIC EYE*

BY

V. K. ZWORYKIN

Director of Electronic Research Laboratory, RCA Laboratories Division
Princeton, N. J.

A **memorandum** sent to DAVID SARNOFF, *President, Radio Corporation of America,* on **April 25, 1934.**

Summary—*This paper, written in April, 1934, presents a detailed suggestion for the control of guided missiles using information obtained by television. Shortcomings of previous systems of guided missile control are briefly mentioned and a general description is given of the television apparatus for use in the new method of control. Approximate weight composition of such a television-controlled aerial bomb or torpedo is included. The suggestion envisions that the torpedo or bomb (or standard airplane) should be equipped both with automatic pilot control and remote radio control with the instrument and target data supplied by an iconoscope camera and transmitter in the piloted weapon.*

Television information furnished would be of two kinds, and would be given simultaneously: (1) an actual view of the target which could be sighted upon by means of crosshairs; (2) accurate information on the readings of instruments in the piloted weapon, given by the position of bright spots on the edges of the picture and read on scales attached to the receiving tube in the control ship. This latter feature is designed to facilitate the checking of instruments in the torpedo prior to release and also while in flight when actual target view is obscured and the automatic pilot is in control.

The particular significance of this paper lies in the large time interval which has elapsed since its preparation. This time element gives adequate proof of the author's foresight and ingenuity, particularly when the details of the system outlined are compared with those of systems in use today, 12 years later.

THERE have been quite a number of attempts to devise an efficient flying weapon. The aerial bomb is the simplest form, and the recent improvements in aerial ballistics make these bombs a most formidable modern weapon. The use of such a bomb usually requires a close approach of the bombing airplane to the target, thereby subjecting the plane to the barrage of the anti-aircraft batteries. It follows that, simultaneous with the development of aerial bombing, there has been improvement in anti-aircraft artillery which has considerably lessened the effectiveness of the aerial bomb.

Considerable work has been done also on the development of radio-controlled and automatic program-controlled airplanes having in mind their use as flying torpedoes. The possibilities of such airplanes were

* Decimal Classification: R583 × 560.

demonstrated repeatedly in various countries during the past few years. Both these methods, however, have the same fundamental difficulty, viz., that they can be used efficiently only by trained personnel at a comparatively close range, thereby being subjected to anti-aircraft gun-fire. Both radio and automatic-controlled planes lose their efficiency as soon as they are beyond visual contact with the directing base. The solution of the problem evidently was found by the Japanese, who, according to newspaper reports, organized a Suicide Corps to control surface and aerial torpedoes. The efficiency of this method, of course, is yet to be proven but if such a psychological training of personnel is possible, this weapon will be of the most dangerous nature. We hardly can expect to introduce such methods in this country, and therefore have to rely on our technical superiority to meet the problem.

General Description

One possible means of obtaining practically the same results as the suicide pilot is to provide a radio-controlled torpedo with an electric eye. This torpedo will be in the form of a small steep angle glider, without an engine, and equipped with radio controls and an iconoscope camera. One or several such torpedoes can be carried on an airplane to the proximity of where they are to be used and there released. After it has been released the torpedo can be guided to its target by short-wave radio control, the operator being able to see the target through the "eye" of the torpedo as it approaches.

The carrier airplane receives the picture viewed by the torpedo while remaining at an altitude beyond artillery range. It is not even necessary to have direct visibility of the target from this plane, as the information is supplied by the torpedo from a much closer range. The distance between the plane and torpedo will always be short; therefore the power of the short-wave radio transmitter on the torpedo can be very low. A transmitter of 5 or a maximum of 10 watts, operating between 3 and 10 meters, will be sufficient for this purpose. Since the image of the target increases in size as the torpedo approaches, it is not necessary to provide an electric eye with great resolution or with highly efficient optics. Therefore, an iconoscope camera operating with a 90-line picture and with a wide-angle lens will be sufficient for this purpose. When the torpedo is first launched from the plane it may not immediately supply any useful information to the control due to the excess height or intervening clouds, but when it begins to approach the ground the visibility will gradually increase and the accuracy of the aiming will be improved. At close range the target will be sufficiently large to provide good visibility even at 90 lines and the accuracy of the aiming will be the greatest just before the moment of contact of the torpedo with the target. This introduces an entirely new principle in ballistics, since in all existing methods the operator has no way of controlling a projectile once it has been released.

The radio receiving equipment of the torpedo can also be simplified by using a directional and more powerful radio transmitter on the mother plane and also by a decrease in the width of the communication channel, due to the necessity of transmitting from the controlling plane only three or four sets of signals. This can be accomplished by a short-wave carrier modulated with widely separated frequencies. The necessary electrical supply for the torpedo is easily obtainable from a propeller-driven generator with several commutators supplying all necessary direct-current potentials.

The radio control of the torpedo can be accomplished by using one of the already-developed schemes, but can be considerably simplified by using, for control purposes, a circuit and tubes which were developed during the past couple of years in connection with radio communication.

It is very difficult to specify at present the probable weight of the total electrical equipment without actually building a model. A preliminary estimate shows that the total weight of the equipment with automatic pilot, including wind-driven generator, will be below 150 pounds, or less than the weight of one pilot. This weight is composed of the following items:

(1) Iconoscope camera for 90 lines with deflection and tilting arrangement, and short-wave radio transmitter with modulation up to 100,000 cycles and 10 watt power	40 pounds
(2) Wind-driven generator for 1000, 300 and 6 volts—125 watts, and three control drums	45 pounds
(3) Short-wave radio receiver for 3 audio tuned channels with relays	15 pounds
(4) Automatic pilot with controls and accessories	40 pounds
Total	140 pounds

The weight of the torpedo can be composed, for instance, of: Control equipment — 140 pounds; fuselage — 120 pounds; explosives — 300 pounds, making the total weight 560 pounds per unit.

Due to the fact that the torpedo has no landing speed, the load per square foot of the wing area can be increased several times in comparison with that of an airplane, therefore the whole torpedo can be made very compact. Four such torpedoes can be packed under the wings of a normal sized bomber. If necessary, the amount of explosives indicated above can be increased by increasing the size of the torpedo.

An approximate idea of the appearance of such a torpedo is shown in Figure 1, which, of course, is probably very far from the actual shape that such a torpedo will have after its final development.

Iconoscope Camera and Transmitter

The iconoscope camera has already been developed by us for television purposes. However, due to the decrease of the required number

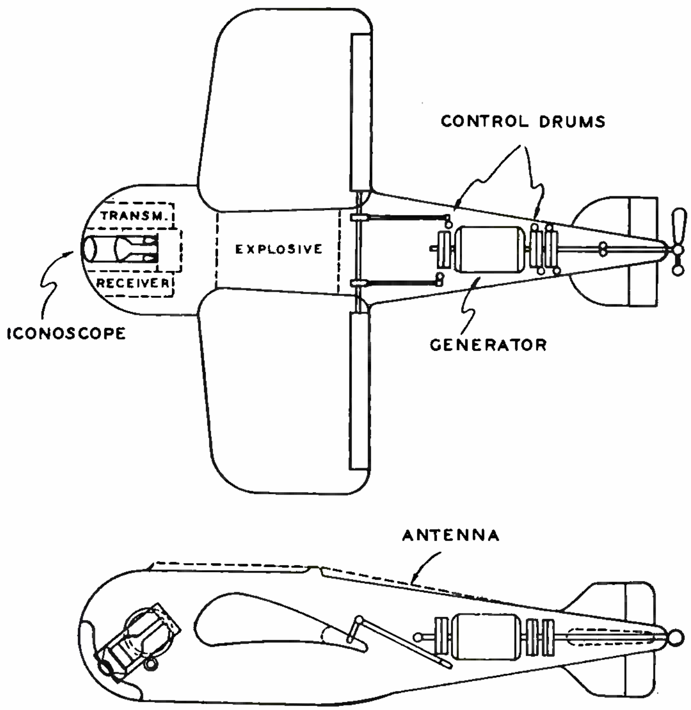

Fig. 1—The Flying Torpedo.

of lines from the present 340 to 90 lines, the whole apparatus will be substantially simpler and smaller. The associated circuits for deflection of the electron beam and the amplifier will contain only a fraction of the number of tubes used in the present system.

The camera mounting is provided with a tilting arrangement, which points it always in such a manner that the center of the received picture coincides with the point to which the torpedo is heading. The tilting is controlled by the same device which controls the level flight of the torpedo and which will be described later. The optical lens of the camera is provided with a sighting cross-wire which, on the reproduced picture, gives the point on which to sight the torpedo.

It appears that it is desirable to watch from the controlling plane not only the picture viewed by the torpedo, but also the condition of the controls of the torpedo, the acceptance of the controlling signals, altitude, etc. This is particularly important if the torpedo is not launched directly at the visible target, but has to pass first through intervening clouds. Such an arrangement can easily be achieved prac-

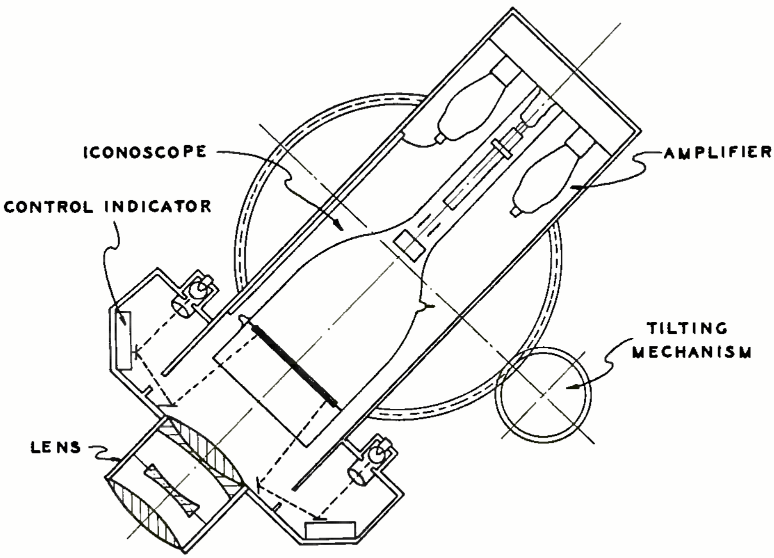

Fig. 2—Iconoscope camera for the Flying Torpedo.

tically without introducing any additional complication in the camera circuits. All the necessary information can be transmitted on the edges of the picture by projecting the small light spots on the sensitive mosaic of the iconoscope. These spots are reflected by mirrors attached either to the controlling mechanism directly, or through the medium of small sized electric motors. This arrangement is shown in Figure 2.

In this way, the information will be given by the position of bright spots on the edges of the picture and can be read accurately on scales attached to the receiving tube in the controlling ship. Since all instruments can be set in operation while the torpedo is still attached to the controlling ship, the function of these instruments, and therefore the preparedness of the torpedo for action, can be checked all the time and particularly just before its launching. It is easy to provide the adjustment connection which would enable the operator on the controlling ship to reset the instruments in the torpedo according to the reading of the accurate instruments of the controlling ship. Due to the fact that the actual free flight of the torpedo will take from one to a maximum of 10 minutes, this initial setting will be kept by the instruments of the torpedo, and the readings on the scale attached to the receiving tube will be very accurate. The appearance of the picture on the receiver with the control indicating spots is shown in Figure 3.

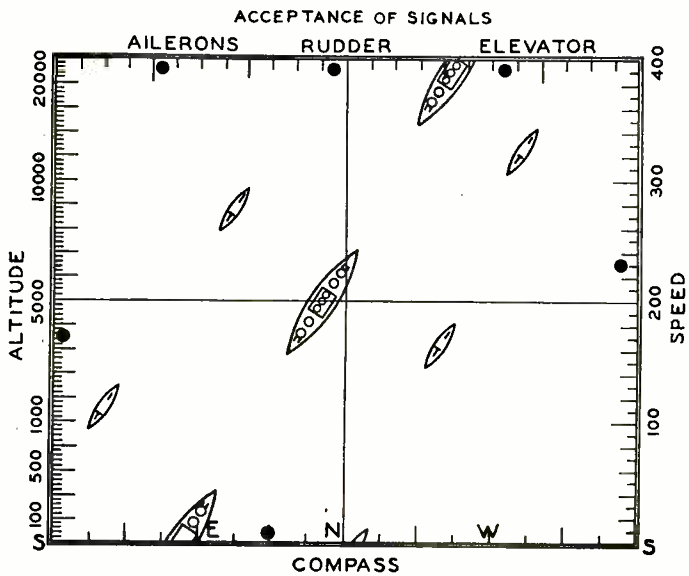

Fig. 3—Sketch of a typical scene reproduced by the Flying Torpedo.

The radio transmitter for the 90-line picture with 16 frames per second requires a modulation band of approximately 100,000 cycles, or only one-tenth of what we are using in our present television system. Such a transmitter for 10 watts output is very simple and requires a small number of tubes. The antenna will be located on top of the fuselage and combined with the receiving antenna.

Power Generator

The voltages necessary to operate the picture transmitter as well as the radio receiver and most of the controls can be confined to three potentials of 1000, 300 and 6 volts. The total power requirement will be about 125 watts. A conventional wind-driven generator with three commutators and automatically adjustable propeller will answer the purpose. The shaft carrying the generator also has three drums, which supply the power for the controlling mechanisms.

Controls

To guide the torpedo from the mother plane, the controlling signals are supplied by the second radio channel, also on ultra-short waves, from the transmitter located on the mother plane. The sensitivity of the radio receiver on the torpedo can be very low, on the order of 10 millivolts. Signals operating the different controls can be separated from one another by sharply tuned filters in the output of the radio receiver.

In order that the torpedo will respond quickly to the controlling signals, the power necessary to move the rudder, elevators and ailerons is taken from drums rotated by the same propeller-driven shaft which carries the generator. Each drum has two friction bands which can be energized by the output of the amplifying tube. This energizing is accomplished either by a relay which tightens the grip of the band around the drum, or directly by an electrostatic or electromagnetic field supplied by the output of the control tube to the band. These two friction bands are connected to a corresponding controlling device, for instance, the rudder, moving it in either of two opposite directions. The shaft operating the rudder carries two potentiometers varying the biases of the corresponding controlling tubes in such a way that the tube which is energized, and therefore moves the rudder in one direction, is biased gradually negatively and the opposing tube at the same time is biased positively. This biasing serves two purposes: First, it allows the control to operate fastest near the neutral position and slow down according to the prescribed formula with the increase of the angle of rotation. It also checks the maximum permissible controlling angle. When the controlling impulse ceases then both tubes, the one which just functioned and the opposing one, will be in an unbalanced state and immediately start to move the controlling element toward the neutral position.

The banking of the torpedo will not require a separate controlling signal because it is possible to arrange the banking to follow automatically the controlling directional signal. This is accomplished by coupling the tube of the rudder so that the movement of the rudder will be automatically followed by the movement of the ailerons according to the prescribed relation. If necessary, this movement can also be made a function of the speed of the torpedo by operating the bias of the aileron control tube from the altimeter or the rate-of-descent indicator. In this way, the banking can always be made exactly right regardless of the speed at which the torpedo turns.

Automatic Pilot

Where the torpedo is to be used against an objective that is not visible from the launching point, it will be necessary to equip it with an automatic pilot as well as remote control. The additional apparatus necessary to accomplish this does not add greatly to its weight or complication.

Stabilization of the torpedo when it is not under remote control is accomplished by two gyros. The construction of these gyros can be the same as the gyro employed in the "artificial horizon" or in the "directional gyro." They are operated either by air from the Venturi tube, or by an electric motor supplied by the main generator. The gyros ought to be fully stabilized, but can be made much smaller than the gyros used in the above mentioned instruments. The control of these gyros is accomplished by means of a mirror, attached to the gyros, which reflects a beam of light into the photocells. The photocells are arranged in pairs serving as two arms of a Wheatstone bridge. The cells, or rather the openings through which the light falls on the cells, are of a wedge shape, as shown in Figure 4.

By this arrangement, the reflected light at zero position of the gyro produces two equal impulses in both cells and therefore balances the bridge. When the body of the torpedo turns with respect to the gyro, the line of light begins to turn with respect to the neutral axis and increases the impulse in one of the cells, decreasing it in the other. At the limiting angle, the impulse from one cell will be zero and maximum in the second, giving a maximum unbalance. Of course, the shapes of the openings can be made according to any prescribed condition so that the change in impulses can follow a desired mathematical relation between the turn of the bomb and the condition of the electrical circuit. By using an alternating-current amplifier tuned to the frequency of the rotation of the gyro, multiplied by the number of mirrors attached to it, it is possible to operate the amplifier, not only from the actual displacement of the torpedo, but also from its first or second derivative, thereby increasing the sensitivity of the controlling circuit. In order to set the control to a desired condition, it is necessary only to turn the housing with the photocells and gyro to a certain angle in respect to the axis of rotation of the stabilizing gyro. This will upset the equilibrium condition of the circuit and will energize the controlling tubes operating the controlling bands, as mentioned in the description of the remote control of the system. When the torpedo attains the new prescribed flying condition the circuit is again balanced and the course of the torpedo will coincide with the neutral position of the controlling gyro. In this way, any outside influence such as a gust of wind, air pockets, etc., which affect the initial course of the torpedo, will be corrected immediately by the controlling gyro.

In order to keep the torpedo under control when the controlling signals cease, the automatic control should be adjusted to a new set of

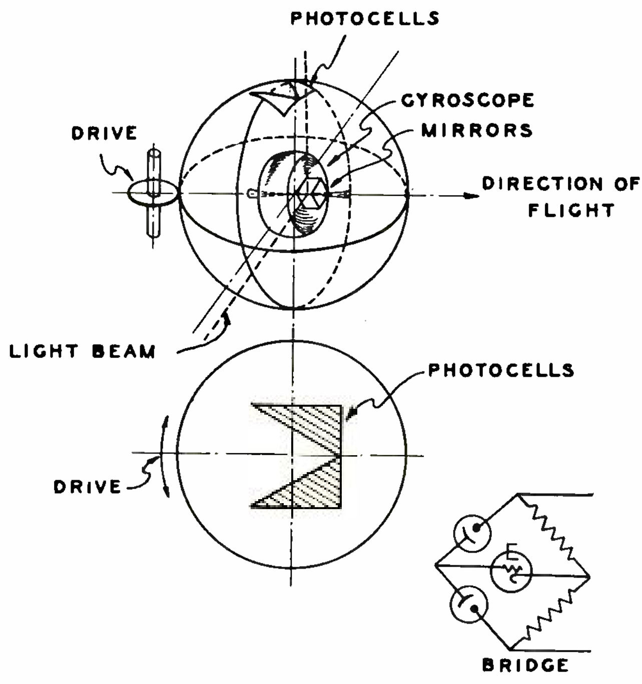

Fig. 4—Control mechanism of the Flying Torpedo.

conditions prescribed by the controlling signals. For this purpose, when the controlling signal changes the initial course of the torpedo, the position of the photocells with respect to the controlling gyro will automatically reset itself to balance the bridge according to the new set of conditions, and therefore will be automatically established for this new course in the controlling gyro circuit. The motion for this adjustment of photocells can be made either by friction from the same drums, or can be provided by separate small electric motors.

Method of Operation

When the torpedo is attached to the mother plane, provision is made to manually adjust all the necessary instruments according to the more accurate instruments located in the mother plane. Also, all the apparatus and controls of the torpedo can be checked by starting the camera and observing the position of control indicators in the receiver.

If the torpedo is to be launched directly at the visible target, the control is very simple and all that is necessary is to keep the center of the picture or the cross-wire sight on the target all the time. For this kind of operation, the automatic pilot is unnecessary; therefore, if only this type of operation is expected, the equipment for the automatic pilot can be omitted. If, while the torpedo is approaching the target, it becomes clear that due to the faulty steering, cross winds, etc., it may miss the target, it is entirely possible to steer the torpedo through a loop, gain altitude and repeat the attempt two or more times before its speed is lost, preventing the further repetition of this maneuver.

It may be desirable to launch the torpedo while the mother plane is at a very high altitude, or screened from the target by intervening clouds, with only approximate information of the position of the target. In this case, the torpedo is launched down in a spiral glide and kept under control of the automatic pilot and also under manual control by observing the controlling marks on the picture. When the torpedo descends low enough to make the target visible, then the target can be brought into coincidence with the cross-wire sight and the torpedo started to glide directly to the target.

A more elaborate form of this torpedo is a regular airplane equipped with an engine and the same controls as described above. This plane can be launched either from a small surface craft or from the shore at a very distant target, and then controlled according to the picture received through the iconoscope camera. This makes this new weapon very versatile since it can be used both on the sea and land.

NAVAL AIRBORNE TELEVISION RECONNAISSANCE SYSTEM*

BY

R. E. SHELBY, F. J. SOMERS AND L. R. MOFFETT

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Summary—*A high fidelity long range television reconnaissance system developed during World War II for the Navy Department is described. The Project Ring equipment was designed for multi-camera attended operation at 20 frames/second, 40 fields/second, 567 lines/frame interlaced and utilizes a 5 megacycle video bandwidth. A high power (1400 watt peak) airborne television transmitter is employed. The maximum plane-to-ground transmission range attained during tests was over 200 miles. Very consistent operation with satisfactory signal-to-noise ratio has been obtained with this equipment at ranges of 100 miles or more with the aircraft flying at altitudes of 7000 to 10,000 feet. The equipment differs from the light weight simplified television gear designed during World War II for unattended operation in guided missiles.*

INTRODUCTION

DURING World War II two general types of airborne television equipments were developed for the U. S. Armed Forces. One type, known by the code designation "Block" was a simplified, light-weight system designed for unattended operation in drone aircraft and guided missiles. A second type, described herein, was developed for long-rang, high-altitude reconnaissance operations. This equipment was designed for attended operation, with weight and complexity considerations secondary to the production of high definition television pictures suitable for airborne military reconnaissance. The project under which the development was carried out was known by the code designation "Ring".

Work on Project Ring was initiated in November 1942 when standard broadcast type transportable television pickup equipment utilizing the type 1840 orthicon camera tube was demonstrated to representatives of the Navy Department and Marine Corps. As a result of this demonstration, in which the pickup equipment was installed on the 85th floor of the Empire State Building to simulate an aircraft at 1000 foot altitude, it was concluded that the information presented by the television screen probably was sufficiently detailed to have value for airborne military reconnaissance. In order to check this conclusion, it

* Decimal Classification: R583 × R520.

was necessary to conduct a series of actual flight tests using television pickup equipment installed in aircraft. Accordingly, arrangements were made by the Navy to carry out such tests at the Naval Air Station, Banana River, Florida using a PBY-4 "Catalina" flying boat.

In making these preliminary flight tests, the use of readily available equipment, even though designed for a different service, was dictated by two factors—the need for a quick answer on the possibilities of television reconnaissance, and the lack of adequate previous experience or data on which the design of specialized high-fidelity equipment might be based. In order to make a start, therefore, standard commercial transportable television pickup gear utilizing the type 1840 orthicon tube, was mounted in the PBY-4 aircraft. The equipment consisted of two cameras, one in the bow position and the other in the waist gunner's position arranged to view from the starboard machine gun blister with the latter open. The cameras were connected via standard multi-conductor cables to the control position, which was located amidships in the space normally used by the navigator. At the control position were the camera control units with their self-contained video monitors, the master switching unit with its monitor showing the outgoing picture, the synchronizing generator and the electronically-regulated power supply rectifiers. A photograph of the control position installation is shown in Figure 1.

In order to obtain sufficient power at 115 volts 60 cycles alternating current for operation of the television equipment, a special auxiliary power unit had to be installed in the aircraft. Here again, it was necessary to use equipment which was readily obtainable. An available 5-kilovolt-ampere, 115-volt, 60-cycle, gas-engine-driven alternator was mounted in the compartment aft of the control position. This unit weighed several hundred pounds and had to be dismantled and then reassembled inside the aircraft in order to place it in position.

A low power video transmitter (60 watts peak), developed for another application, was adapted for the experiments to expedite the work. The receiving equipment on the ground consisted of Navy type Block 1 television receivers feeding viewing monitors equipped with 12-inch kinescopes. A projection type viewing monitor, utilizing refractive optics and producing a picture 18″ x 24″ in size, was also installed at the ground station.

The ground station receivers, having been designed for airborne use, were operated from 28 volts direct current. The viewing monitors were modified commercial television receivers and were operated from the local 60-cycle mains. The transmission standards used were the 525 line, 30 frame, 60 field interlaced commercial broadcast standards for which the equipment (except the Navy Block I receivers) was designed. The transmitter operated on a carrier frequency of 90 megacycles with an effective bandwidth of 4.5 megacycles on each side of the carrier. Negative transmission (maximum carrier amplitude corresponding to tips of synchronizing pulses) was used. The antenna polarization was vertical. This polarization was chosen principally because it is simpler to obtain uniform azimuthal radiation from an aircraft with a vertical antenna.

A comprehensive series of flight and ground tests using this hastily assembled airborne television system was conducted during the spring and summer of 1943 at the Naval Air Station, Banana River, Florida,

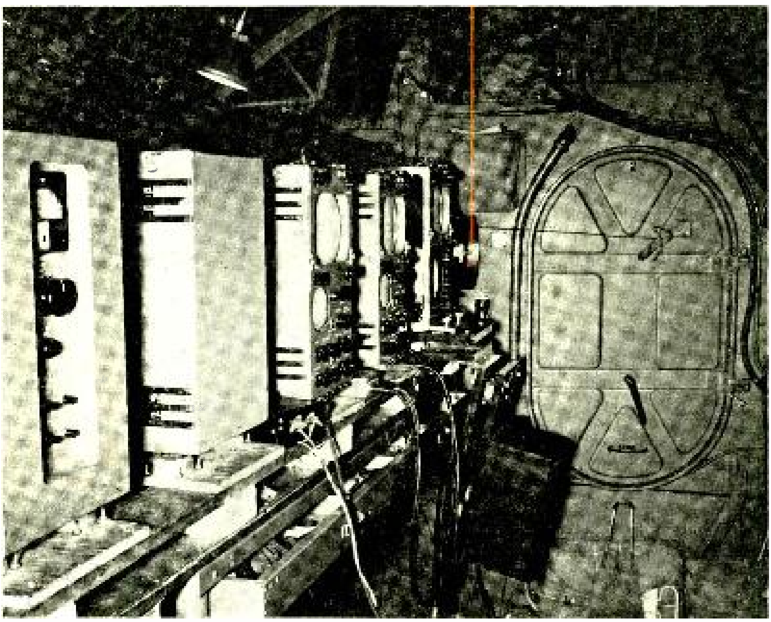

Fig. 1—Control position in PBY-4 aircraft installation using commercial television equipment.

culminating in a demonstration for Navy, Marine Corps and NDRC personnel in September of that year.

Results of Initial Airborne Tests

These initial tests using available commercial television equipment in an airborne system provided information and experience on which to base the design of specialized airborne television equipment.

This experience and information may be classified under the follow-

† NDRC—National Defense Research Committee.

ing headings:

(a) General electrical and mechanical requirements for airborne television equipment.

(b) Desirable operating and maintenance features in airborne television equipment.

(c) Purely technical features, such as transmitter power output, types of antennas, practical video bandwidths, etc.

A brief summary of the conclusions drawn from the results of these tests is given in the following paragraphs.

In regard to the general electrical and mechanical design requirements for airborne television equipment, it may be said that they are similar to the requirements for satisfactory airborne radar or radio communication gear. Ruggedness, compactness and light weight, as well as the ability to operate satisfactorily over wide ranges of altitude, temperature and humidity are required of airborne television gear. In addition, special precautions must be taken to eliminate microphonic disturbances, as television equipment is more susceptible to this type of trouble than either radar or communication equipment. Microphonic effects in communication equipment can be minimized through the use of a restricted audio bandwidth, (200 to 2500 cycles, for example), special high-level microphones and reasonable care in the application of mechanical vibration isolators. In the case of radar, most systems do not deal with low-level signals below 500 cycles per second. On the other hand, an important part of the energy and information in a television signal is included in the frequency range from 20 or 30 cycles to 1000 cycles per second and these frequencies must be dealt with in low-level video amplifier stages. The designer of airborne television equipment must, therefore, observe special precautions to minimize the effects of vibration and acoustical noise if microphonic effects are to be minimized.

The initial flight tests using commercial transportable television equipment also served to emphasize the practical operating requirements for airborne gear. The equipment should be simple to operate. All electrical adjustments should be made at the control position, leaving the camera operators free to direct the cameras, change lenses and adjust lens iris stops as required. All electrical controls which may have to be changed in flight should be equipped with adjustment knobs rather than being left as "screwdriver adjustments" as the latter are not practical when operating in bumpy air. Also, complete equipment bench test facilities should be provided at the ground station for servicing the airborne equipment, as only a limited amount of servicing is possible when the aircraft is in flight. Ground test facilities should also include an auxiliary power source for pre-flight ground checks of the operation of the equipment prior to take-off.

Definite conclusions on the technical requirements for a satisfactory airborne television system were drawn from the initial tests. Some of these are:

1. The television pickup equipment preferably should include two cameras, one with a short focal length lens for wide angle views and the other with a long focal length lens for telephoto views.
2. All electrical adjustments should be made by an operator at a master control position. The master control position should provide facilities for rapid switching of the output of either camera to the video transmitter. The master control operator should be provided with an oscilloscope, for checking video signal levels, and two video monitors. Switching facilities should be arranged so that either of the monitors or the oscilloscope can be independently switched to camera No. 1 video output, camera No. 2 video output, the input to the modulator of the video transmitter, or to the output of a radio frequency detector coupled to the transmitting antenna.
3. Means should be provided for rapid checking of the depth of modulation of the video carrier during the operation of the transmitter and pickup equipment.
4. Interlaced scanning should be used to gain the maximum picture resolution, within the limits of tolerable image flicker for a given video bandwidth.
5. The video transmitter should have adequate power output to provide reliable picture transmission up to 100 miles.
6. Special precautions should be observed to eliminate the effects on interlaced scanning of power supply frequency differences between the airborne power supply and the ground station power supply.
7. The type 1840 orthicon was found to be unsatisfactory for airborne operation under illumination conditions combining both high peak scene brightness and high scene contrast. The iconoscope type pickup tube, though satisfactory in this respect, is lower in light sensitivity than is desirable for general airborne use. It was therefore concluded that newer developmental types of tubes, which gave promise of improved results, should be considered in the design of specialized equipment for airborne use.

As a result of these tests, a study of general military television requirements, observations and reports on other military television equipments, and a study of commercial television systems, recommendations and specifications for a set of airborne television reconnaissance equipment were drawn up and submitted to the Bureau of Ships of the Navy Department. It was considered that a practical airborne television reconnaissance system should provide reliable picture transmission over a distance of at least 100 miles with the aircraft at an altitude of 7000 feet. Having settled on the range requirements, the other features of the proposed system—keeping in mind that maximum image resolution was required—were largely determined by the practical limitations imposed by such factors as the maximum practical video transmission bandwidth, the minimum frame repetition rate within the limits of tolerable image flicker and blurring (due to the relative motion between the aircraft and objects on the ground), attainable signal-to-noise ratios, and the state of the television art at the time. Determination of the system standards is discussed in the next section.

System Design

The radio propagation characteristics between an aircraft at various altitudes and distances and a receiving antenna 30 feet high is shown for vertical polarization over sea water by the theoretical curves[1, 2] of Figure 2. Figure 3, which gives calculated[1, 2] values for horizontal polarization over land, is considered to be reasonably accurate also for vertical polarization. Supplementing the above propagation studies, it was determined by measurements on practical television receivers and the results of the initial flight tests at Banana River, that, in this application, the minimum useable signal at the receiver input terminals would be on the order of 50 microvolts, (5-megacycle video bandwidth). From the above data, it was estimated that for a 100 mile range (aircraft at 7000 ft.) with a vertical dipole receiving antenna 30 feet above the ground, the average carrier power output of the transmitter should be in excess of 200 watts (800 watts peak). Vertical polarization of the antennas was chosen because of its non-directional characteristic in the horizontal plane; also, cancellation of the direct path and multi-path signals is not as severe, especially at relatively short distances with the aircraft at high altitudes, as when horizonal polarization is used.

Consideration of various limiting factors, such as weight, size, the

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[1] K. A. Norton, "The Effect of Frequency on the Signal Range of an Ultra-High Frequency Radio Station with Particular Reference to a Television Broadcast Service", Statement made before the Federal Communications Commission, Television Hearing, Report No. 48466, March 20, 1941.

[2] K. A. Norton, "The Calculation of Ground-Wave Field Intensity Over a Finitely Conducting Spherical Earth", *Proc. I.R.E.*, Vol. 29, No. 12, pp. 623-639, December, 1941.

required power output, available carrier frequencies and the requirement for maximum video bandwidth led to the design of an amplitude modulated video transmitter producing an average carrier power output of 350 watts (1400 watts peak) with a video bandwidth of 5 megacycles (i.e. 5 megacycles above and below the carrier frequency), operable at carrier frequencies of either 90 or 102 megacycles.

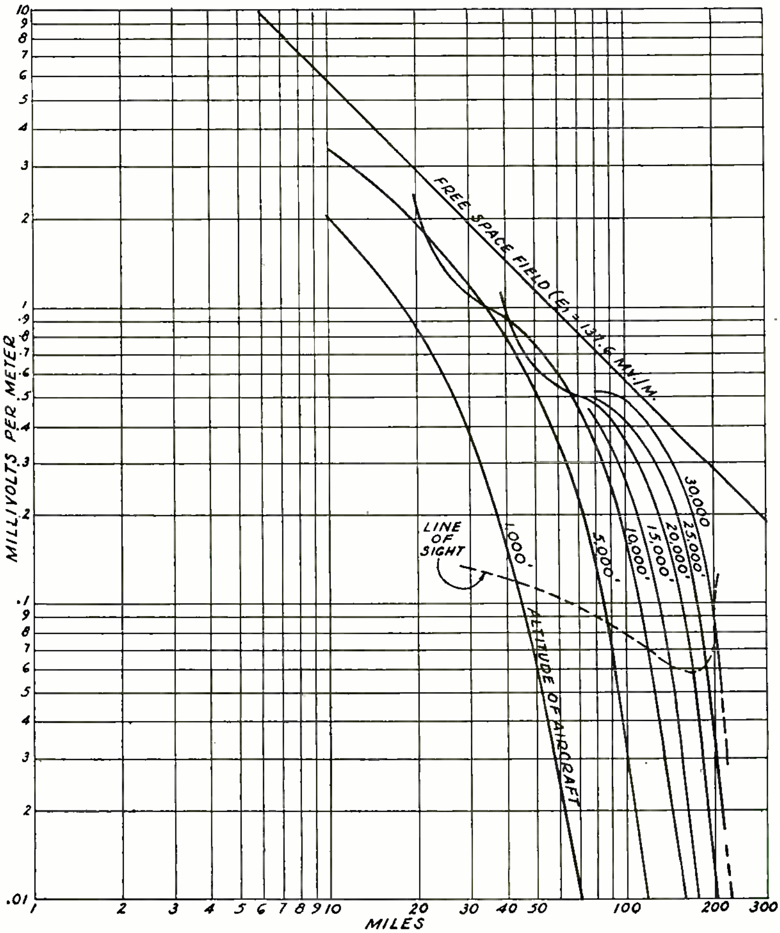

Fig. 2—Calculated field strength intensity versus distance for the indicated altitudes of the aircraft. (Receiving antenna 30 feet high, 200 watts radiated power at 100 megacycles, for vertical polarization over sea water with a ground conductivity of 4.3 mhos/meter and a dielectric constant of 81.)

Figure 4, which is a plot of actual flight test data obtained with a developmental model of this transmitter, shows that this power output is adequate for the required transmitting range and shows good correlation with the calculated curves of Figures 2 and 3. While a video bandwidth greater than 5 megacycles could have been obtained with this design at a correspondingly lower power output, the 5 megacycles was chosen as the best compromise value.

Having determined the video bandwidth (5 megacycles), the next

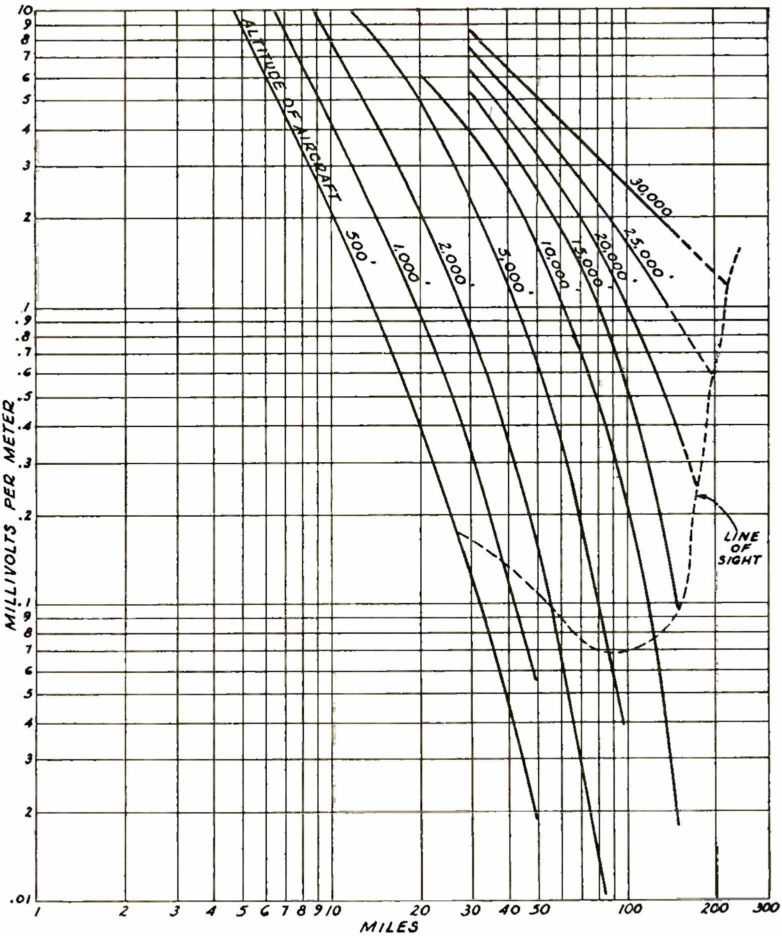

Fig. 3—Calculated field strength intensity versus distance for the indicated altitudes of the aircraft. (Receiving antenna 30 feet high, 200 watts radiated power at 105 megacycles, for horizontal polarization over land with a ground conductivity of 5×10^{-14} electromagnetic units and a dielectric constant of 15.

step in the design was to select the system standards to attain the greatest practical image resolution. To secure the maximum amount of information in the television image, it is desirable to operate at the lowest frame repetition rate practicable. However, the frame rate cannot be reduced below the point where blurring occurs due to the relative movement between the aircraft and objects on the ground or where image flicker becomes troublesome. In addition, interlaced scanning is dictated if maximum picture resolution with minimum flicker is to

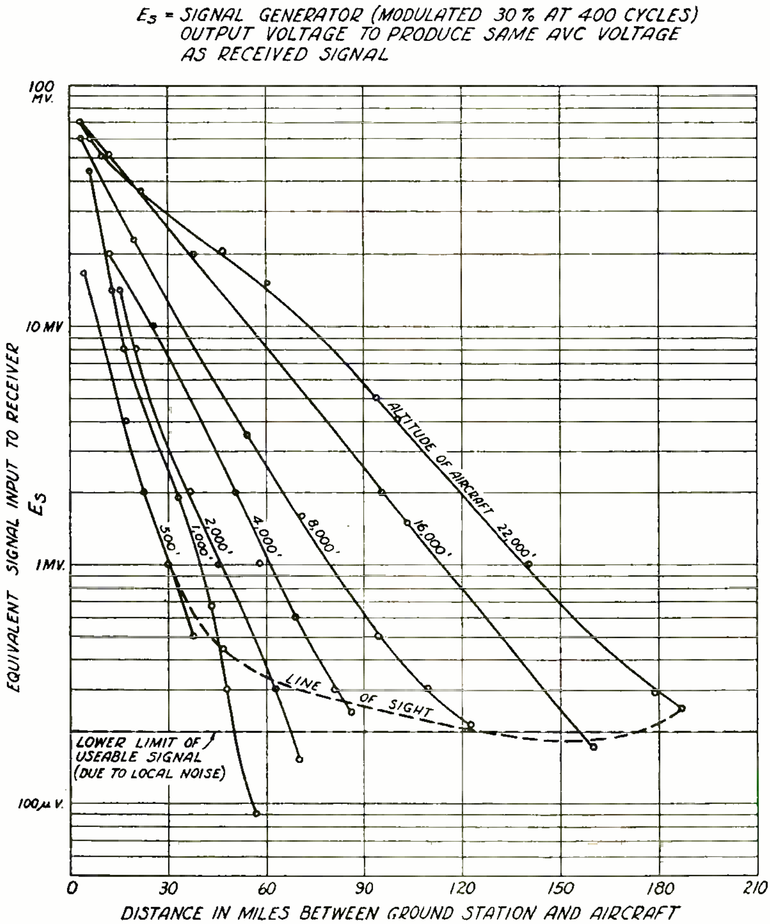

Fig. 4—Measured values of relative signal input to the receiver versus distance, the aircraft flying at the altitudes indicated, receiving antenna height 30 feet, and 350 watts radiated power. (Multiply E_s by 0.2 to obtain the approximate field strength at the receiving antenna.)

be realized. As a result of a number of laboratory tests to determine minimum frame frequency, it was found that a frame repetition rate of 20 per second with a field frequency of 40 per second (2:1 interlaced) was the lowest practical value that could be used for this application. The amount of flicker produced by this low frame rate is greater than would be acceptable for entertainment television but is tolerable for television reconnaissance. The aspect ratio of the image was chosen to be 4:3, the same as commercial television standards, after due consideration of military requirements. The Project Ring standards and commercial television standards are compared in Table I. The theoretical total numbers of picture elements per frame for the two systems are included as a matter of interest. The theoretical resolution, however, generally cannot be fully realized in practice for various reasons, such as the relative movement between the object being televised and the camera, aperture effects of the camera pickup tubes and the receiver kinescopes, the effects of shot and thermal noise, residual phase distortion in the overall system and other practical limitations.

Table 1

	Project RING	FCC Standards
Video bandwidth—megacycles	5	4.25
Fields per second (2:1 interlaced) .	40	60
Frames per second	20	30
Aspect ratio	1.33	1.33
Vertical blanking—per cent of field period	8 per cent	7 to 8 per cent
Horizontal blanking—per cent of line period	18 per cent	16 to 18 per cent
Lines per frame	567	525
Line frequency	11,340	15,750
Vertical resolution (lines)	522	483
Horizontal resolution (lines)	500	311
Horizontal resolution × Aspect ratio	667	415
Total picture elements/frame	348,174	200,445

In the above choice of standards, the horizontal resolution of the system has been made approximately equal to the vertical resolution. The horizontal resolution (lines) is:

$$N_h = \frac{2f\ (1 - T_v)\ \ (1 - T_h)}{N_v\ \ \ (a)\ (r)}$$

where f is the video bandwidth in cycles, T_v is the fraction of the vertical period devoted to blanking, T_h is the fraction of the horizontal period devoted to blanking, N_v is the number of lines per frame, a is the aspect ratio and r is the number of frames per second.

To simplify the design of the synchronizing generator, as well as to reduce its weight and size, a somewhat simplified type of synchronizing signal was chosen for interlaced scanning. This type of synchronizing signal, developed by RCA Laboratories Division,[3, 4] is shown in Figure 5. This waveform is not as flexible as to the number of different ways it may be utilized in a television receiver as is the synchronizing signal prescribed by the Federal Communications Commission for commercial television broadcasting. The integration time required for vertical synchronization, to secure a well-interlaced picture, is several times longer than that required by the standard commercial synchronizing waveform. However, this type of synchronizing signal has proven satisfactory for this application and resulted in the saving of at least ten tubes and associated components in the synchronizing generator.

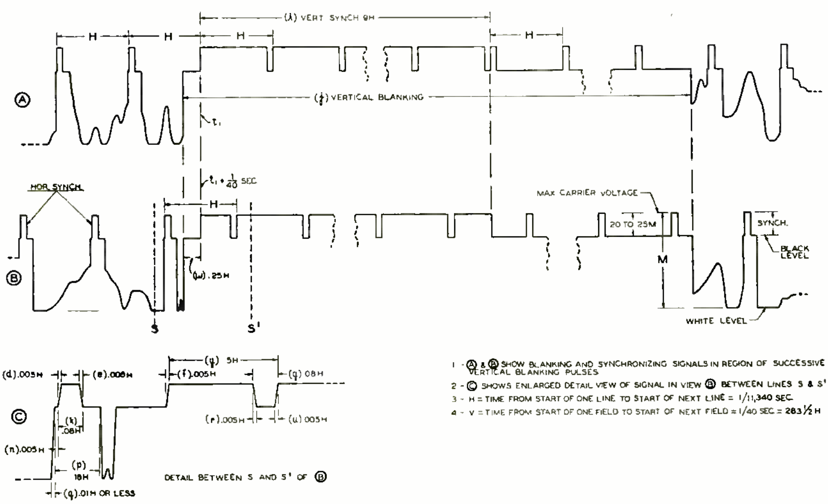

Fig. 5—Synchronizing signal waveform used for Project Ring.

In addition to the above standards which have to do with scanning and video bandwidth, it was necessary to standardize on several other items. It was decided to use amplitude modulation and transmit both side bands. The choice of amplitude rather than frequency modulation was based upon the following considerations:—

1. A great deal more experience was available in the use of amplitude modulation for video transmission than in the use of frequency modulation.

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[3] A. V. Bedford, "Synchronizing in Television", RCA Report prepared for use by Panel 8 of the National Television Systems Committee, October, 1940.

[4] D. G. Fink, TELEVISION STANDARDS AND PRACTICE, McGraw-Hill Book Company, New York, N. Y., 1943.

2. Pre-war field tests employing FM† with vestigial side band transmission and without limiting in the receivers gave results that were unsatisfactory, since this system was considerably more vulnerable to multipath transmission effects than was the standard AM* system.
3. Theoretical studies and laboratory tests had been reported showing that a FM† signal would be more vulnerable to multipath effects than an AM* signal.[5]
4. Under an NDRC contract covering work on the Block project, comparative tests were made between FM† and AM* using airborne transmitters operating near 300 megacycles. This work was not carried to conclusion but the preliminary results obtained indicated again that FM† was more vulnerable to multipath effects than was AM.*

Offsetting the above unfavorable experience with FM for television transmission was the highly successful use of FM for a 500 megacycle television relay link reported by RCA Communications, Inc.,[6] and other work done utilizing FM for airborne television transmission.

In view of the above uncertainty, it was decided that the safest course would be to employ amplitude modulation for this application. It is emphasized, however, that this finding should not be construed as necessarily applying in the future, particularly at higher frequencies and with the application of more thorough development of FM for television.

The decision to transmit both side bands was based purely upon the desire to avoid the additional weight and complications of a side band filter in the airborne transmitter. Under many conditions, vestigial side band operation of the receiver was utilized by proper detuning of the receiver circuits.

Negative transmission (i.e. the tips of the synchronizing pulses corresponding to maximum carrier amplitude) was chosen for Project Ring for the same reasons which led to its choice for commercial television broadcasting—principally because interference produces, in such operation, less objectionable effects in the received picture than with positive modulation.

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† FM—frequency modulated or modulation.

* AM—Amplitude modulated or modulation.

[5] Murlan S. Corrington, "Frequency-Modulation Distortion Caused by Multipath Transmission", *Proc. I.R.E.*, Vol. 33, No. 12, pp. 878-891, December, 1945.

[6] F. H. Kroger, Bertram Trevor and J. Ernest Smith, "A 500-megacycle Radio-Relay Distribution System for Television", RCA REVIEW, Vol. V, No. 1, pp. 31-50, July, 1940.

Choice of Power Supply

The presence in a television receiver of power supply hum of a frequency different from the field repetition rate usually makes interlaced scanning operation difficult. Considerable trouble from this source was encountered in the early tests with the PBY-4 installation at Banana River. In that case, the efficiency, and therefore the speed, of the gas engine driving the airborne power supply would change with altitude in such a way that the power supply frequency would be several cycles per second lower than the nominal 60-cycle value by the time the aircraft had reached an altitude of 5000 feet. At the same time, the local ground station power supply, also nominally 60 cycles, would vary above and below this value at different times of the day. This resulted in a situation where the airborne and ground power supply frequencies would often be different by several cycles per second. Under these conditions, a good interlace was always obtained on the monitors in the aircraft. The airborne synchronizing generator and therefore the vertical scanning frequency was locked in with the airborne power supply; consequently, any residual power supply hum in the pickup or monitoring equipment did not show up in the airborne video monitors as it produced a steady and almost unnoticeable pattern on the television picture. (The vertical scanning frequency automatically remained synchronous with the airborne power supply alternator even though the latter varied in frequency). Considerable trouble with interlace was experienced at the ground station due to this power supply frequency difference because the electrical filtering and shielding of the modified commercial television receivers used as monitors was inadequate for operation from a power source not synchronous with the vertical scanning frequency. Trouble from this source was minimized by additional filtering and shielding of the monitor circuits and kinescopes against power supply hum effects.

Obviously, use of pure direct current power supply sources for the airborne and ground equipments would have been an ideal solution to this problem. However, such a solution for the airborne equipment would have been uneconomical because of the amounts of power required and the number of different direct current voltages needed. An all-direct-current power supply system using individual dynamotors operated from 28 volts also would weigh more and be less efficient than an equivalent alternating current system.

A practical solution to the airborne power supply problem, in the case of the equipment specially designed for Project Ring, was found in the use of a combination of 28-volt direct current and 115-volt 400 to 2400 cycles alternating current power sources. The 28-volt direct current power is used for the filaments and heaters of the tubes in the pickup and transmitting equipment. The 115-volt 400- to 2400-cycle alternating current is used for all plate and bias supply rectifiers. The vertical scanning frequency is not locked in with the alternating current power supply, but is the 567th sub-multiple of a stable vacuum tube oscillator operating at 22,680 cycles per second, (twice the line scanning frequency). The vertical scanning frequency (field frequency) therefore remains very close to 40 cycles at all times regardless of the frequency of the airborne power supply. Adequate power supply filtering and careful magnetic shielding of the pickup and other cathode-ray tubes is effective in reducing the residual power supply hum to a sufficiently low value to allow satisfactory interlaced scanning operation. The use of 28 volts direct current for all filaments, except the video monitors and the oscilloscope, was found to be very helpful in reducing power supply hum trouble.

It was desirable to design the ground station receiving and monitoring equipment for transportable operation using a basic power supply of 28 volts direct current. All ground station equipment filaments, except those of the kinescope anode supply rectifiers, are operated from 28 volts direct current. The television receiver has a built-in dynamotor supplying plate and bias voltages, while the 4500-volt direct current kinescope anode supply is obtained from rectified pulses derived from a step-up winding on the horizontal deflection output transformer. The filament of the rectifier for the 4500-volt supply is fed with current at the horizontal deflection frequency supplied by a separate winding on the horizontal deflection output transformer. Plate supply for the viewing monitors may be obtained from a 28-volt to 350-volt direct current dynamotor. The 8500-volt direct current kinescope anode voltage for each viewing monitor is obtained from a self-contained single phase rectifier of conventional design operated from 115 volts 400 cycles, the 400-cycle voltage being supplied by a 28-volt direct current inverter. Adequate filtering and shielding of the 400-cycle rectifier eliminates hum troubles from this source. The ground station equipment may also be operated from 60 cycle alternating current using an electronically-regulated plate supply rectifier for the viewing monitor, a 28-volt rectifier and storage battery for the filaments and a 28-volt direct current to 115-volt 400-cycle alternating current inverter for the 8500-volt anode supply rectifier.

Airborne Pickup Equipment Design

The division of the airborne equipment into a number of separate units was dictated by the following factors:

(a) The necessity of providing small packages of reasonable weight and size that could be conveniently removed from the aircraft for servicing and quickly re-installed.

(b) The desirability of designing monitors, power supplies, etc., as interchangeable identical units so that in case of failure of a single monitor or power supply during flight, the rest of the system would still be operable. (Also, a single spare of each type unit could be carried in the aircraft for installation in case of failure during flight.)

(c) The division of the system into a number of relatively small units interconnected by suitable cables provides flexibility in installations in aircraft where space is at a premium, and makes possible more uniform weight distribution.

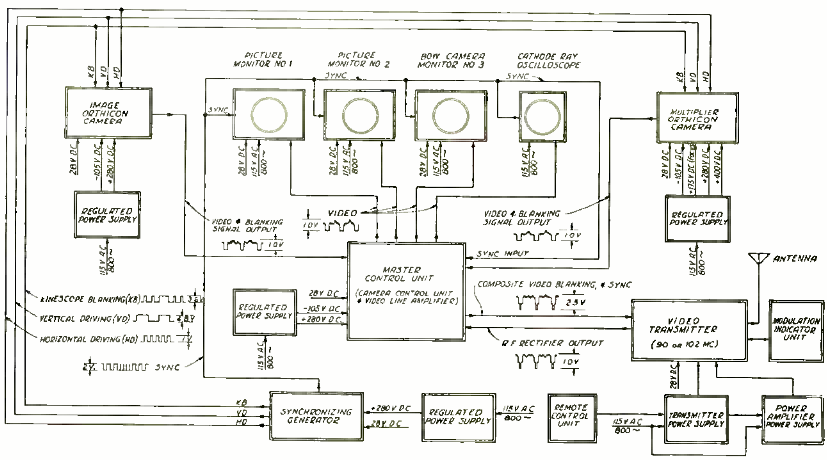

Fig. 6—Block diagram of airborne television equipment.

The block diagram of Figure 6 shows the units comprising the Ring airborne pickup and transmitting system. The video monitors are interchangeable units as are the regulated power supplies (except the multiplier orthicon camera power supply which provides two additional voltage outputs). Identical interconnecting plugs are used on both types of cameras and on both types of regulated power supplies for the video equipment. Plug connections are arranged so that any combination of camera types can be plugged into the system. When two image orthicon cameras are used, all video power supplies are units of the same type.

The block diagram, Figure 6, also shows the video and synchronizing pulse interconnections between the various units. The synchronizing generator provides four pulse outputs with amplitudes and waveforms as indicated on the diagram: vertical driving, horizontal driving, kinescope blanking, and synchronizing signals. The vertical and horizontal driving pulses are fed via 72-ohm coaxial cables to the two cameras where they energize the vertical and horizontal beam scanning circuits. The vertical driving pulses have a frequency of 40 cycles per second and the pulse duration is 6 per cent of one cycle. The horizontal driving pulses have a frequency of 11,340 cycles per second and a duration of 8 per cent of a horizontal scanning period. The kinescope blanking signals are added to the picture signals in each television camera and consist of a composite wave comprising 40-cycle pulses having a duration of 8 per cent of a field period and horizontal blanking pulses (11,340 cycles) having a duration of 18 per cent of one horizontal scanning period. The kinescope blanking pulses are timed to start earlier and last longer than the corresponding driving pulse components. Distribution of the blanking signals is via 72-ohm coaxial cables. The coaxial cable carrying the synchronizing signal output loops through the monitors and oscilloscope which are bridged across the line and is finally terminated in the master control unit. The wave form of the synchronizing signal is as shown on Figure 5.

The feeding of synchronizing signals separately to the video monitors and the oscilloscope has the advantage that these units may be used to monitor video signals which do not contain synchronizing signals. This is the case when the monitors or oscilloscope are switched to the camera video outputs directly, since synchronizing signals are added to the video signals only in the line amplifier which feeds the video transmitter. The monitors and oscilloscope are equipped with "internal-external" synchronizing switches, however, and may be synchronized from the incoming video signal by throwing the switch to the proper position when the incoming signal contains synchronizing pulses. The latter type of operation is desirable as a check on the proper video-to-synchronizing signal amplitude ratio when checking the transmitter output by means of the radio frequency detector provided.

It will be noted in Figure 6 that the master control unit receives video signals from the two cameras as well as from a radio frequency detector. The detector is coupled to the antenna transmission line and extracts and rectifies a small percentage of the transmitter output energy for monitoring purposes. This detected signal is fed to the master control unit via a terminated 72-ohm coaxial line. The control unit provides video monitoring outputs to the cathode-ray oscilloscope and the video monitors. It also houses a line amplifier for feeding the output of either camera to the transmitter. Synchronizing signals are added to the output of this line amplifier.

By means of push buttons provided on the control unit, any monitor or the oscilloscope may be independently switched to Camera No. 1 output, Camera No. 2 output, the control unit line amplifier output, or the output of the radio frequency detector. The front panel of the control unit is also the location of all electrical controls for the two cameras.

While the control circuits used are conventional, the video switching arrangement is thought to present novel features and will be described in some detail. This can best be done by reference to a simplified block diagram of the video and switching portion of the

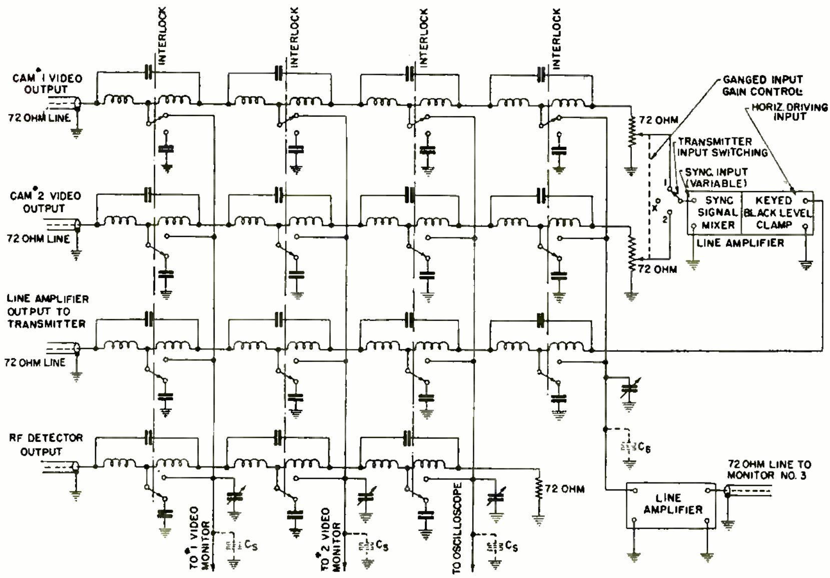

Fig. 7—Master control unit. (Simplified video block diagram.)

master control unit, Figure 7. It will be noted that Camera No. 1 video output passes through four monitoring networks in cascade, the last network being terminated in a resistance of 72 ohms in the form of an output gain control potentiometer. The Camera No. 2 output, line amplifier output and radio frequency detector output also pass through sets of monitoring networks in cascade. By means of groups of mechanically-interlocked push button switches indicated in vertical rows on Figure 7, the No. 1 monitor, No. 2 monitor, or the oscilloscope can be switched to any of these four outputs independently, the interlocks being arranged to prevent any monitor or the oscilloscope from being bridged across more than one network at a time. Only three input points are provided for No. 3 (utility) monitor as there is no occasion to use this monitor to look at the radio frequency output during operations. A line amplifier with bridging input and 72-ohm output is provided so that No. 3 monitor can be placed at any desired location in the aircraft and fed from a 72-ohm cable.

The operation of the monitoring filters is shown in more detail in Figure 8. It will be noted that during normal operation, with the switch in position *A*, the shunt capacitance consists of C_2 and C_3 in parallel. When the switch is thrown to position *B* to feed the video signal to a monitor, an equivalent capacitance to C_3 consisting of C_4 and C_5 in parallel replaces C_3. The capacitance C_5 represents the value of the stray capacitance in the connecting lead and input to the monitor, while C_4 is a trimmer capacitor adjusted to take care of different lengths of monitoring cables in various installations. This monitoring network

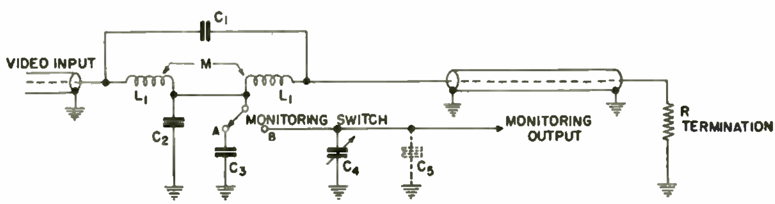

Fig. 8—Monitoring network.

is a constant resistance, bridged-tee type utilizing negative mutual inductance. Values which give constant resistance, approximately zero attenuation and linear phase are:

$$L_1 = \frac{0.158R}{f}$$

$$M = \frac{-0.050R}{f}$$

$$C_1 = \frac{0.029}{Rf}$$

$$C_2 + C_3 = \frac{0.315}{Rf}$$

Where R = surge impedance of the cable

$f =$ top video frequency component considered

M, C_1, C_2 and C_3 as in Figure 8.

A further requirement is that the shunt resistance of the monitoring tap be high compared to the surge impedance of the line. This requirement is easily met in the usual monitoring input which has a direct-current resistance of 250,000 ohms or more and an equivalent shunt input capacitance, including several feet of coaxial input cable, of 100 micro-microfarads or less. This type of monitoring filter has been successfully used in the commercial television operations of NBC for the past several years. It has economical advantages over the use of a low-impedance video bus for monitoring purposes. It can also be designed to fit in a small space, the overall dimensions of the shield housing for the filters of Figure 7 being 1½ x 6 x 12 inches approximately.

As indicated on Figure 7, the line amplifier feeding the transmitter also incorporates a keyed "black level clamp" circuit.[7] This circuit performs the function of maintaining the tips of the video blanking signals at a constant direct-current level at the grids of the cathode follower tubes feeding the transmission line. Low frequency surges caused by switching the input of the line amplifier from one camera to another are thereby ironed out and prevented from affecting the transmitter. While this is not a new idea, it will be described here in some detail since it is also used in the television cameras to discriminate against microphonic disturbances.

Figure 9 shows the basic circuit of the keyed black level clamp. In operation, the diodes D_1 and D_2 of V_3 are periodically rendered conducting by the application of keying pulses supplied by V_2. The keying pulses are of line frequency and are timed to occur during the "back porch" portion of the video blanking pedestals. Application, simultaneously, of positive pulses to the plate of D_1 and negative pulses to the cathode of D_2 provides a low resistance discharge path for the coupling capacitor C_1. The potential on the grid side of C_1 is therefore brought back to a fixed value ($-C$ in this case) at the end of each scanning line. By adjustment of R_3 and R_4 to provide keying pulses of equal amplitude and some adjustment of the relative values of R_1 and R_2, the keying pulses can be balanced out so that only a small residual pulse signal appears at the grid of V_4. Provided that the peak-to-peak video signal at the point where the clamp is applied amounts to several volts, the residual unbalanced pulse signal can be made so small as to have negligible effect on the output of V_4.

[7] K. R. Wendt, U. S. Patent No. 2,299,945, October, 1942.

Camera Design

As already indicated, two types of television cameras were designed for Project Ring. The PH-536/AXS-1 camera utilizes the Image Orthicon,[8] a super-sensitive pickup tube producing a satisfactory picture with 1/100th the light required by the iconoscope. The PH-537/AXS-1 camera utilizes a developmental type orthicon similar to the type 1840, but incorporating an electron multiplier signal amplifier. The sensitivity of this tube is intermediate between the iconoscope and the Image Orthicon. The use of an electron signal multiplier, with the resulting increase in effective sensitivity, makes this tube useable over a greater dynamic light range than is possible with the type 1840.

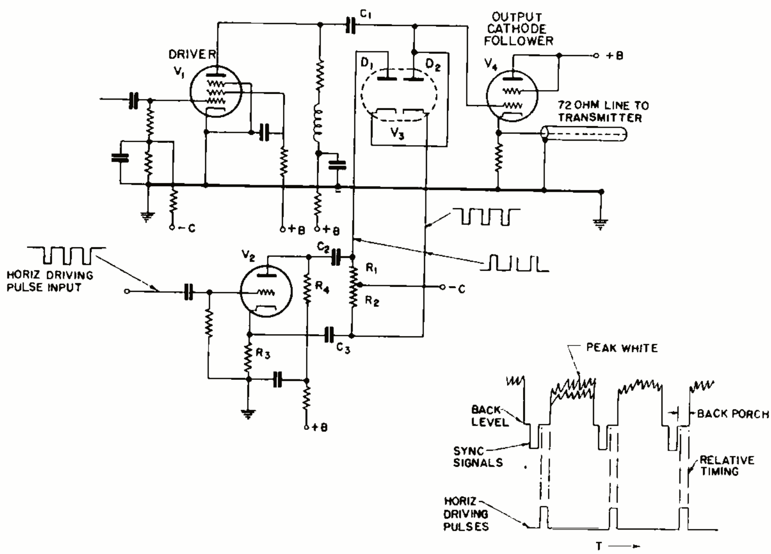

Fig. 9—Keyed black-level clamp circuit.

Photographs of these two camera types are shown in Figures 10 and 11.

Functionally, these cameras differ from the usual commercial designs in that they incorporate within a single housing all the tubes and components needed to produce a complete video signal (except the synchronizing signal generator). Their video outputs have a peak-to-peak voltage level of 1.0 volt into a 72-ohm load and are complete with video blanking pedestals. The chief advantage of this arrangement is that there is a saving in overall weight of the equipment as compared

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[8] Albert Rose, Paul K. Weimer and Harold B. Law, "The Image Orthicon—A Sensitive Television Pickup Tube", *Proc. I.R.E.*, Vol. 34, No. 7, pp. 424-432, July, 1946.

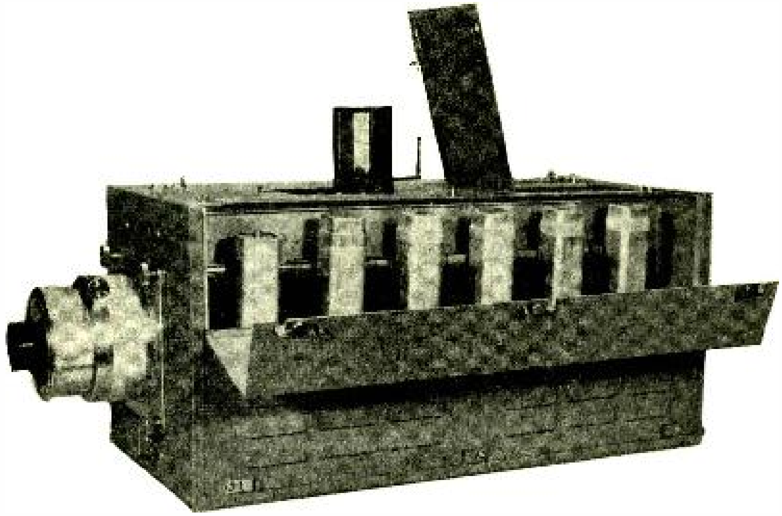


Fig. 10—Image orthicon camera with viewfinder. (Hinged cover opened to show video amplifier—top access door open.)

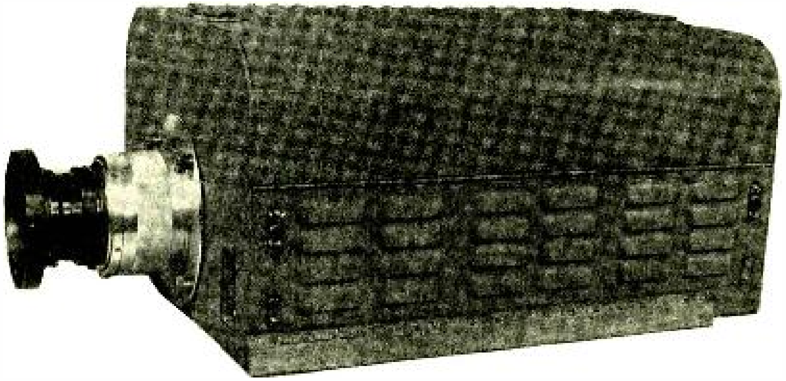


Fig. 11—Multiplier Orthicon camera with 7½ inch f/2.5 lens.

to the commercial practice of locating camera deflection amplifiers and the main video amplifier remote from the camera proper. The image orthicon camera is 10⅜ x 9¾ x 21¼ inches in size and weighs 46 pounds, less lens and lens mount. The camera utilizes 21 tubes, of which nine are dual types. The Multiplier Orthicon camera is 10¼ x 15½ x 20¾ inches in size and weighs 74 pounds. This camera utilizes 21 tubes, of which eight are dual types.

Since the subjects to be televised are always at a distance, in normal operation, the camera lenses are locked at infinity focus for this application. A simple viewfinder such as the combination ball sight and plano-convex lens with cross-hairs, as shown in Figure 10, may be used. A cathode-ray-tube viewfinder using a green zinc-orthosilicate fluorescent screen with a green optical filter has also been found to be convenient for airborne television use. The No. 3 (utility) video monitor has been used for this purpose in connection with the nose position camera where operating space is restricted.

In addition to special selection of non-microphonic tubes for the first video amplifier stages and careful design of the vibration isolators on which the cameras are mounted, keyed black level clamp circuits are used to eliminate microphonic signals from the camera video outputs. The early video amplifier stages of both types of cameras are purposely designed to have a drooping gain characteristic for signals below 500 cycles. This is followed in each case by a stage incorporating a black level clamp at a point where the video signal is at a sufficiently high level so that microphonic disturbances produced by subsequent stages are negligible. Video stages following the black level clamp, which effectively "restores" the low frequency components of the signal, are designed for uniform response from 20 cycles up to the top video frequency.

Another circuit artifice which counteracts microphonics is the use of a value of signal load resistor which is high compared to the effective shunt capacitance existing at the output of the pickup tube electron multiplier. The resulting loss in video signal output and the phase shift at high frequencies is compensated for in one of the higher level video stages by use of a "high-peaker" circuit. This results in a greater video signal input to the thermionic amplifier at low and medium frequencies than if the load resistor were chosen for more uniform response over the entire video band. A form of "high-peaker" compensation used in the Ring equipment is shown diagrammatically in Figure 12. Since both the electron multiplier and the amplifier tube V_1 can be considered as constant-current generators, and since the gain versus frequency characteristic of the intermediate video stages is uniform, the overall response of the system is proportional to the product of the impedances of the reactance arms consisting of R_1 and C_1 in parallel and R_2 and L_2 in series. These reactance arms became inverse networks ($Z_1 Z_2 = A^2 = \text{Constant}$) when the values of L_2 and R_2 are chosen so that:

$$R_1 C_1 = \frac{L_2}{R_2}$$

When this is done, the phase and amplitude distortion produced by the R_1C_1 combination at the input to the amplifier can be exactly compensated over a wide band of frequencies within the limitations imposed by resonance of L_2 with the interstage shunt capacitance C_2. As a practical matter, satisfactory compensation can be obtained by choosing L_2 small enough so that the parallel resonant frequency of L_2 and C_2 is well above the top video signal frequency of the system. A ratio of resonant frequency to top video frequency of 1.5:1 was found to be satisfactory.

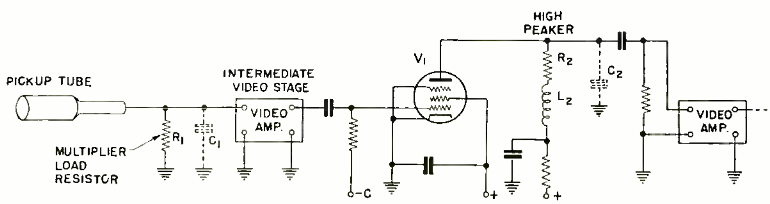
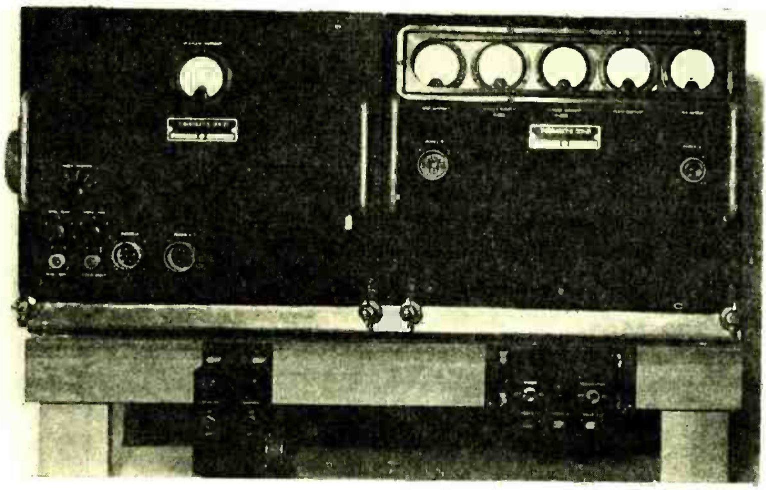


Fig. 12—Block diagram illustrating "high-peaker" correction network.

By use of such a compensating system, the orthicon low-frequency-signal output fed to the grid of the first thermionic amplifier tube can be increased many times over the value obtained with a flat amplifying system. This results in a worthwhile discrimination against microphonic disturbances originating in the thermionic amplifier portion of the video system.

Airborne Video Transmitter

The video transmitter was based upon a preliminary design worked out for this project by RCA Laboratories Division. It was designed and constructed to provide for either of two types of installation. The low-power installation—100 watts average carrier or 400 watts peak carrier output—is comprised of the transmitter unit, transmitter power supply unit (units on left side of Figure 13), remote control box, modulation indicator unit, antenna coupling unit, antenna, shock mounts, wavemeter, test meter and cables. The installed weight is 200 pounds and the power required is 14 amperes at 28 volts direct current and 14 amperes at 115 volts 400/2400 cycle alternating current. Cooling air at the rate of 200 cubic feet per minute is required. The high power installation—350 watts average carrier or 1400 watts peak carrier output—consists of the video transmitter, power amplifier and two power supplies shown in Figure 13 plus the associated equipment, cables and



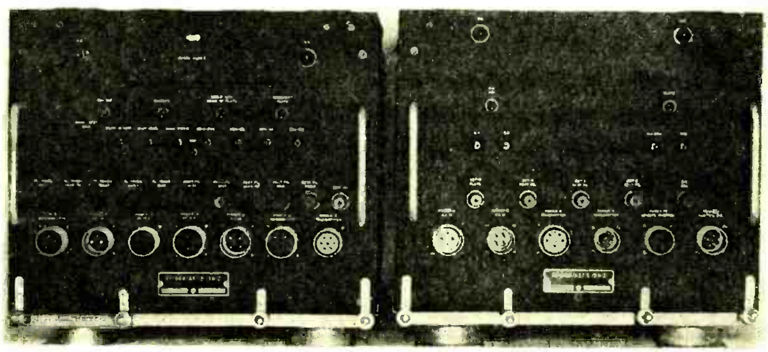


Fig. 13—The video transmitter and linear power amplifier. (These are shown at the top, mounted together as a unit on a special shock mounting. The remote control box and modulation indicator unit are shown mounted below the transmitter. The lower two units are the transmitter and power amplifier power supplies.)

antenna. The installed weight is 400 pounds (30-pound cathode-ray oscilloscope not included). The power required is 40 amperes at 28 volts direct current and 45 amperes at 115 volts 400/2400 cycle alternating current. Cooling air at the rate of 800 cubic feet per minute is required. The air for cooling the transmitter and power amplifier is supplied in flight by an air scoop mounted on the fuselage of the aircraft. An auxiliary cooling blower is used for ground testing. The high-power transmitter is shown in Figure 13.

The radio frequency section of the transmitter contains the following tube and circuit arrangements: A type 826 oscillator tube is operated in an ultra-audion (colpitts) type oscillator circuit, at a plate potential of 750 volts, at either 90 or 102 megacycles. The oscillator is very loosely coupled to two type 3E29 pentode tubes, connected in parallel push-pull, operating as a buffer stage. The buffer drives a grid-modulated stage through a four-terminal inductively-coupled band-pass circuit. The secondary of this network is heavily damped to provide a band-pass of 85 to 107 megacycles and also to improve the voltage regulation of the buffer stage. Provision of this wide bandpass eliminates the need for retuning for operation on either of the two carrier frequencies, 90 or 102 megacycles. Four type 4E27 pentode tubes, connected in parallel push-pull, are operated at a plate potential of 1100 volts as a grid-bias amplitude-modulated Class C stage. The output of this modulated Class C amplifier unit may be fed to an antenna system through an antenna coupling unit or may be used to drive the linear power amplifier unit used in the higher power installation.

The first stage of the video modulator section of the transmitter consists of two type 6AG7 pentodes with the plates connected in parallel. Input connections to each of the grids are provided so that synchronizing signals may be fed to one grid, and video signals to the other as required in some applications. When being fed mixed video and synchronizing signals from the pickup equipment described here, the two modulator inputs are operated in parallel. A video pre-emphasis network in the first video stage provides for the selection of several degrees of high-frequency peaking as may be required to compensate for sideband attenuation in the modulated radio-frequency section of the video transmitter. The second video stage consists of a type 3E29 pentode tube operating in a conventional video amplifier circuit. The video modulator stage contains two type 3E29 tubes operated in parallel. The video output signal of the modulator, approximately 120 volts peak-to-peak, is applied in series with the grid bias supply of the amplitude-modulated radio-frequency amplifier. High-frequency compensation is effected in the video stages by conventional means, i.e., combination (series shunt) peaking and LCR (inductance-capacitance-resistance) networks in the cathodes.

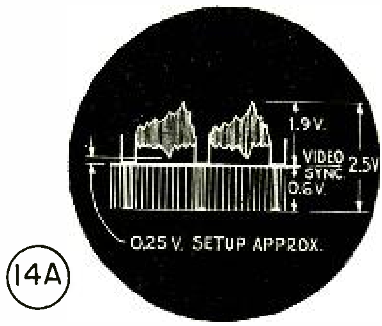
The Class B linear power amplifier unit contains two type 827R air-cooled screen-grid tubes connected in push-pull and operated at a plate potential of 2400 volts. The coupling to this stage is effected through a heavily damped four-terminal band-pass network. An LCR two-terminal network is inserted in series with the grid of each 827R tube. The combination of the tube impedance and this equalizing network provides a reasonably constant input impedance to the 827R stage between 85 and 107 megacycles. An LCR network is also placed in series with each filament lead of the 827R tubes. The capacitive reactances of these networks are adjusted to equalize the filament lead inductances over the range of 85 to 107 megacycles, thus effectively placing the filaments at radio frequency ground potential. The output of the power amplifier stage is inductively coupled to the 50 ohm transmission line and antenna. A 35Z5 diode tube connected as a detector and bridged across the transmission line provides a video monitoring voltage that can be used to check the modulation and overall performance of the transmitter. A direct-current milliammeter connected in the diode rectifier load circuit indicates the transmission line voltage or relative power output of the transmitter. Meters are also provided to read total grid, screen and plate currents of each tube of the transmitter.

The power supply for the low-power section of the transmitter contains five full-wave rectifiers and supplies the following direct-current voltages: 350 volts to the video modulator section, 350 volts to the 3E29 buffer stage, 1100 volts to the oscillator and 80 volts for bias. Xenon gas type 3B25 rectifiers are employed in all rectifier circuits except for the 5Z4 full wave high vacuum rectifier used for the bias supply. The Xenon gas rectifiers are preferred to the mercury vapor type for this application, since they will operate in any position and also over the wide temperature limits encountered in aircraft installations.

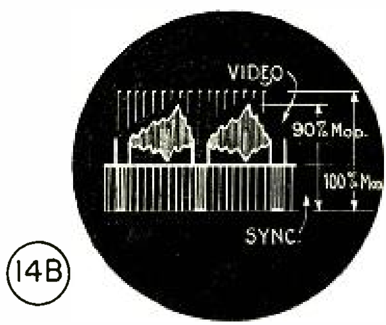
The ripple filtering circuits are conventional with the exception of the 1100-volt supply which contains a 50-ohm constant impedance network. This LCR network has constant impedance to all modulating frequencies up to 5 megacycles. The power supply unit also contains a thermal 40-second delay relay tube for timing the application of high voltages and the necessary fuses, interlock circuits, and contactors.

The power-amplifier power supply consists of eight 3B25 tubes connected in a bridge rectifier circuit and supplies 2400 volts for the plates and 1400 volts for the screens of the 827R tubes. A 50-ohm constant impedance network is used for filtering.

The modulation indicator unit, see Figure 13, is used in connection with a cathode-ray oscilloscope to give a visual indication of the percentage of modulation of the transmitter. The video signal from the radio-frequency-detector is fed to the modulation indicator unit and thence to the cathode-ray oscilloscope. The modulation indicator unit[9] contains a mechanical vibrator which short-circuits the detector load circuit at a rate of 300-400 times per second. The time of short-circuit of the video line (zero voltage) corresponds to zero power output of



OUTPUT OF CONTROL UNIT LINE AMPLIFIER FEEDING TRANSMITTER AS SEEN ON OSCILLOSCOPE USING 20 CYCLE SWEEP



MODULATION INDICATOR OUTPUT AS SEEN ON THE OSCILLOSCOPE USING 20 CYCLE SWEEP.

Fig. 14—Signal level and modulation check using oscilloscope.

the transmitter. The tips of the synchronizing signals, as seen on the oscilloscope fed by the detector, correspond to maximum carrier amplitude, as the transmitter is operated with an input level such that the

[9] T. J. Buzalski, "A Method of Measuring the Degree of Modulation of a Television Signal", RCA REVIEW, Vol. VII, No. 2, pp. 265-271, June, 1946.

tips of the pulses just begin to be compressed in the output of the modulated stage. The percentage of modulation of the carrier may therefore be quickly estimated visually on the oscilloscope screen as shown in Figure 14B. The dots at the top of the trace in Figure 14B occur when the contactor is closed and correspond to zero carrier while

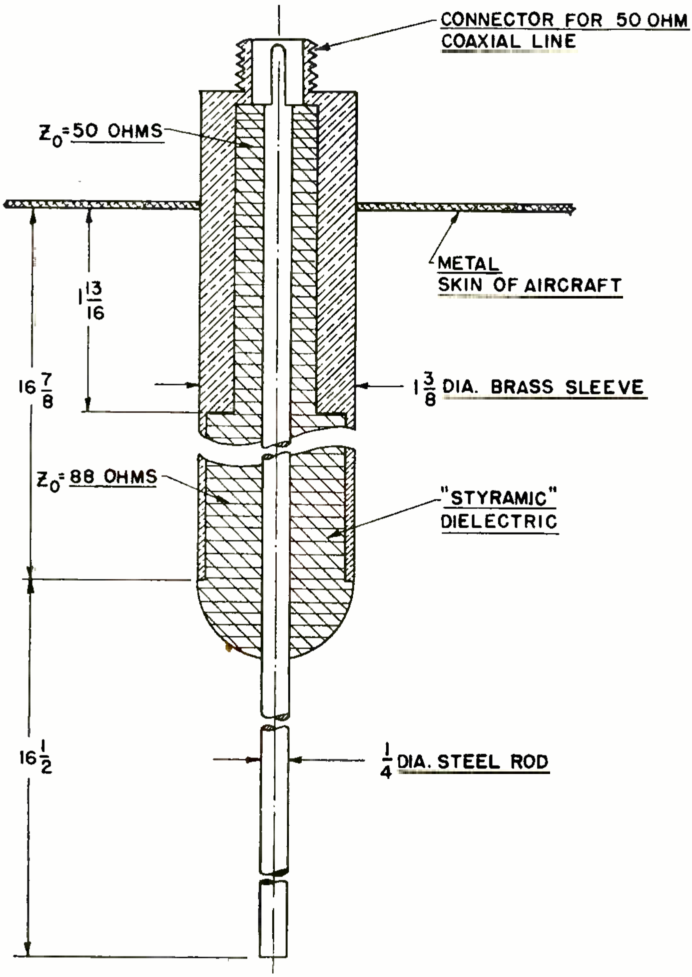


Fig. 15—Transmitting antenna.

the tips of the synchronizing pulses at the bottom of the trace correspond to maximum carrier.

The transmitting antenna follows a design by Mr. P. S. Carter. This antenna, shown in Figure 15, provides satisfactory operation on carrier frequencies of 90 or 102 megacycles without readjustment.

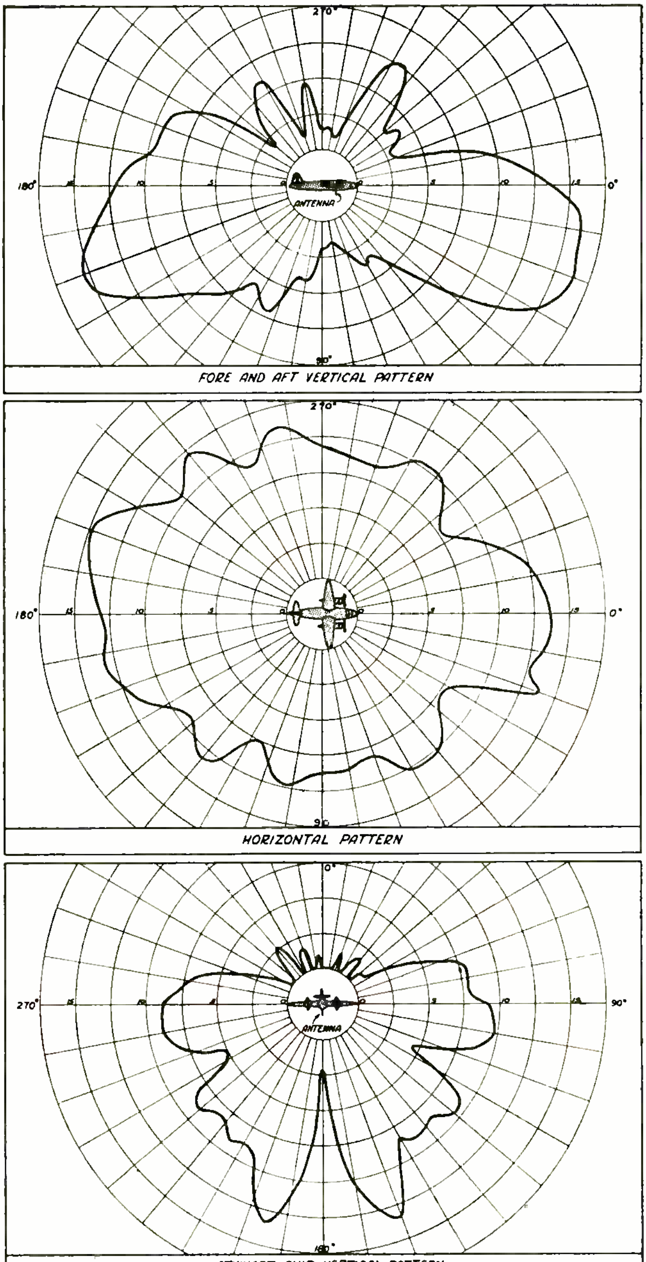


Fig. 16—Measured radiation pattern of relative field intensities of a vertically polarized quarter-wave antenna mounted below forward bomb bay of JM-1 aircraft model, scaled 30 to 1 and measurements made at 3,000 megacycles.

The location of the antenna on the aircraft was determined on the basis of scale model tests performed by the engineers at Rocky Point, Long Island. Figure 16 shows a plot of data obtained in this way for the location finally chosen. As indicated, this provides a reasonably uniform horizontal radiation pattern.

AIRCRAFT INSTALLATION

The installation of the Ring equipment in a Navy JM-1 "Martin Marauder" aircraft, as used in developmental flight tests, is shown in Figures 17 and 18. The total installed weight including the two television cameras, control and monitoring equipment, the transmitter, video and transmitter power supplies, power and video cabling, cable

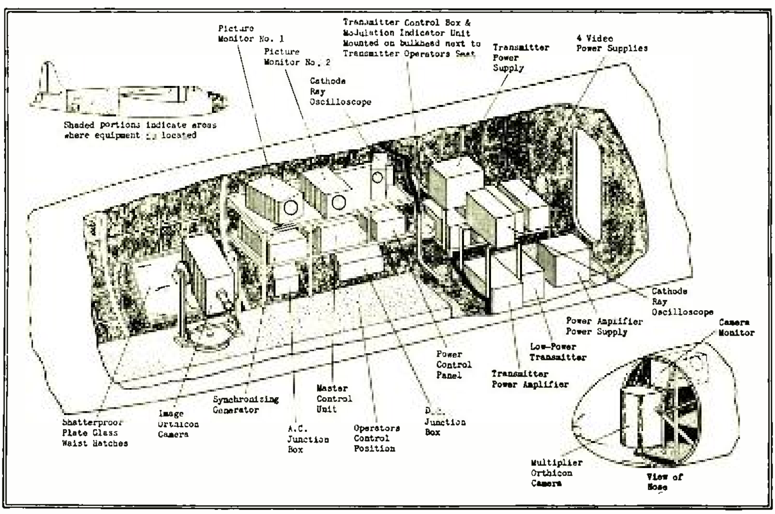


Fig. 17—Phantom view of the location of the various units in the JM-1 aircraft. The transmitter is located in the after bomb bay, and the antenna is located just forward of the transmitter beneath the fuselage.

junction boxes, equipment shock mountings, an assortment of camera lenses, spare tubes, meters, tools, etc. is 1400 pounds. These figures do not include the engine-driven generators and their voltage regulators.

Power for operating the equipment in flight is obtained from two Navy type NEA-8, 7.25 kilovolt-ampere 115-volt, 400- to 2400-cycle alternators, one mounted on each aircraft engine. Direct-current power at 28 volts for operating the video and transmitter filaments is obtained from two 200-ampere generators, one on each engine, operated in parallel. The power required for the video pickup and control equipment is 2.2 kilovolt-amperes at 115 volts 400 to 2400 cycles and 19 amperes at 28 volts direct current. The transmitter requires approximately 5 kilovolt-amperes at 115 volts 400 to 2400 cycles and 40 amperes at 28 volts direct current. The transmitter and video equipments are supplied from separate alternators. These alternators, operated on separate engines, are not synchronous but owing to adequate power supply filtering no trouble has been experienced from beats between the frequencies of the two power sources. At normal cruising speed, the alternator frequencies are in the vicinity of 1000 cycles.

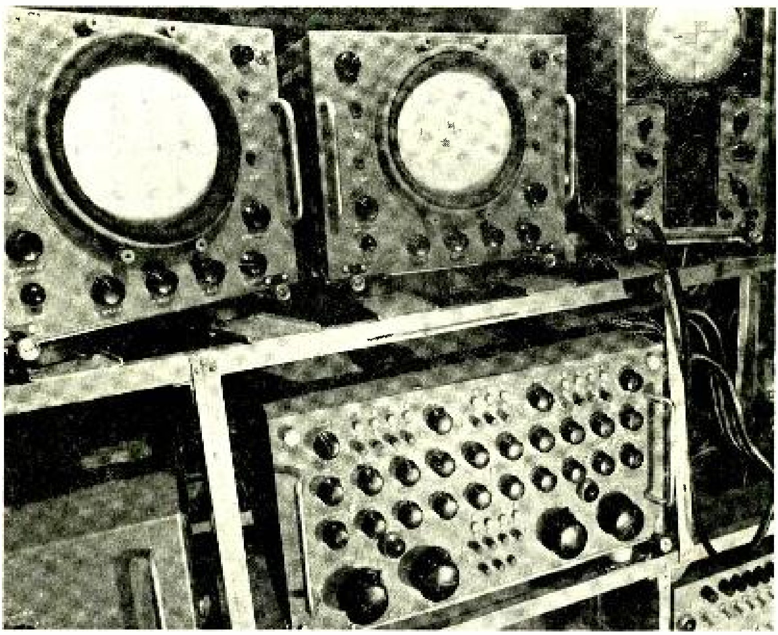


Fig. 18—Photograph of the master control position in the aircraft. (The picture monitors and cathode-ray oscilloscope (with calibration unit attached) are shown mounted above the synchronizing generator, master control unit and video switch panel. This position provides complete adjustment and control of the transmitted picture—including "on the air" monitoring of the picture, check of per cent of synchronizing signal transmitted and measurement of the modulation percentage of the transmitter.)

Power changeover switches and a power connection plug are provided for operation from an auxiliary power sources for pre-flight testing and maintenance when the aircraft is on the ground.

Ground Station Equipment

The R-90/UXR-2 television receiver shown in Figure 19 is continuously tunable over a range of 76 to 116 megacycles and accepts a video band extending 5 megacycles above and 5 megacycles below the carrier. The receiver sensitivity is such that an input signal of 35 microvolts with 40 per cent modulation produces an output signal with unity signal-to-noise ratio. The signal-to-noise ratio is expressed in terms of the ratio of peak-to-peak video signal output to peak-to-peak output noise. A half-wave vertical dipole antenna matched to a 72-ohm coaxial line is normally used to feed this receiver. While the design of this receiver follows conventional superheterodyne principles, it incorporates a very important feature in the form of a fast-acting automatic volume control operated from the peak value of the detected synchronizing signals. This automatic volume control serves to iron

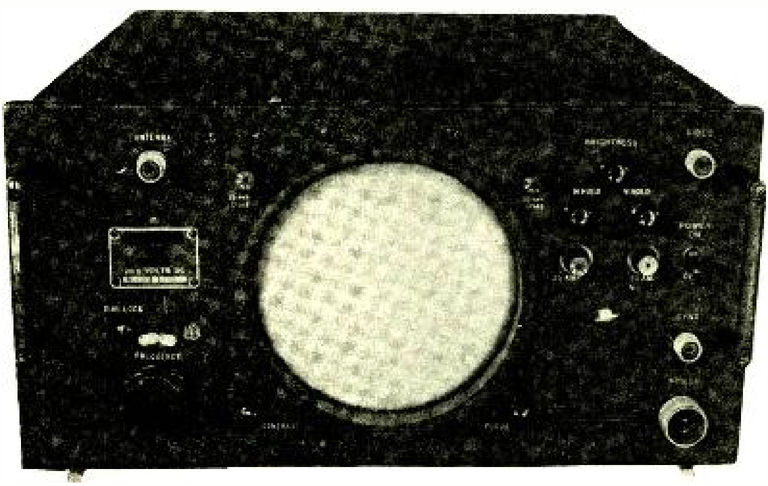


Fig. 19—Type R-90/UXR-2 television receiver.

out the fluctuations in received signal which occur due to addition or cancellation of the direct wave from the airborne transmitter by waves received over an indirect path.

The receiver provides an output of 1 volt peak-to-peak composite video signal at an impedance of 72 ohms for feeding one or more of the 12-inch viewing monitors shown in Figure 20.

Test Results

Numerous flight tests of the Ring equipment installed in a JM-1 aircraft were conducted at the Naval Air Station, Willow Grove, Pennsylvania and at the Naval Air Test Center, Patuxent River, Maryland, between November 1944 and July 1945 when Navy altitude and acceptance tests were completed.

In one test to determine the range of the transmitter, an acceptable television picture was received over a path length of 205 miles with the plane carrying the transmitter flying at 23,000 feet over Putnam, Connecticut and the receiver located at the Naval Air Station at Willow Grove, Pennsylvania. A vertical half-wave dipole at a height of 50 feet above the ground was used at the receiving end. A monoscope was used as a video signal source in the aircraft for this test so that the maximum transmission range could be determined independently of conditions of weather and visibility.

On another occasion with the aircraft flying over Philadelphia at an altitude of 10,000 feet, observers at the Naval Air Test Center at

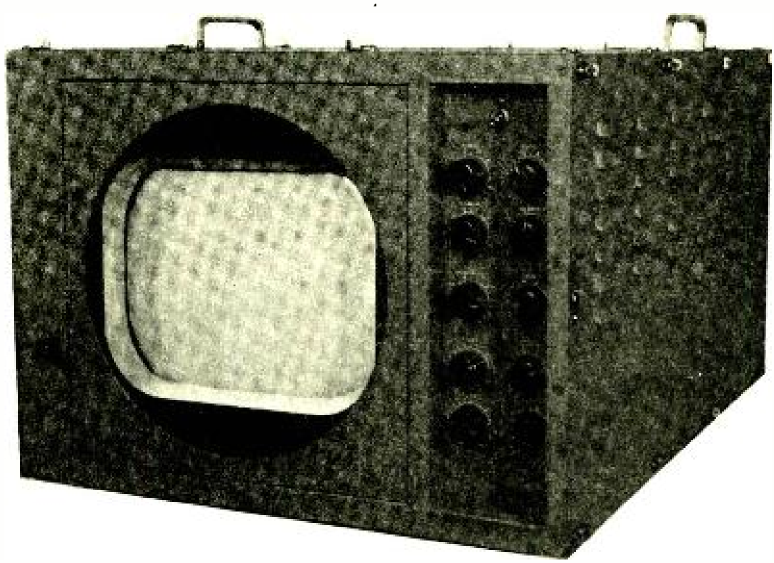


Fig. 20—Type ID-86/UXR-2 12-inch viewing monitor.

Patuxent River, Md., 120 miles away, were provided with views of the city buildings, railroad yards, ships in the Delaware River and other objects of interest. Using a 20 inch f/10 lens on the Image Orthicon camera, which provides a viewing angle of only 3.4 degrees, telephoto views of the Philadelphia-Camden Bridge showing moving traffic in sufficient detail to distinguish between automobiles, trucks and buses were received at Patuxent. Alternate overall views provided by the

Multiplier Orthicon camera equipped with a 7.5 inch f/2.5 lens (17.5 degree viewing angle) were also transmitted. After circling the Philadelphia-Camden area, the aircraft proceeded to Washington, D. C., via Baltimore, Maryland, providing television views of ships, oil refineries, etc., arriving over the Capitol at an altitude of 17,500 feet. Using the Image Orthicon tube with the 20 inch f/10 lens, at this altitude, moving trucks, buses and automobiles were easily distinguishable. Circling down to 5,000 feet over Washington views of the National Airport and the Naval Air Station at Anacostia were transmitted to Patuxent, a distance of 55 miles, in clear enough detail so that expert observers were able to tell the number and types of planes parked on the airfields.

The altitude from which objects on the ground can be picked up by the television cameras is naturally controlled by conditions of illumination and visibility. The extent to which weather conditions govern the operating altitude is similar to that existing in the case of aerial photography. As in aerial photography, various optical filters, such as the Wratten No. 23, have been found helpful in improving picture contrast in the presence of ground haze. The type LM-15 Image Orthicon tubes used in these tests had considerable sensitivity in the near infra-red light region. The use of a Wratten No. 89A infra-red filter produced improved results with this tube in dealing with ground haze under some conditions.

ACKNOWLEDGMENT

The design, development and testing of the Ring equipment was the cooperative effort of a number of NBC television engineers under the direction of Mr. O. B. Hanson, Vice-President and Chief Engineer, Mr. R. E. Shelby, Director of Technical Development and Mr. G. M. Nixon, Assistant Director of Technical Development. Among the engineers taking an active part in the work were Messrs. R. M. Fraser, C. L. Townsend, Edward Wade, E. Stolzenberger, R. A. Monfort, W. L. States, E. C. Wilbur, A. W. Protzman, C. W. Turner and W. C. Resides. Preliminary transmitter design drawings were supplied by Mr. T. L. Gottier of RCA Laboratories Division; final transmitter development and construction were handled by Messrs. T. J. Buzalski, W. L. States and A. L. Hammerschmidt of NBC. Mr. F. J. Somers was the project engineer on design, development and engineering of the Ring equipment. Mr. H. P. See was in charge of installation, field testing and technical liaison with the Navy Department. In addition to the participation of the engineers already mentioned, substantial assistance was obtained from a number of groups and individuals in various

divisions of RCA. Administration of the several contracts under which the project was carried out was by the Government Development Section of RCA Victor Division; these contracts were NXss-20596, NXsr-47375 and NXsr-66811 between Radio Corporation of America and the U. S. Navy. Lt. Comdr. L. R. Moffett, USNR, was in active charge of the project for the Bureau of Ships of the Navy Department.

MINIATURE AIRBORNE TELEVISION EQUIPMENT*

By

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Princeton, N. J.

Summary—*A developmental television camera, designed especially for airborne applications and using the image orthicon, is described. This camera is part of a complete airborne television transmitter system weighing 50 pounds. The transmitter has a power output of eight watts in the 260-to-380-megacycle range. Experimental results in guiding a medium-angle bomb with the aid of the miniature equipment are given.*

INTRODUCTION

DURING the course of the World War II, it became apparent that extended application for television might be found if the transmitting equipment could be made smaller and lighter than the then-existing field equipment. One particular application for a minia-

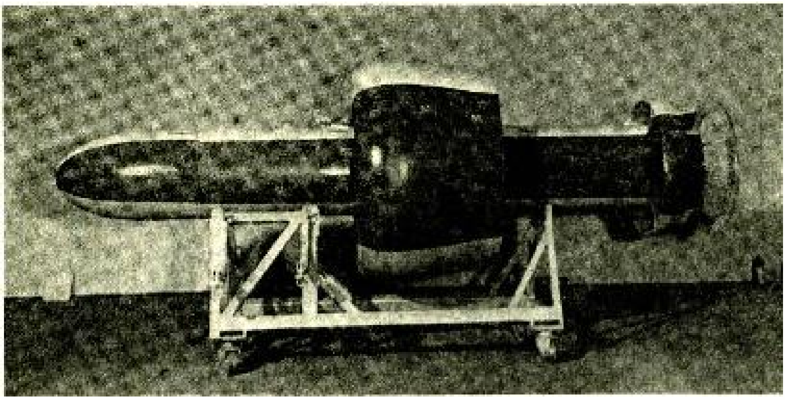


Fig. 1—The "Roc bird" (Courtesy of Douglas Aircraft Company, Inc.)

ture television equipment was a new medium-angle guided-bomb type of missile developed by the Douglas Aircraft Company, Inc., and known as the "Roc". The "Roc bird" is shown in Figure 1. After a preliminary study of miniature tubes and other components, it was decided to develop miniature television equipment for this project. The system was to consist of a small cylindrical camera unit placed in the nose of

* Decimal Classification: R583 × R560.

the missile, a small transmitter and power supply placed in the after part, and a dipole antenna placed on the rear of the missile.

Some of the preliminary work was based upon tube operating conditions so severe that the life of the tubes would be materially shortened. The object was to get maximum performance for a short time with minimum apparatus, since, in use, the entire unit was expended after a few minutes of service. This design consideration was applied in the case of numerous expendable electronic apparatus, but due to the complexity of the equipment, it was decided that the advantage of the slight weight reduction, obtainable by severely overworking the tubes, was offset by the disadvantages of frequent tube replacements

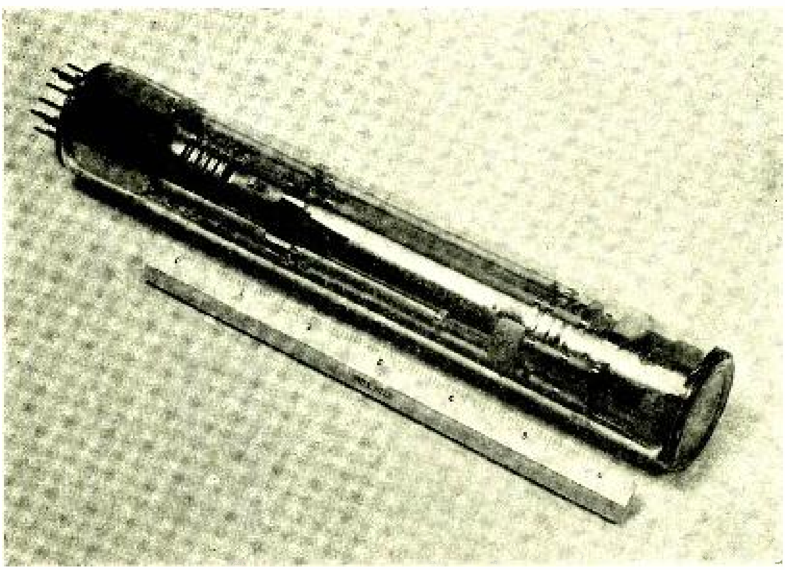


Fig. 2—The Mimo tube.

during development and the difficulty of adjusting and testing the equipments with the identical tubes to be used in service.

The Miniature Image Orthicon

Since the space for the television camera unit was limited, a special pickup tube was developed for this project.[1] The tube is shown in Figure 2. It is called the "Mimo" tube (miniature image orthicon). The tube is 1½″ in diameter and 9″ in length.

[1] P. K. Weimer, H. B. Law, and S. V. Forgue, "Mimo—Miniature Image Orthicon", RCA REVIEW, Vol. VII, No. 3, pp. 358-366, Sept., 1946.

The Camera Unit

The camera unit is shown at the right in Figure 3. An airborne iconoscope camera of earlier design is shown at the left for comparison of their sizes. The requirement for a cylindrical camera unit was met by mounting the tubes and components on three disc-shaped chassis surrounding the focusing coil and camera tube, as shown in Figure 4. The chassis, focusing coil, deflecting coils and alignment coils are assembled on and in a steel tube which also supports the lens mounting. The cylindrical case of the camera unit is so constructed as to be airtight, providing normal atmospheric pressure for the circuits regardless of altitude. The required controls pass through special vacuum-tight bushings in front of the camera unit case. The lens end of the case is covered with a flat disc of optical glass treated on both sides with non-reflecting film.

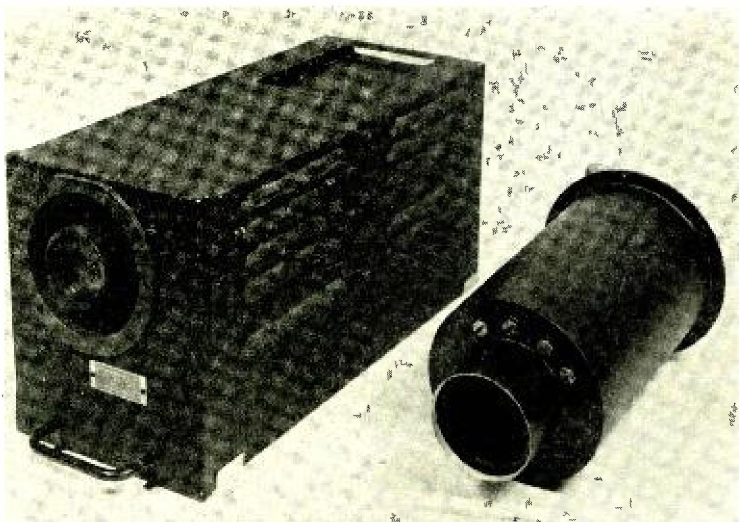


Fig. 3—The BC-1212 iconoscope camera and the Mimo camera.

The schematic diagram of the camera unit is shown in Figure 5. The video amplifier uses type 6AK5 tubes. It has a frequency characteristic which is approximately flat to 4 megacycles. The third video-amplifier stage has a conventional "high peaking" grid input circuit which compensates for the high-frequency attenuation of the orthicon output circuit. The grid of the fourth video-amplifier stage is "clamped" by a 6AL5 duo-diode to black level; thus the low-frequency components, lost in the small coupling capacitors preceding this stage, are reinserted.[2] Also, the clamping removes amplifier microphonics with the exception of those components near or above the line frequency of 14,000 cycles. Pulses for the clamp circuit are obtained from the balanced horizontal pulses appearing across the horizontal deflecting coils. Video blanking is added in the plate circuit of the fourth video stage. The cathode output stage acts as a clipper, setting a level of 0.3 volts, thus tending to limit the video output to 0.6 volts peak-to-peak.

The vertical deflection system, which operates at 40 cycles, consists of a 3A5 blocking oscillator and discharge tube (tube No. 8) and another 3A5 tube (No. 7) with both sections operating in parallel as the final amplifier. Blocking oscillators are used for driving both vertical and horizontal scanning circuits. The oscillator transformers are constructed with small mu-metal cores. The vertical speed of 40 cycles

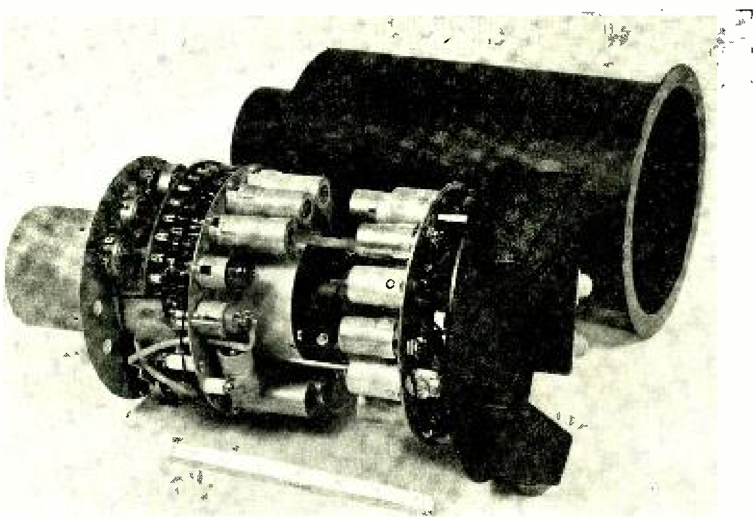


Fig. 4—Mimo camera with case removed.

remains constant to approximately 1/10 cycle for supply voltage variations from 21 to 24 volts.

The 14-kilocycle horizontal deflection circuit consists of a 3A5 dual-triode (tube No. 1) operating as a blocking oscillator and as a discharge tube, a 25L6 power pentode (tube No. 2) as the final amplifier and one-half of a 3A5 dual triode (tube No. 14) as a horizontal deflection regulator. This regulator, which uses the 50 volts across an NE-2 tube as a reference value, increases the plate voltage of the horizontal dis-

[2] R. D. Kell and G. C. Sziklai "Image Orthicon Camera", RCA REVIEW, Vol. VII, No. 1, pp. 67-76, March, 1946. (See page 70).

charge tube and thus tends to increase the deflection if the +335 voltage decreases. This cancels the reduction of deflection which would occur otherwise and provides substantially constant amplitude of horizontal deflection. This regulator also serves to keep the high voltages derived from the deflection-flyback voltage constant.

The horizontal oscillator has a regulated power supply, but its heater supply varies directly with the primary power sources. Under this condition the deflection frequency tends to increase with decreasing battery supply voltage. To counteract this effect a special compensating bias arrangement is used in the grid circuit. The grid leak is supplied with a positive voltage obtained partly from the 26-volt battery and partly from the regulated +150 volts. A drop in the +26 volts tends to cause the speed to decrease. The bleeder resistor for combining the two voltages is proportioned to make this effect cancel the effect of the heater temperature change.

The core of the horizontal output transformer is two small loops of hypersil core material. The secondary winding is shielded and carefully balanced to reduce pickup from the beam-deflecting yoke to the video input. Resistance-capacitance damping is used. The positive high voltages for the image-orthicon electron multipliers are supplied by a 1654 rectifier. The photo-cathode and ring voltages are supplied by a 6AK5 (tube (No. 4) in a constant-voltage rectifier circuit which is also self-regulating, using the regulated +150 volts from the power supply unit as a reference. This circuit operates on the same principle as that described for the large orthicon camera[2], and provides a very well regulated source of —350 volts for the photocathode and ring of the camera tube.

The first half of a 3A5 (tube No. 6) is used to produce a wide vertical blanking pulse. This is mixed with horizontal pulses in the first half of a 3A5 (No. 14) to provide kinescope blanking. The two pulses are also mixed in the second half of a 3A5 tube (No. 6) to provide orthicon blanking. Three volts of orthicon blanking are supplied to the target at a direct-current level variable from about —1½ to +1½ volts.

The video input circuit picks up an appreciable amount of undesired horizontal pulse voltage, mostly from the target blanking. This is partially neutralized by mounting near the input capacitor a terminal with a few volts of the opposite-polarity horizontal pulse on it, obtained from the clamp circuit. The remainder of the pickup is removed by blanking. The focusing coil and the alignment coil, connected effectively in parallel, are supplied with current from an Amperite regulator.

Horizontal and vertical sync (synchronizing) pulses are supplied

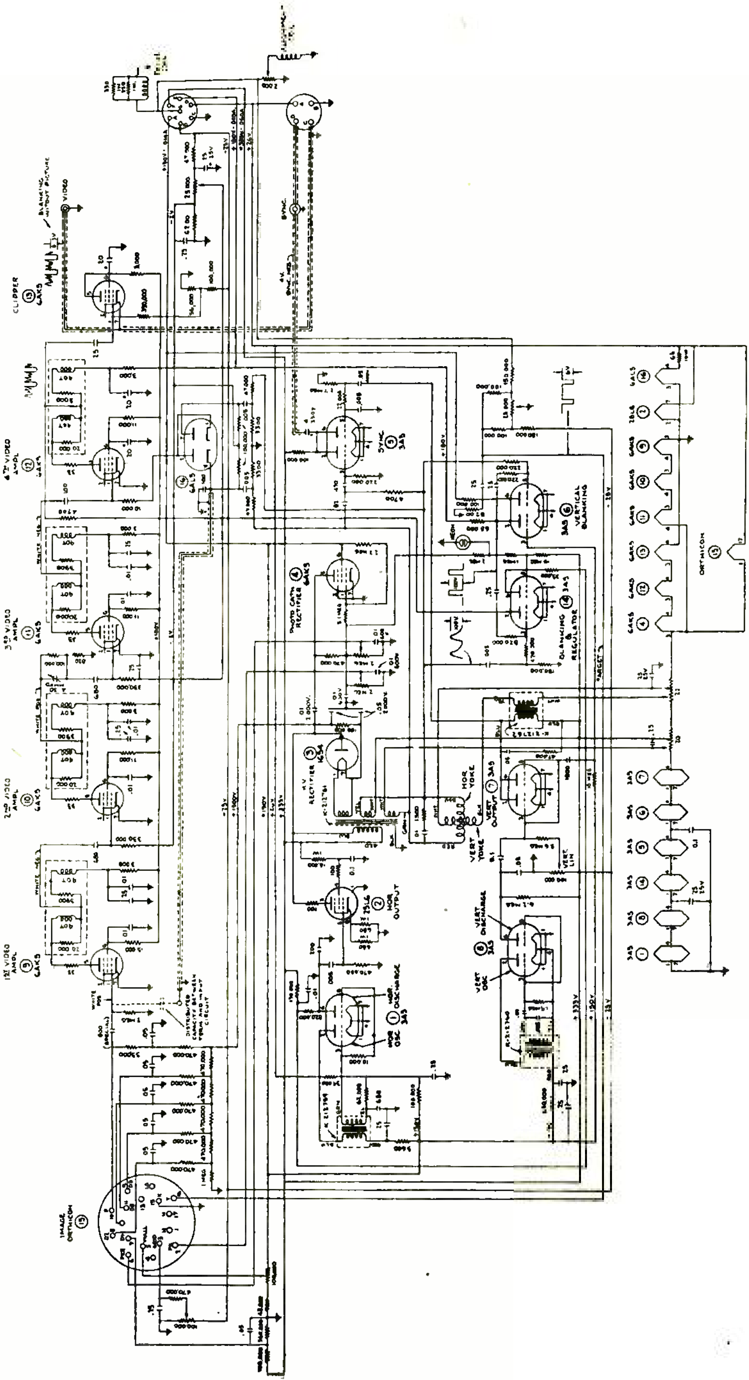


Fig. 5—Mimo camera diagram.

through the two halves of 3A5 tube No. 5. Both pulses are delayed in their respective grid circuits, providing a "front porch" on each blanking pulse. Since the plates, which are in parallel, operate at a low voltage, the tube tends to limit the horizontal pulses during the vertical sync pulse. Four volts peak-to-peak of sync signal appears on the output when it is coupled into a 150-ohm load.

The cathode of the image orthicon is at ground potential. Voltage for its bias adjustment is obtained from the negative supply of the dynamotor. The "wall" voltage for the tube is provided by the regulated +150-volt supply.

The camera unit has ten potentiometer adjustments. Four of these may be adjusted with the sealed cover in place. They are the image-orthicon grid bias, "wall" voltage or beam focus, photocathode or image

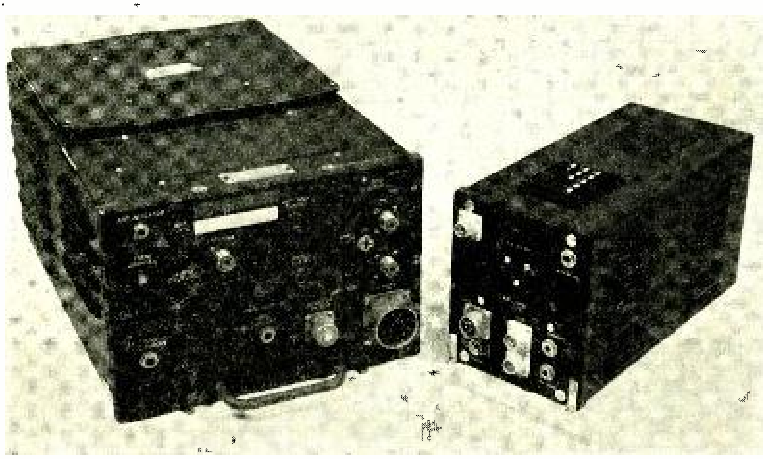


Fig. 6—The BC-1212-T3 and the Mimo transmitter.

focus, and video gain. The other adjustments are the two centering controls, the photocathode ring voltage, vertical linearity, alignment-coil current, and target voltage. No adjustments are provided for the deflection amplitudes and speeds, these being permanently adjusted during test.

The Transmitter

The Mimo transmitter unit is shown at the right in Figure 6. An earlier airborne television transmitter is also shown to indicate the relative size. The schematic diagram of the transmitter is shown in Figure 7. The transmitter is tunable between 260 and 380 megacycles and has a power output of 8 watts. Figure 8 is a side view of the transmitter, showing the relative location of the oscillator and the power amplifier. Figure 9 is a view of the bottom of the chassis, showing the master oscillator. Figure 10 shows the top of the chassis, with the power amplifier and modulator tubes.

The master oscillator is a 2C43 lighthouse tube, with a resonant-line tuning circuit and Colpitts feedback. The feedback capacitor is adjusted for the proper plate current, which may be measured across a 10-ohm resistor in the cathode. A tuned link circuit feeds the grid

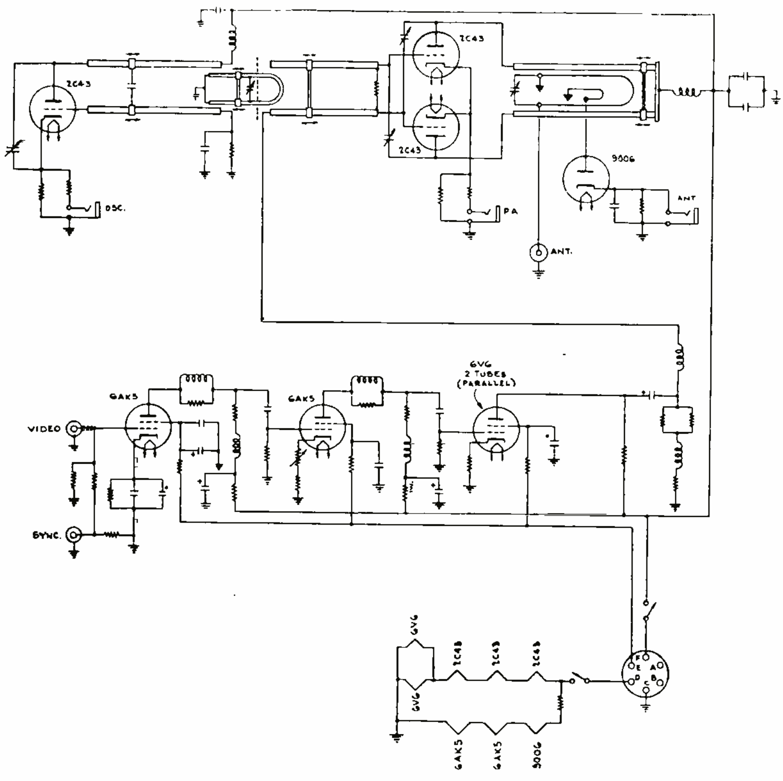


Fig. 7—Mimo transmitter diagram.

circuit of the push-pull power amplifier. The link circuit is fed through the chassis and it has a short-circuiting bar which is ganged with the short-circuiting capacitor of the oscillator. The power amplifier consists of two 2C43 lighthouse tubes in push-pull neutralized with a dual ceramic trimmer. The amplifier is grid modulated by two 6V6 beam tetrodes in parallel. The video and the sync signals coming from the camera unit are mixed at the grid of the first video amplifier (6AK5).

Each input terminal is terminated by a 150-ohm resistor and the 4-volt peak-to-peak sync signal is attenuated fifteen times before mixing. This circuit also attenuates the undesired flow of the video signal toward the camera, thus preventing cross-modulation which would cause parts of the picture signal to act as spurious sync pulses.

The second video amplifier has an "unbypassed" 1000-ohm variable cathode resistor acting as a gain control. With the gain control fully closed, the 0.7-volt peak-to-peak video input from the camera provides approximately 50 volts peak-to-peak across the plate lode of the 6V6

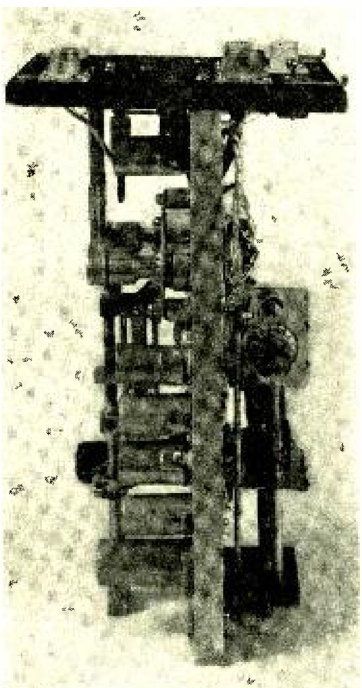


Fig. 8—Mimo transmitter chassis, side view.

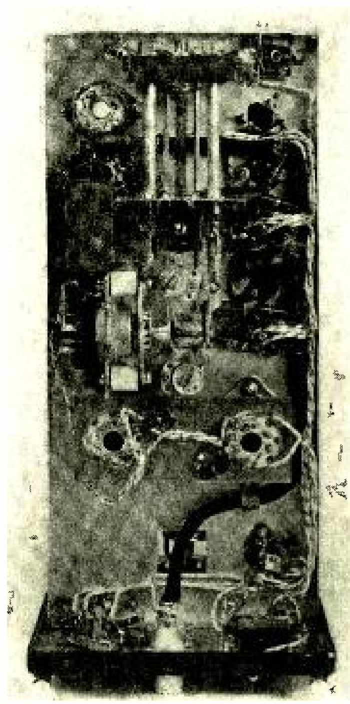


Fig. 9—Mimo transmitter chassis, bottom view.

tubes, corresponding to a modulation in excess of 90 per cent. The video amplifier is flat out to 4 megacycles.

A 9006 diode coupled to the antenna provides a monitor signal or a direct antenna tuning indication to a plug-in meter. The plate and grid currents of the power amplifier can also be measured by means of a plug-in meter.

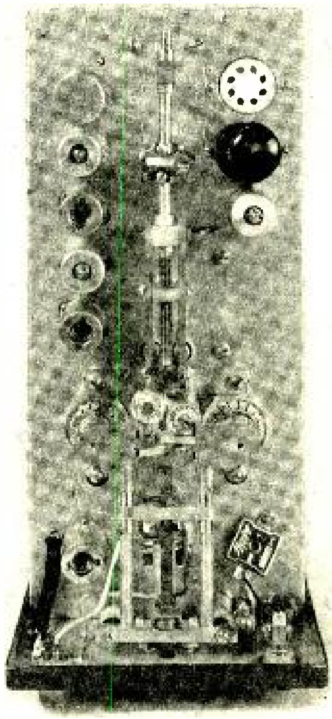


Fig. 10—Mimo transmitter chassis, top view.

Power Supply Unit

The power supply is shown on the right-hand side of Figure 11. This may be compared in size with the dynamotor and junction box of the earlier airborne equipment in the same photograph. Figure 12

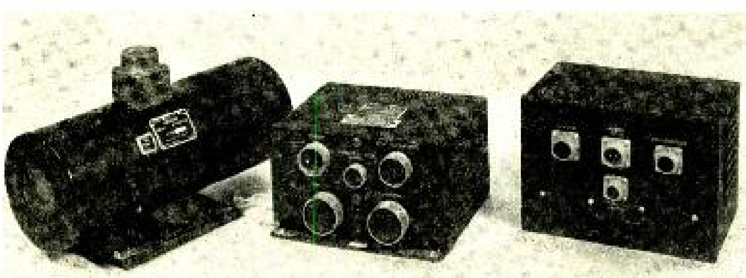


Fig. 11—The BC-1212-T3 dynamotor and junction box and the Mimo junction box including the dynamotor.

is a view of the Mimo power supply showing the Amperite regulator for the focusing coil in the camera, the 150-volt regulating tube, the electrolytic capacitors and the dynamotor. The schematic diagram of the power supply is shown in Figure 13.

ANTENNAS

The project involves the simultaneous operation of two radio links, namely, the Mimo link by which the picture signal is transmitted from the "Roc bird" or missile to the control plane, and the radio link by

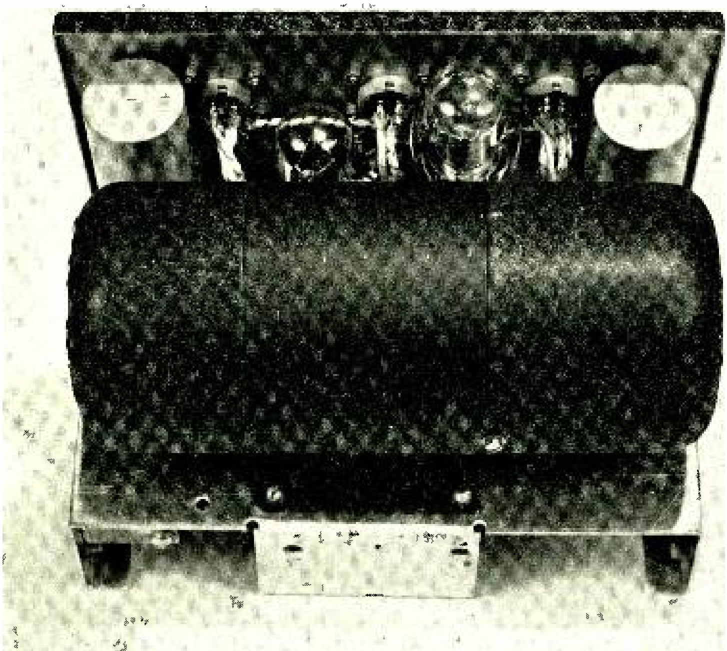


Fig. 12—Internal view of the Mimo junction box.

which the control signal is transmitted to the missile. This requires four antenna installations which will be referred to as Mimo-Roc, Mimo-plane, control-plane, and control-Roc, respectively.

The desired characteristics of the antennas are prescribed by certain operational and tactical conditions which will be discussed. In the first place, adequate coupling between the sending and corresponding receiving antennas must be maintained for every likely position of the "Roc bird" with respect to the launching plane from the time of dropping until impact. Since the plane is always roughly at the rear of the bird, the Roc antennas should have maximum radiation in this general direction to provide a favorable signal-to-noise ratio. Also, these antennas should have negligible radiation in a forward or downward direction in order to avoid strong signals being reflected from the ground. This is particularly true of the Mimo antennas because a television picture is inherently very susceptible to multipath reception. Also, in this case, the effect of multipath reception would be made worse by the Doppler effect due to the high velocity of the bird.

Obviously the antennas on the plane should have their maximum

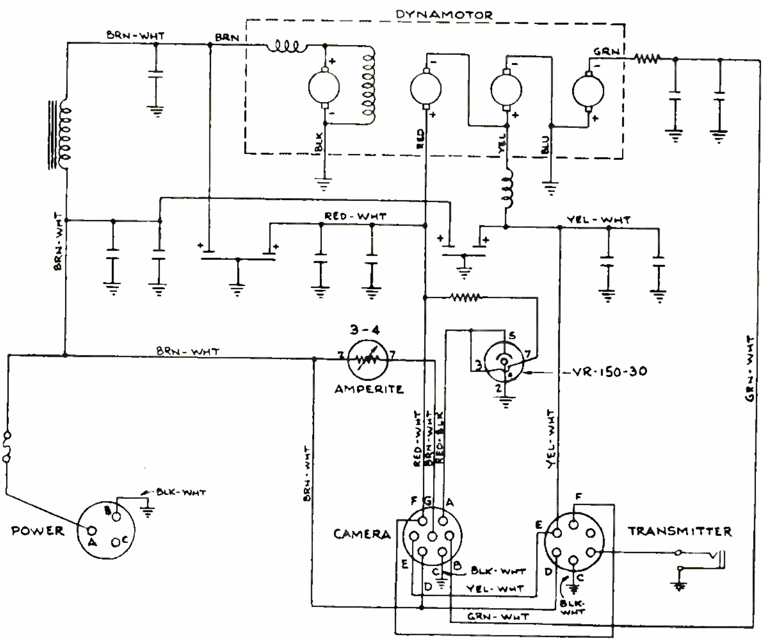


Fig. 13—Mimo power supply diagram.

radiation in a downward direction in order to bracket the Roc missile during its fall to earth. Also, adequate coupling between sending and receiving antennas should be retained even when the plane turns. It is not expected that the directivity of the plane antennas can be of any value in excluding multipath reception.

Secondly, it was required that it be possible to adjust the Mimo antennas to match the impedance of the lines at any spot frequency in the band (260 to 380 megacycles) and have a several-megacycle bandwidth in order to transmit a picture of adequate detail.

Both the directivity requirements and the fidelity requirements are somewhat less severe for the control link than for the Mimo because the signal transmitted is of a simpler character. However, the control frequency (84 megacycles) is several times lower so that more space would normally be required to obtain a prescribed antenna performance. At the start, the required size of the control antenna presented a serious problem in the "Roc bird" because of the danger of interfering with the aerodynamic performance of the missile. After considerable study, a satisfactory solution of the problem was found by insulating

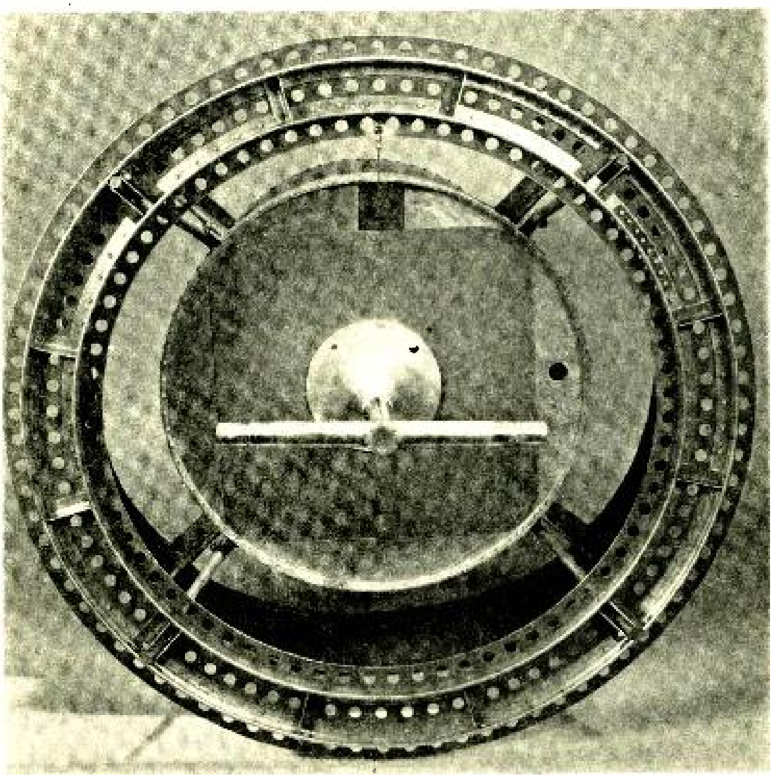


Fig. 14—The brake ring and dipole antennas on the "Roc bird."

the brake ring, which is primarily part of the aerodynamic equipment, and using it as the control-Roc antenna. This brake ring, however, affects the radiation pattern of the Mimo-Roc antenna. On this account it was found necessary to devise a method of effectively grounding the brake ring at the Mimo frequencies, and at the same time insulating it at the radio-control frequencies. Figure 14 shows the Mimo dipole transmitting antenna and the brake ring used for the receiving control antenna on the rear of the "Roc bird."

The supporting rods of the brake ring are made up as coaxial lines which are a quarter wavelength long at the Mimo frequency, and thus ground the brake ring to the body of the "Roc." The impedance of these lines is high at the control frequency, and consequently insulates the brake ring from the body of the "Roc" at this lower frequency. Figure 15 shows the radiation pattern of this assembly in the elevation and azimuth planes. The reduction of secondary lobes from the Mimo antenna was of great importance in reducing the interference that reception of the radiated energy could cause in the control receiver. The brake ring is connected at a point 90 degrees with respect to the Mimo antenna, as shown in Figure 14, thus reducing the coupling between the two antennas to very low value.

The Mimo-plane antenna consists of two dipoles, identical in con-

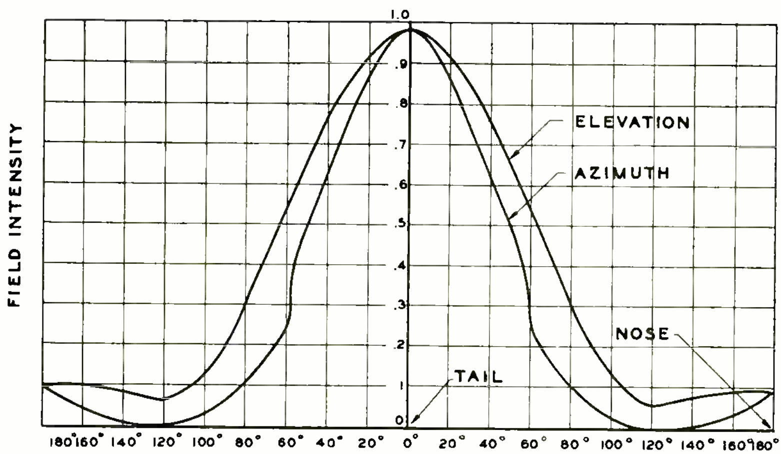


Fig. 15—Radiation patterns of the "Roc" dipole at 310 megacycles.

struction with those used on the "Roc." They are mounted on the underside of the plane with centers spaced 0.417 of a wavelength at mid-band, and oriented so that the extended axes of the dipoles intersect at 90 degrees at a point equidistant from the two dipoles. The physical layout is shown in Figure 16. The dipoles were fed equally and in phase.

Comparison of Weights of Earlier Airborne Television and Mimo Equipments

While photographs give a fair indication of the size reduction accomplished in the Mimo design, it may be interesting to note that the weight of the total equipment was cut in half. The weights of the various components of the two systems are as follows:

	Earlier Airborne Television Equipment	Mimo 3
Camera Unit	33¼ lbs.	20 lbs.
Transmitter	26¾ lbs.	7 lbs.
Power Supply Unit	21½ lbs.	15 lbs.
Shock Mounts, Cables, etc., approx.	18½ lbs.	8 lbs.
Total	100 lbs.	50 lbs.

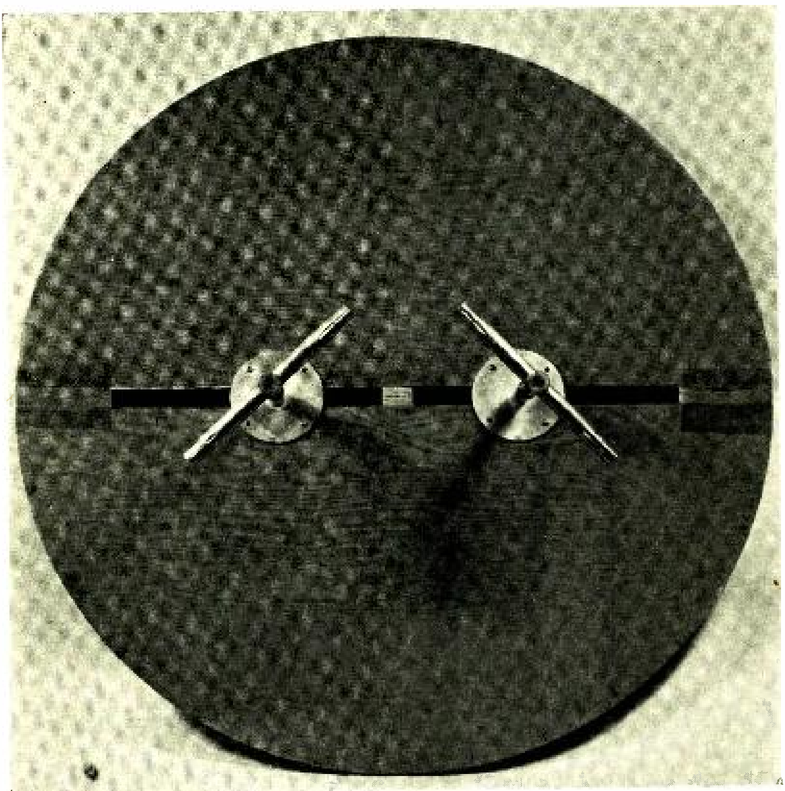


Fig. 16—Two dipoles as Mimo-plane antenna.

PERFORMANCE

In the early flight tests, made in the East, the camera and transmitting equipment was mounted in an AT-11 type aircraft. The signal was received on the ground. The camera unit was mounted in the plastic nose of the plane on a tiltable platform. The transmitter and power supply were in the rear of the plane and the antenna was mounted on the underside of the plane. A single horizontal dipole mounted on a wire screen was used as the receiving antenna at the ground station. On several occasions very satisfactory signals were obtained from a distance of 20 miles with the plane at 10,000 feet altitude. A useful signal was obtained at the same altitude even 40 miles away, when the nose of the plane was tipped down, thus taking greater advantage of the antenna directivity.

In actual drops of the "Roc" missile, of course there were no distances of such magnitudes involved. There were, however, several other difficulties encountered in obtaining good signals from the missile. The most important among these difficulties was a predominant Doppler effect, due to the multipath reflections from the ground (in spite of the directivity of the antenna) and the high speed of the "Roc."

When the source of a radiation is moving, an apparent wavelength will be observed according to the relation:

$$\lambda' = \frac{c \pm v_t}{f} \tag{1}$$

where λ' is the apparent wavelength, c is the velocity of propagation, v_t is the velocity of the radiating source, and f is the frequency. The sign is positive when the path increases, and it is negative with a reduced path. Since

$$f = \frac{c}{\lambda} \tag{2}$$

the frequency f' observed at the receiver is:

$$f' = \frac{c \pm v_r}{\lambda'} \tag{3}$$

where v_r is the velocity of the receiver. Substituting the value of λ' from (1), we have:

$$f' = \frac{c \pm v_r}{c \pm v_t} f \tag{4}$$

Assuming two straight paths, one increasing as the bird travels from the plane, and one reflected from the ground decreasing as the bird approaches the ground, two signals will be received producing a beat frequency according to the relation:

$$\Delta f = f_1' - f_2' = f \left(\frac{c + v_r}{c + v_t} - \frac{c + v_r}{c - v_t} \right)$$

$$\Delta f = f \frac{2c\, v_t}{c^2 - v_t^2}, \quad (5)$$

Since $c^2 >> v_t^2$,

$$\Delta f \approx f \frac{2v_t}{c}, \quad (6)$$

assuming a missile velocity of approximately 500 miles per hour, or 224 meters per second and a carrier frequency of 300 megacycles,

$$\Delta f = 448 \text{ cycles per second.}$$

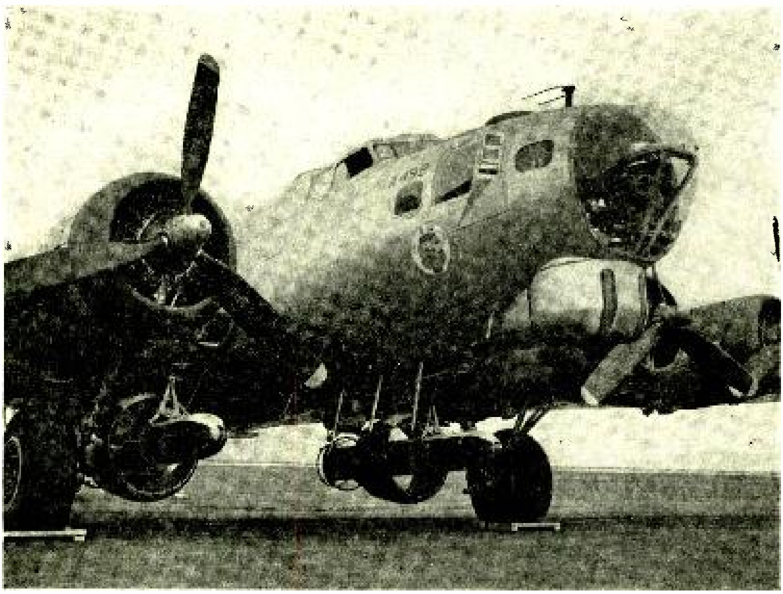


Fig. 17—Two "Roc birds" on a B-17 plane (Courtesy of Douglas Aircraft Company, Inc.)

Another difficulty encountered was the microphonics caused by the control surfaces. The microphonic problem, while considerably less serious than the Doppler effect, aggravated the situation. Since these two difficulties produced similar effects in the form of horizontal bars, the causes were not easily separated. In the course of actual drops these difficulties were reduced to the extent that very satisfactory pictures were obtained for guiding purposes.

Figure 17 shows two "Roc birds" attached to a B-17 plane. Figure 18 shows a photograph of a test target in the western United States.

Figures 19-21 are enlargements from 16-millimeter moving picture films taken from the television picture received at the control plane. In this particular drop the plane flew at 19,200 feet, which was 15,000 feet above the target area when the missile was dropped. The vertical bars caused by the Doppler effect are noticeable in all three pictures, particularly in Figure 21, which is taken less than a second before impact, but they do not destroy the value of the information. The reproductions through the 16-millimeter motion picture film enlarging and finally the printing process destroy much of the detail and clarity of the picture appearing on the monitor, but even from these repro-

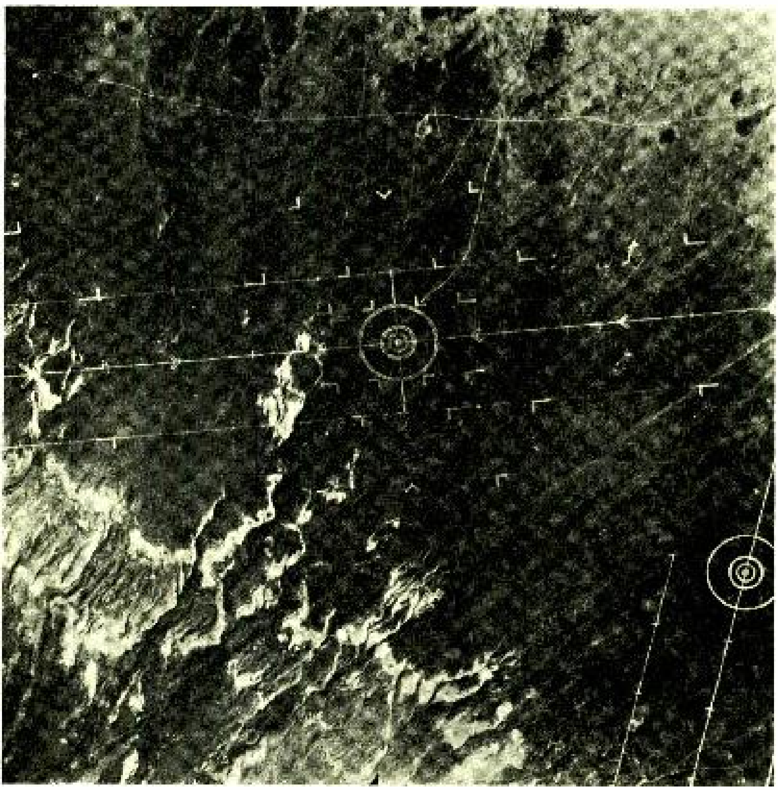
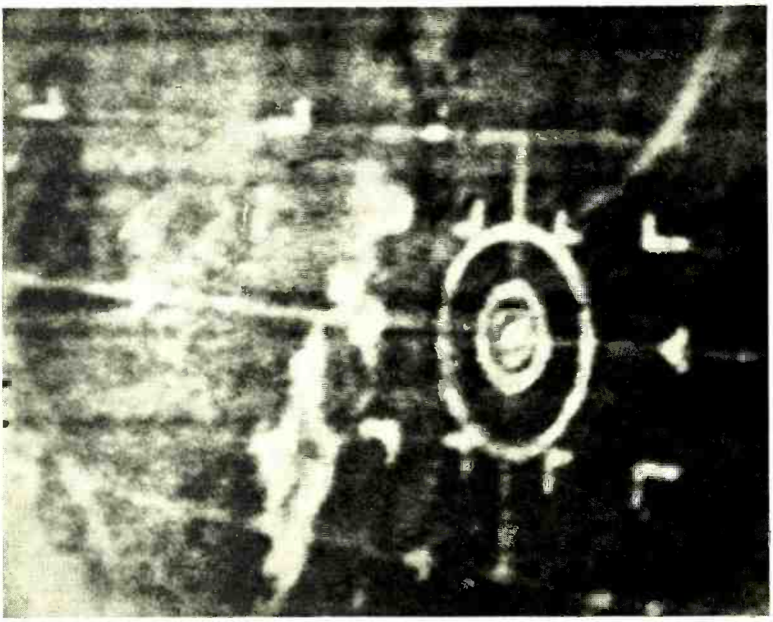


Fig. 18—Photograph of a test target.

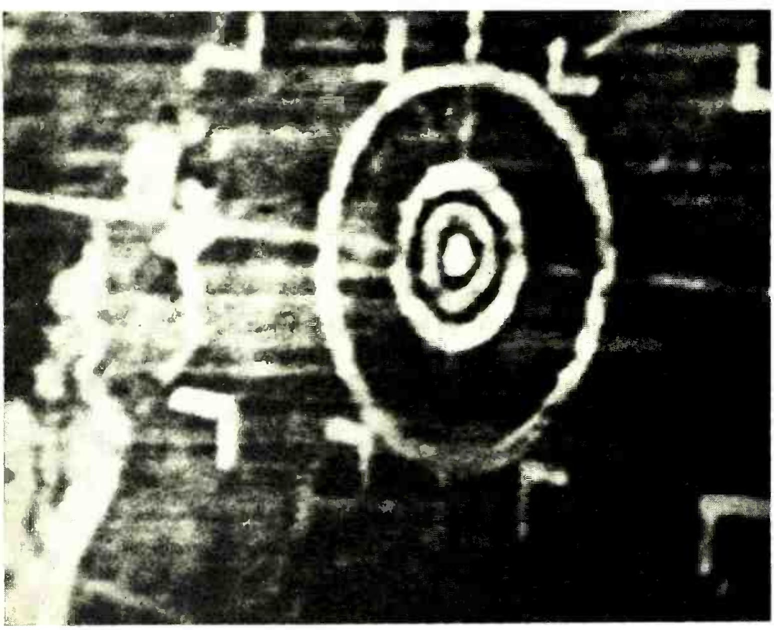
ductions, the value of the information for guiding the missile may easily be seen.

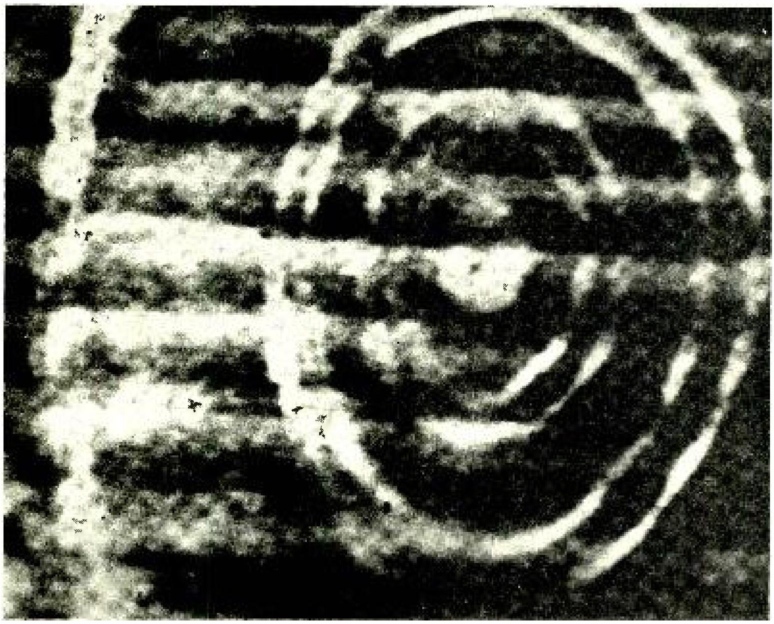
Acknowledgment

Acknowledgment is made to the engineers of the Douglas Aircraft Company, Inc., and RCA Laboratories Division who cooperated on the



Figs. 19-21—Progressive photographs of the monitored picture.





project. In particular, special credit is due Messrs. R. R. Thalner and K. R. Wendt, who helped in the design as well as the tests, to M. A. Jackson of NBC, who assisted in the drop tests, and to Dr. G. H. Brown and Mr. J. Epstein, who designed the antenna systems. The work described in this article was done in whole or in part for the Office of Scientific Research and Development under Contract OEMsr-441 with Radio Corporation of America.

MIMO-MINIATURE IMAGE ORTHICON*

BY

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Summary—*A miniature image orthicon, known as the "Mimo" tube, has been developed for use in airborne television equipment. Its reduced size and power requirements permit a substantial reduction in the dimensions and weight of the pickup-tube camera. The Mimo incorporates an improved mounting technique and employs additional fine mesh screens in front of the photocathode and target for the purpose of shaping the electric fields and simplifying operation. The resolution and signal-to-noise ratio of the Mimo approach that of the larger image orthicon at high light levels under carefully controlled conditions. Performance considerations as a function of the tube size are discussed.*

INTRODUCTION

MILITARY applications for a miniature television camera have prompted the development of a pickup tube considerably smaller than any of the tubes in commercial use. At the same time, the aim was to approximate the performance of the larger tubes. Of all of the well-known types of pickup tubes, the image orthicon because of its high sensitivity and high signal level output was most suited for scaling down. Accordingly, a miniature image orthicon called the "Mimo" tube has been designed for use in airborne television equipment.[2] Figure 1 shows a comparative photograph of the Mimo tube and an image orthicon.[†]

The mechanism of operation of the Mimo tube is essentially the same as the image orthicon whose cross-sectional diagram is shown in Figure 2. The optical image is projected on the semi-transparent photocathode laid on the inside surface of the glass envelope. The resulting photoelectrons are focussed by the uniform magnetic field, and they land at high velocity on the thin, semi-conducting glass target. Since the secondary emission ratio of the glass is greater than unity, a positive charge pattern is built up on the glass corresponding to the light and

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* Decimal Classification: R583.6.

[1] A. Rose, P. K. Weimer, and H. B. Law, "The Image Orthicon—A Sensitive Television Pick-up Tube", *Proc. I. R. E.*, Vol. 34, pp. 424-432, July, 1946.

[2] R. D. Kell and G. C. Sziklai, "Miniature Airborne Television Equipment", RCA REVIEW, Vol. VII, No. 3, pp. 338-357, Sept., 1946.

† Throughout this paper the term "image orthicon" will refer only to the tube described in Reference 1.

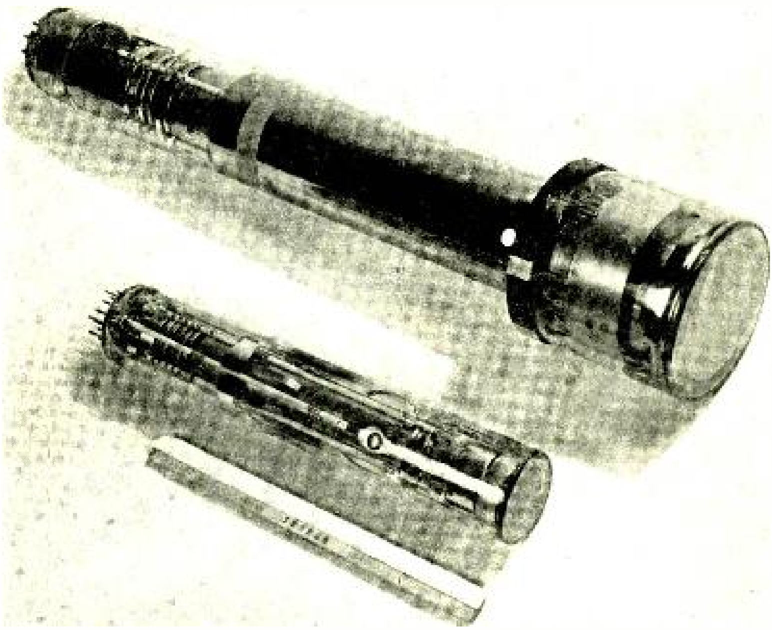

Fig. 1—Comparison of the Mimo tube with an image orthicon.

shade in the optical image. The target screen collects the secondary electrons from the glass and serves to limit the maximum potential to which the glass may rise. A low-velocity beam scans the other side of the glass target and deposits sufficient electrons in the positive areas to drive the glass down to the potential of the thermionic cathode of the gun. The conductivity of the glass is so chosen that the charge is con-

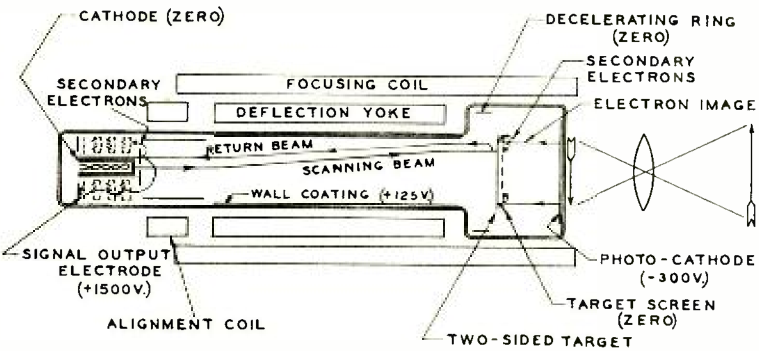

Fig. 2—Cross-sectional diagram of the image orthicon.

ducted through the glass in a frame time while lateral leakage is negligible. Excess beam electrons not deposited on the glass form a modulated return beam which is directed into a five stage multiplier. The video signal from the output of the multiplier is fed into the camera video amplifier.

Aside from reduced size, the principal ways in which the Mimo tube differs structurally from the image orthicon are:

(1) All electrodes including the image section are mounted on a single assembly with all the electrical connections brought out through a single 18-lead stem of the miniature button type.

(2) Additional fine mesh screens are used in front of the target and photocathode for the purpose of controlling the shape of the electric fields.

The results of these changes are described in the following sections along with a discussion of performance as a function of target area.

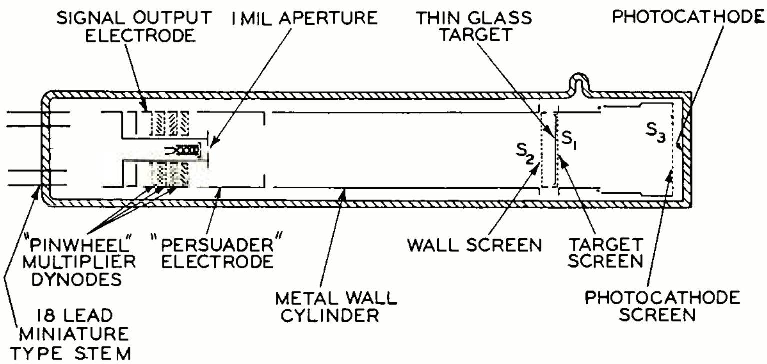

Fig. 3—Cross-sectional diagram of the Mimo tube.

Structural Details of the Mimo

A cross sectional drawing of the Mimo tube is shown in Figure 3. The overall length is 9″ (as compared to 15¼″ for the image orthicon) and the maximum diameter has been reduced from 3″ to 1½″. These dimensions allow a substantial reduction in weight of copper, and power required for the focusing and deflection coils, as well as the use of a smaller lens.

In the type of assembly used in the Mimo tube the metal wall cylinder is of thin nichrome and replaces the platinum coating used in the image orthicon. Ceramic tubing supports all electrodes (except within the gun) and the target connections are made to the stem by means of wire leads pushed through the ceramic tubing. Mandrels are used to align the cylinders during assembly, making possible a more accurate alignment than if the target structure were mounted independently as was done in previous tubes.

A gap of 180 degrees between two ceramics is left between the target structure and the wall for convenient insertion of the glass target and wall screen just prior to sealing. A spring contact to a metal button on the inside of the glass envelope connects the photocathode to the proper lead in the stem.

A glass envelope of uniform diameter is used for the Mimo tube in order to take advantage of the single unit construction without requiring the additional sealing operation over the target. This fact, combined with the elimination of the leads at the shoulder, greatly simplifies the glass blowing operations. The molded miniature type stem which requires no basing is extremely convenient.

It was found that the performance of the multiplier was unaffected by scaling it down from 1½″ to 1″ diameter. The persuader electrode is tied electrically to the first stage instead of being brought out on a separate connection as before. The gun is made slightly smaller in diameter and the defining aperture reduced to about 1 mil.

Vibration tests showed the Mimo to be structurally quite strong. One tube was found to be operable after having been subjected to an acceleration of 25 g's.

Use of the Wall and Photocathode Screens

The availability of fine mesh screens of high transmission and uniformity have made practical the use of screens for controlling the electric fields in front of the target and photocathode. These screens, labelled S_2 and S_3 in Figure 3, are mounted directly on the wall and target structures, replacing the separate "decelerating ring" and "photocathode ring" of the image orthicon. Unlike the target screen, S_1, they are positioned far enough from a nodal plane of the electron stream that their meshes are not superimposed on the transmitted picture.

One advantage of using screens in this manner is that good focus at the edges of the picture and freedom from distortion are automatically assured without requiring separate adjustment of ring voltages. Furthermore, the screens permit high fields in front of the target and photocathode without requiring high voltages. Uniform landing of the low-velocity beam at the edges of the target is easily obtained, and the position of the deflection coil for best landing is less critical.

Another important advantage gained by the use of the wall screen is the elimination of the multiplier shading control found in the image orthicon. The screen compels the electric field in front of the target to become more nearly parallel to the magnetic field. This reduces the translational effect on the beam which is the major cause of the scanning of the first stage of the multiplier by the return beam. The consequence of this reduction in scan is that the requirement of uniform gain of the first stage is somewhat less stringent. As a result there is no need to adjust the persuader voltage for controlling uniformity of gain. The persuader electrode of the Mimo is connected internally to the first stage lead.

It should be pointed out that the screens result in some loss in signal-to-noise ratio (in some cases as much as 30 per cent). Also, the two extra screens are potential sources of spurious signal. The wall screen is the more critical of the two because the beam passes through it twice. In spite of the fact that both the scanning beam and the return beam are out of focus when passing through this screen a spurious interference pattern simulating a mesh appears under certain conditions. This pattern can be minimized by proper spacing of the wall screen and the target.

In the airborne application for which the tube was designed, the advantage of the screens in simplifying operation considerably outweighed the accompanying disadvantages.

Performance As a Function of Size

The active target area of the Mimo tube is slightly more than one quarter of that used by the image orthicon. This reduction affects performance from the standpoint of resolution, signal output and optics of the camera lens.

1. *Resolution*

Assuming that the resolution is limited electron-optically only by chromatic aberration and the stiffness of the beam at the target, it follows that a reduction in size of the tube, while keeping the voltage constant, should have no effect on the number of television lines which may be transmitted. The higher fields in the smaller tube should reduce the spot size in proportion to the change in dimensions. Actually, other less fundamental factors enter in to determine resolution — factors whose contributions are not as readily scaled down with tube size.

Loss of resolution by target leakage, for example, may arise from the volume conductivity of the glass or from the surface conductivity caused by a conducting coating of caesium on the glass. The first cause depends mainly on the resistivity and thickness of the glass and may be practically eliminated by using thinner glass in the small tube.

(Targets as thin as 0.05 to 0.1 mil were used in the Mimo tube). However, caesium leakage, when present, will deteriorate resolution to a greater extent with a target of small dimensions.

The superposition of the target screen upon the transmitted picture requires a finer mesh screen for the Mimo tube. An improvement in maximum resolution resulted when a screen of 500 meshes per linear inch was replaced by a screen of 1000 meshes per linear inch.

Cross talk in which the stray deflection fields disturb the paths of the photoelectrons in the image section might be expected to scale down proportionally with tube size. However, in the Mimo tube the deflection coil, for compactness, has been placed relatively closer to the target than in the image orthicon. This makes the cross talk a more critical problem. An effective solution is the use of iron wire wound over the deflection coil in combination with a cylindrical copper shield over the image section, but the position of the copper shield is quite critical. Alternative methods of reducing cross talk are an iron ring on the end of the deflection coil or a "bucking coil" over the image section fed by a small fraction of the horizontal deflection voltage. The cross talk from the horizontal deflection coil is more persistent than from the vertical coil. The shortened storage time of the image orthicon type of target, when the light is raised, rapidly erases the effect of "vertical" cross talk but has no effect on the "horizontal" cross talk until extremely high lights are reached.

The resolution required of the Mimo tube for the airborne television project was 250 lines at high lights, and this was easily met. (See Figure 4 and Figure 5). A number of tubes when carefully set up under experimental conditions with high light illumination showed more than 500 lines. The high limiting resolution of the scanning beam is evidenced by the fact that by under-scanning the target (to remove the video amplifier frequency band limitation) the individual wires of the 1000 mesh target screen can be resolved. This is equivalent to 2000 television lines per inch. Separate tests have shown that under ideal conditions the image section is also capable of equal resolution. The contrast ratio near the limiting resolution is, of course, very low.

The limiting resolution of the small tube is enhanced by the use of the wall and photocathode screens as well as by the use of a smaller defining aperture in the gun. However, it should be pointed out that high light resolutions approaching that of the image orthicon can be attained only if great care is taken in selection and adjustment of the tube.

2. *Signal Output*

At very low light levels, where full storage occurs, the signal output at the target is independent of tube size. This assumes that the camera lens aperture is adjusted to give the same depth of focus.

At high lights the area of the target is important in determining signal output. For a "close spaced" target (i.e. glass-screen spacing less than one picture element) the signal output varies as the target area and signal-to-noise ratio varies as the diameter. For "wide spaced" targets (i.e. glass-screen spacing wide compared to a picture element) the signal output varies more nearly as the diameter of the target and signal-to-noise ratio as the $(\text{diameter})^{1/2}$. The target spacing of the Mimo is of the order of two mils which is about the same as in

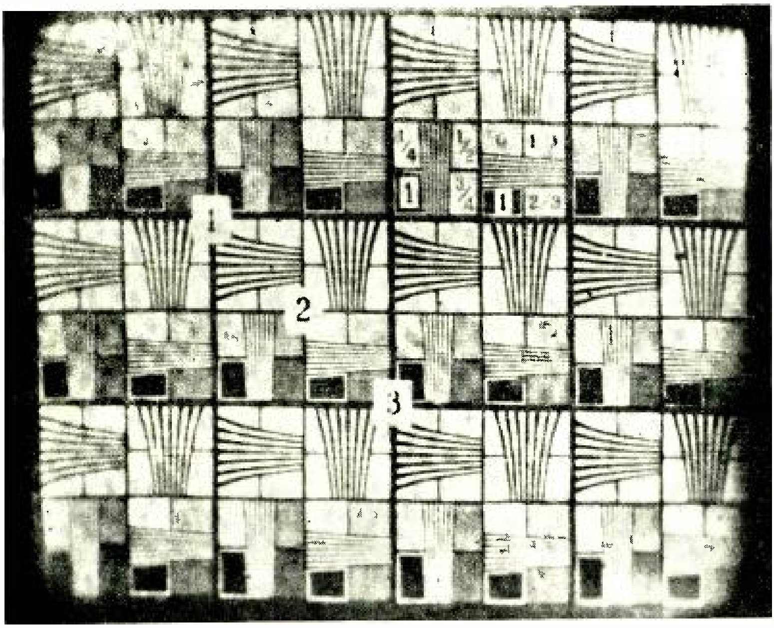

Fig. 4—Photograph of a test pattern transmitted by the Mimo tube.

the image orthicon. Because this is somewhat intermediate between "close" spacing and "wide" spacing, the drop in signal-to-noise ratio is bracketed by the above limiting cases.

Another factor influencing the variation of signal with target area at high lights is the degree of overlapping of the beam spot in adjacent lines. Some overlapping does occur in the Mimo tube (in spite of the high *limiting* resolution quoted above), and this would contribute to enhanced signal at high lights owing to the recharging of the target between successive scans.

3. *Choice of Lens*

The first consequence of the smaller photocathode of the Mimo tube is that a shorter focal length lens may be used for the same angle of view. This results in a saving in space although a faster lens is required. If, in addition, the lens diameter is also scaled proportionally, so that the numerical aperture remains unchanged, increased depth of focus is obtained at the expense of operating sensitivity.

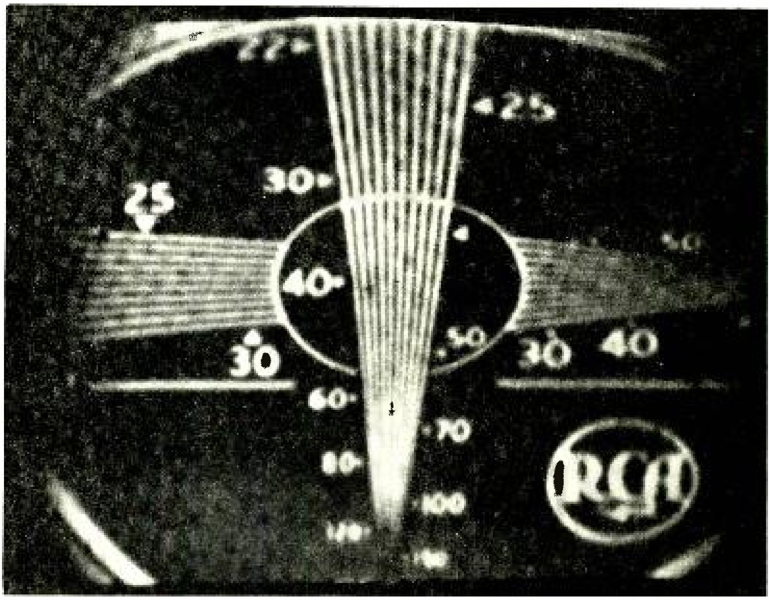

Fig. 5—Enlarged section of a test pattern transmitted by the Mimo tube. (The optical pattern was projected on the photocathode at normal size while the scanning amplitude was reduced to cover only the center portion of the target. This procedure tests the resolving power of the tube by reducing the limitations of the amplifier frequency response as well as cross talk in the image section. The numbers on the pattern should be multiplied by ten to give the resolution in television lines.)

At high light levels, in which range the signal output is substantially independent of scene brightness and in which range the Mimo was mostly used, lens speed is of no importance. Here the shorter focal length lens is an unalloyed gain in conserving space.

The size of the image projected on the photocathode of the Mimo is approximately the same as that of one frame of a 35-millimeter motion picture film. Thus a wide choice of lenses for the Mimo is at hand. An f/2.0 lens was used in the camera but light conditions in the airborne application were such that the lens was often stopped down to as small as f/22.

CONCLUSIONS

A useful television pick-up tube of reduced size has been developed for airborne television purposes. This tube retains the high sensitivity and stability under adverse lighting conditions which have characterized the image orthicon. At the same time changes in design have been incorporated which make for simplified operation of the camera. It is believed that the Mimo tube represents a first step toward the development of a television camera which approaches the miniature photographic camera in convenience and portability.

ACKNOWLEDGMENTS

The writers wish to acknowledge the interest and valuable suggestions of Drs. V. K. Zworykin and Albert Rose. The production of the tube was greatly aided by the contributions of R. R. Goodrich, P. G. Herkart, and C. S. Busanovich.

DEVELOPMENT OF RADIO RELAY SYSTEMS*

BY

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Summary—Radio relay systems for long distance electrical communications over land have been accepted as replacements for wire lines and cables over some of the most heavily loaded telegraph circuits in the world. They are beginning to revolutionize and expand communications over land just as the development of short wave transoceanic communication 20 years ago revolutionized international communications.

During the war this company developed the AN/TRC-8 and AN/TRC-5 radio relaying equipments for the U. S. Army Signal Corps; at the end of the war, it developed Types CW-1a and CW-2a radio relay equipment which it demonstrated for the Western Union Telegraph Co., with the result that Western Union has announced plans for establishing a national radio relay network.

Long distance radio relaying is expected to be done in a band of frequencies ranging from about 1000 to 8000 megacycles, the upper limit of frequency being set by effect of rain storms upon reliability.

Suggested minimum carrier-to-effective or apparent noise power ratios are as follows: for printer telegraph, 18 decibels; on-off-keyed printer telegraph 21 decibels; for ordinary telephone, 40 decibels; for ordinary broadcast material, facsimile, and television, 50 decibels; and for high grade music, 60 decibels. The frequency bandwidth occupied by a phase modulated multichannel radio relay system is $2B + \frac{2Bd}{\sqrt{3}}$ *where B is the modulation frequency band and d is the peak phase deviation.*

Radio relay equipment development is still in a state of flux but, since costs are mostly for sites, towers, and auxiliary facilities, which are permanent, there is no need to delay investment in radio relay systems. Automatic facsimile message communication at television speeds may well be the best answer to competition for the record communications industry.

INTRODUCTION

A REVOLUTION in methods and a great commercial expansion in long distance electrical communication over land are beginning. For many years it has been necessary to depend upon physical connections, by wire lines and cables, to carry telegraph and telephone messages. Now radio relay systems, operating in frequency bands ranging from about 1,000 to 10,000 megacycles per second can be used to supplement and replace the wire lines and cables.[1, 2]

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* Decimal Classification: R480.

[1, 2] See following page.

Radio relays require no physical connections between repeater points and are therefore free from many of the hazards to which wire lines and cables are exposed. They offer lower costs for the older types of service and open up possibilities for many new types of service.

Within the next ten to twenty years commercial development of radio relay systems throughout the world should bring about a great expansion in overland communications facilities and a great increase in traffic.

The present situation in long distance communications over land is strikingly similar to that which existed in transoceanic communications twenty years ago. At that time a new band of radio frequencies, extending from about three to twenty-five megacycles, had been opened up. Its commercial development revolutionized and greatly expanded international communications. It made possible practically instantaneous communication to all points on the earth, without the limitations and heavy investment costs imposed by transoceanic cables. It provided new types of service and a great increase in traffic at much lower rates.[3, 4]

Although radio relay development in recent years has placed most emphasis on providing means for the distribution of the new service of television it now appears that its initial commercial development may be very largely in the field of telegraphy, the oldest of the electrical communications industries. The Radio Corporation of America, with the cooperation of the Western Union Telegraph Company developed a radio relay system designed to take the place of wire and cable telegraph lines and Western Union has announced plans to establish a system of radio relays linking the larger cities of the United States within the next few years.[2] (Note (a).)

This early acceptance of radio relaying in an old and well-established branch of electrical communications was a welcome surprise to engineers who have spent much time and effort on radio relay development. They had expected that radio relaying for general communica-

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[1] C. W. Hansell, "Radio Relay Systems Development by the Radio Corporation of America", *Proc. I.R.E.*, Vol. 33, No. 3, pp. 156-168, March, 1945.

[2] Julian Z. Millar, "A Preview of the Western Union System of Radio Beam Telegraphy", *Jour. Frank. Inst.*, Vol. 241, No. 6, pp. 397-413, June, 1946, and Vol. 242, No. 1, pp. 23-40, July, 1946.

[3] H. E. Hallborg, L. A. Briggs, C. W. Hansell, "Short Wave Commercial Long Distance Communication", *Proc. I.R.E.*, Vol. 15, No. 6, pp. 467-499, June, 1927.

[4] H. H. Beverage, C. W. Hansell, H. O. Peterson, "Radio Plant of R.C.A. Communications, Inc.", *Elec. Eng.*, Vol. 52, No. 3, pp. 75-82, March, 1933.

NOTE (a)—A paper by L. E. Thompson entitled "A Microwave Relay System" is scheduled to appear in a forthcoming issue of *Proc. I.R.E.*

tions purposes would be accepted first, and most readily, in those parts of the world where there were few existing investments in wire lines and cables but where there were growing needs for communications. Now it appears that the commercial development of general purpose radio relay systems will go forward simultaneously in all parts of the world.

Prewar development of radio relay systems by this corporation has been described in a previous paper.[1] During the war the line of development was directed toward solving some of the communications problems of the Armed Forces. Since the war, development of systems for general purpose commercial applications has been followed intensively and radio relay equipment is now being manufactured.

Because radio relay systems are about to have an important effect upon the commerce and habits of most of the population of the earth it may be interesting and pertinent to bring the history of this activity up to date and to outline some of the technical problems involved in designing commercial systems which were not taken up in the previous paper.[1]

Historical

During the war radio relay systems had important applications for military purposes and their advantages were increasingly recognized. The U. S. Army Signal Corps set up a program of military radio relay equipment development in connection with which two radio relay systems were developed.

Immediately following the end of the war advantage was taken of some of the wartime vacuum tube developments to work out still another radio relay system especially designed to compete with wire lines and cables in the simultaneous handling of many telegraph, telephone, facsimile, and similar types of communications channels.[2] (Note (a).)

1. *AN/TRC-8 Frequency Modulated Radio Relay Equipment*[5]

During the war a relatively simple, light weight, radio relay system was developed for the Armed Forces for use in conjunction with the Signal Corps "spiral four" type of cable and its associated terminal communications equipment.[6] It employed frequency modulation and provided a modulation frequency band about 12,000 cycles wide, to accommodate four speech channels or four groups of telegraph channels

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[5] Andrew R. Boone, "The Army's Radio Relay Equipment", *Radio News*, Vol. 35, No. 1, pp. 25-28, 151-155, January, 1946.

[6] O. B. Jacobs, "Carrier System for the Spiral-4 Cable", *Bell Labs. Record*, Vol. 22, No. 4, pp. 168-172, December, 1943.

simultaneously. Figure 1 is a photograph of this equipment.

In this equipment the received signals were demodulated in a receiver at each relay point and used to frequency modulate a trans-

Fig. 1—The AN/TRC-8 equipment developed for the U. S. Army Signal Corps.

mitter. The transmitters and receivers could be used separately with connection to the cable terminal equipment at relay system terminals.

The transmitters provided easy and quick adjustment of carrier frequency over a band of 230 to 250 megacycles, with accurate maintenance of frequency at any set value. This was accomplished by using a foreshortened, adjustable, temperature-compensated, resonant line frequency control circuit.[7]

A characteristic of this equipment, which was particularly important for military applications but which would also be useful in commercial applications, was that the number of frequencies present in the transmitter, on which suppression of radiation was desired, was much less than the number present in transmitters employing piezo-electric quartz crystal-controlled oscillators and frequency multipliers. Because of this feature, interference to other services, which proved to

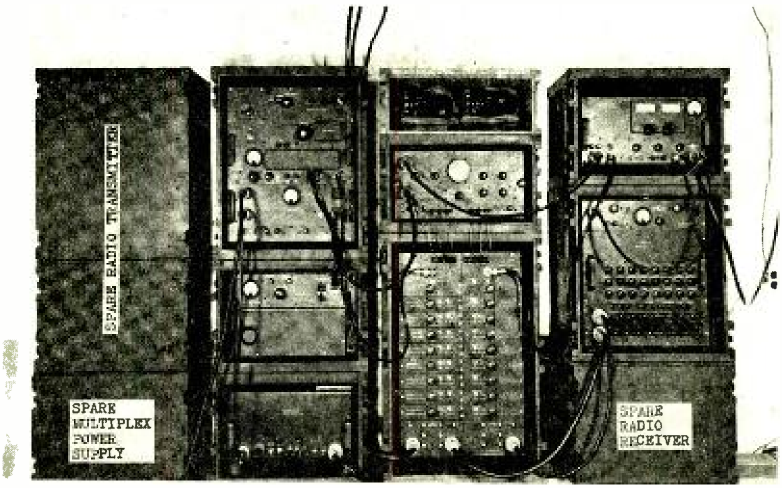

Fig. 2—The AN/TRC-5 equipment developed for the U. S. Army Signal Corps.

be a serious problem in military operations, was reduced. In addition, absence of radiation on unwanted frequencies made it more difficult for the enemy to locate and destroy the equipment.

2. *AN/TRC-5 Pulse Type Radio Relay Equipment*[8, 9, 10]

Another type of radio relay equipment, (shown in Figure 2) devel-

[7] C. W. Hansell and P. S. Carter, "Frequency Control By Low Power Factor Line Circuits", *Proc. I.R.E.*, Vol. 24, No. 4, pp. 597-619, April, 1936.

[8] Robert Endall, "Microwave Pulse Modulation", *Radio News*, Vol. 35, No. 4, pp. 41-44, 88-94, April, 1946.

[9] Tom Gootee, "Radio Relay Communications With Pulse Modulation", *Radio News*, Vol. 35, No. 5, pp. 16-20, 32-34, May, 1946.

[10] John J. Kelleher, "Pulse Modulated Radio Relay Equipment", *Electronics*, Vol. 19, No. 5, pp. 124-129, May, 1946.

oped during the war for military applications, employed very short radio carrier current pulses of the kind commonly used in radar. By the use of pulses it became possible to use radar components and to reach up to the highest ranges of radio frequency then available for any type of application.

In the AN/TRC-5 equipment provision was made to handle eight telephone channels simultaneously by means of a system of synchronous time division so that successive pulses were assigned to different telephone channels. The means for accomplishing automatic synchronism between sending and receiving electronic commutators was similar in principle to that used for holding synchronism in television. A synchronizing pulse was transmitted once for each revolution of the electronic commutator which was distinguishable from signal pulses because it was longer.

The pulses of carrier current were about 0.4 microsecond in length and occupied about 3.6 per cent of the time period assigned to each pulse. Modulation was applied to the succession of pulses used for each channel by varying the time position of the pulses within their assigned time periods. Definite limits on the peak time deviations were established so that pulses representing any one voice channel could not approach too closely to time periods assigned to another channel. As a result interference between channels was kept to very low values.

Repeating was accomplished by completely demodulating down to audio frequencies in a receiver and using the output of the receiver to modulate a transmitter, in which case all audio channels were available for tapping at each repeater, or by deriving the pulses from the receiver and using them to pulse the transmitter.

In pulse communication of the kind used in the AN/TRC-5 equipment the signal modulation is carried by variations in the timing of the pulses. Noise tends to cause some unwanted variation in the timing but the effect of the noise is inversely proportional to the steepness of the sides of the pulses and therefore to the frequency bandwidth occupied. The net result is that there is a suppression of the relative effects of noise with increasing bandwidth in a manner analogous to noise reduction obtainable by increasing degree of modulation in phase and frequency modulation systems.

An interesting characteristic of pulse systems is that, as the occupied frequency band is increased by shortening the pulses, keeping the average power constant, the ratio of peak signal pulse power to peak noise power remains constant. As a result the required average power, to keep above the threshold level so that the noise reduction effect will be obtained, does not increase as the frequency bandwidth is increased.

This is in marked contrast to phase and frequency modulation phenomena which requires that the average signal power be increased in proportion to the frequency bandwidth, to keep above the improvement threshold level.

Because of this difference in the effect of frequency bandwidth upon the threshold level there are circumstances where the average power required in a pulse system may be much less than that required in a phase or frequency modulated continuous wave system. Generally the smaller the amount of communications to be handled over a system, in proportion to radio frequency bandwidth available, the greater will be the probability that short pulse communication will be advantageous. It is less likely to be advantageous in systems where the volume of traffic is heavy and the demand for frequency space is great.

3. *Radio Relay System Types CW-1a and CW-2a*

Before the end of the war development of tubes for continuous wave operation had made enough progress so that it was possible to devise still another type of radio relaying equipment. This type of equipment was demonstrated by using it to carry a large volume of traffic, in parallel with Western Union cable circuits between Philadelphia and New York. Results were so promising as to cause Western Union to announce plans for establishing a nationwide radio relay network in the next few years.[2] The equipment has been given the designations CW-1a and CW-2a. Details of the system are described by L. E. Thompson. (Note (a).)

In this equipment a large number of communications channels were arranged in one broad band of modulation frequencies through the use of conventional heterodyning and frequency selective methods. The broad band of modulation frequencies was then used to frequency modulate a low radio-frequency subcarrier current which, in turn, was used to frequency modulate an extremely high radio frequency carrier current. The resulting double modulated very high-frequency current was then transmitted through space to the distant repeater.

At repeaters, demodulation was carried out only so far as to recover the modulated low radio-frequency subcarrier current which, after amplifying and limiting, was used to modulate a second extremely high-frequency radio carrier current for retransmission.

Radio Propagation Phenomena[11-18]

Long distance radio-relay communication over land is expected to

[11] B. Trevor and P. S. Carter, "Notes on Propagation of Waves Below Ten Meters In Length", *Proc. I.R.E.*, Vol. 21, No. 3, pp. 387-426, March, 1933. (See following page for remaining references.)

be done in a band of frequencies ranging upward from about 1000 megacycles. This is a range of frequencies too high for radio waves to be returned to earth by the ionized layers of the upper atmosphere. Therefore the propagation characteristics are determined by conditions found in the lower regions of the earth's atmosphere, and by reflections, refractions, and absorption caused by the presence of the curved and irregular surface of the earth, with its covering of vegetation.

Generally the radio waves will be transmitted from highly directional antennas, in narrow beams nearly tangent to the surface of the earth. Experience has shown that the beams do not follow straight lines but generally are bent into paths which are curved toward the curvature of the surface of the earth. This bending of the waves is caused by the fact that air and, what is more important, the water vapor in the air, increase the refractive index and slow the velocity of the waves more at lower levels than at the higher levels where the pressure and temperature are less.

In taking into account the bending of the rays due to water vapor and air it is customary to assume that the earth's radius is from a quarter to a third larger than the actual radius. It then is assumed that the waves reaching the receiving antenna are the vector sum of waves arriving over a direct path through the air and an indirect path provided by reflection from the ground.

The waves reflected from the ground, in the band of frequencies which will be used for relaying, are, in general, considerably reduced in strength compared with those received over the direct path, largely due to absorption and scattering by trees and other obstacles. The efficiency of reflection steadily diminishes as the frequency is increased and generally the received reflected wave will be small at frequencies above 1000 megacycles.

Unfortunately the radio characteristics of the lower atmosphere

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[12] H. O. Peterson, "Ultra-High-Frequency Propagation Formulas", RCA REVIEW, Vol. IV, No. 2, pp. 162-167, October, 1939.

[13] C. R. Englund, A. B. Crawford, and W. W. Mumford, "Ultra-Short-Wave Transmission Phenomena", *Bell. Sys. Tech. Jour.*, Vol. XIV, No. 3, pp. 369-387, July, 1935.

[14] Charles R. Burrows, "Radio Propagation Over Spherical Earth", *Bell. Sys. Tech. Jour.*, Vol. XIV, No. 3, pp. 477-488, July, 1935.

[15] Sloan D. Robertson and Archie P. King, "The Effect of Rain Upon the Propagation of Waves in the 1- and 3-Centimeter Regions", *Proc. I.R.E.*, Vol. 34, No. 4, pp. 178P-180P, April, 1946.

[16] G. E. Mueller, "Propagation of 6-Millimeter Waves", *Proc. I.R.E.*, Vol. 34, No. 4, pp. 181P-183P, April, 1946.

[17] D. A. Quarles, "Radar Systems Considerations", *Elec. Eng.*, Vol. 65, No. 4, pp. 209-215, April, 1946.

[18] Martin Katzin, U. S. Patent No. 2,303,644, 12/1/42. (Height diversity system to reduce effects of fading).

are not constant but vary with temperature and absolute humidity and with changes in their distribution. Therefore the bending of the waves is subject to variations, particularly under hot and humid conditions where the air can hold relatively large amounts of water. Variations in the bending of the waves causes variations in received signal strengths.

This type of fading may be dealt with in practice by: employing antenna heights substantially greater than that required to give barely a clear line of sight between antennas, taking into account refraction; by designing the system with an adequate safety factor in respect to signal-to-noise ratio; and by providing connections between cities over geographically separated routes.

Under some circumstances of irregular bending of the waves two,

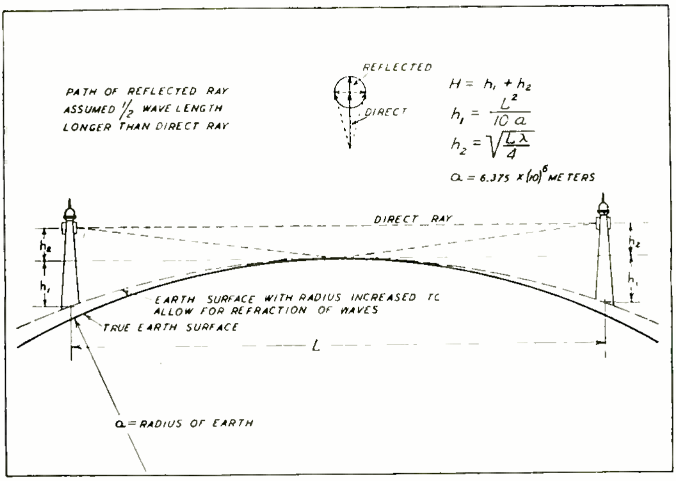

Fig. 3—The radio relay space circuit.

or perhaps more, direct rays of radiation from the transmitter may be so bent as to arrive simultaneously at the receiver with more or less equal signal strength. This can cause deep fading of the received waves, the seriousness of which increases with increasing frequency because of the decreasing differences in path lengths required to make the waves arrive with opposing polarities.

The space circuit which applies to these discussions is shown in Figure 3.

Fortunately this type of fading causes minima in the resultant waves which are fairly well localized in space. It, therefore, is possible to deal with it by employing two or more receiving antennas located at different heights provided the received currents are separately demodulated before being combined into a single current for retransmission. The modulation frequency currents generally are low enough in frequency that the time differences of arrival of waves received on the two antennas can cause only negligible phase differences between the combined modulation frequency currents. In contrast, if we should try to combine 6000 megacycle waves, where the wavelength is only about two inches, path length difference changes of only one inch would cause relative phase reversal of waves received on the two antennas.

The CW-1a and CW-2a radio relay equipment is especially well suited to the use of diversity reception and therefore can operate reliably at power levels much lower than would be possible if the diversity principle were not used.

In addition to the refraction and multipath phenomena which have been mentioned the radio waves also are subject to attenuation and scattering, particularly when they must pass through rain storms. The attenuation due to rain begins to increase so rapidly at frequencies above 6000 to 8000 megacycles as to constitute a serious hazard to service unless excessive safety factors are provided. Based on present inadequate knowledge it appears that important long distance radio relay systems should be placed in frequency channels below 8000 megacycles. Less important systems, and systems of less overall length, with shorter distances between relay points, particularly those where occasional service interruptions can be tolerated might operate in frequency bands above 8000 megacycles.

Carrier to Noise Ratio Requirements

As was pointed out in the previous paper,[1] it is expected that noise produced in the repeater equipment, rather than noise from outside sources, will set the lower limit of carrier power level. At present it seems reasonable to assume that the noise power produced in each repeater will be about ten times, or 10 decibels, greater than the minimum theoretical noise level due to thermal agitation in the repeater input circuits, at 20 degrees Centigrade, when the receiver is matched in impedance to the antenna system. Based on the usual practice of rating receivers as if they had infinite input impedance this corresponds to an assumed noise equivalent of 20 to 1 in power, or 13 decibels.

In a radio relay system the noise introduced at each repeater continues on with the signal through the remainder of the system so that the final resultant noise power level is proportional to the number of repeaters, if all repeaters are alike. Therefore, when the overall signal-to-noise power ratio in a system is determined this ratio must be multiplied by the number of radio space circuits to determine the ratio of signal to the noise introduced at each repeater.

In designing a radio relay system for any specific purpose it is necessary to provide for carrier power levels in the system sufficiently above the noise power levels to provide an adequate quality of service. The required overall carrier-to-noise power ratio varies over quite a large range depending upon the kind of service, the method and degree of modulation employed, the required degree of reliability, and other factors. In many cases there is a range of opinion and judgment as to what quality of service can be called satisfactory. What follows should therefore be taken as present opinion only, and may be subject to correction as more experience is obtained.

1. *Frequency Modulated Facsimile and Television*

As was indicated in the previous paper[1], an overall minimum carrier-to-noise ratio of 50 decibels is recommended for page-per-frame facsimile and the present standard black-and-white television. This applies to a system utilizing simple phase and frequency modulation of the radio carrier current by video modulating frequencies.

Until recently this was a rather high standard in comparison with the signal-to-noise ratio at which television observers became conscious of the noise. However, it may be pointed out that the recent addition of aluminum-backed screens over the inside of the layer of luminescent material in television receivers has extended the brightness range so that, in the future, the effects of noise, as well as of fine detail of images, will be much more noticeable.[19]

2. *General Purpose Phase Modulation Relaying*[20-25]

In applying many relatively narrow band communications channels to a wide-band radio relay system, by subdividing the modulation

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[19] D. W. Epstein and L. Pensak, "Improved Cathode Ray Tubes with Metal-Backed Luminescent Screens", RCA REVIEW, Vol. VII, No. 1, pp. 5-10, March, 1946.

[20] Murray G. Crosby, "Communication by Phase Modulation", *Proc. I.R.E.*, Vol. 27, No. 2, pp. 126-136, February, 1939.

[21] Murray G. Crosby, "Frequency Modulation Noise Characteristics", *Proc. I.R.E.*, Vol. 25, No. 4, pp. 472-514, April, 1937.

[22] Murray G. Crosby, "Frequency Modulation Propagation Characteristics", *Proc. I.R.E.*, Vol. 24, No. 6, pp. 898-913, June, 1936.

[23] Edwin H. Armstrong, "A Method of Reducing Disturbances in Radio Signaling By A System of Frequency Modulation," *Proc. I.R.E.*, Vol. 24, No. 5, pp. 689-740, May, 1936.

[24] B. D. Holbrook and J. T. Dixon, "Load Rating Theory for Multi-Channel Amplifiers", *Bell. Sys. Tech. Jour.*, Vol. XVIII, No. 4, pp. 624-644, October, 1939.

[25] Margaret Slack, "The Probability Distributions of Sinusoidal Oscillations Combined in Random Phase", *Jour. Inst. Elec. Eng. (London)*, Vol. 93, Part III, No. 22, pp. 76-83, March, 1946.

frequency band, phase modulation is preferable to frequency modulation because it provides for a uniform distribution of noise among the channels.

In relaying telegraph, telephone, and similar types of signals by means of phase modulation it is possible, provided a certain threshold level of signal-to-noise ratio is obtained before demodulation, to make a reduction in the effects of noise in the demodulating process. This reduction in the effects of noise is obtained by first employing more than the minimum radio frequency bandwidth before demodulation and then increasing the degree of phase modulation of the carrier current in response to the modulation currents.

In order that the maximum benefit from noise reduction due to any increased degree of modulation may be obtained it is necessary that the peak value of the carrier current be at all times substantially greater than the peak value of the noise current in the increased band of frequencies allowed to reach the demodulator.

If the noise is thermal agitation and shot effect, or any other noise coming simultaneously from small sources of many frequencies, the ratio of peak to root-mean-square values of the noise will be about 16 to 1 in power, or 12 decibels. Since the ratio of peak to root-mean-square value of the carrier is 3 decibels the root-mean-square carrier-to-noise power ratio in the effective pass band ahead of the demodulator of the final receiver should be somewhat greater than 9 decibels even when a large reduction in the effects of noise is obtainable by increased degree of modulation. As a practical matter, for the type of noise expected in radio relay systems, and for probable ratios of radio frequency to modulation frequency pass bands, we may set a figure of 12 decibels carrier-to-noise power ratio required to obtain substantially full benefit from the noise reduction effects of increased degree of phase modulation. This 12 decibel ratio corresponds to the assumed improvement threshold, as it has been defined in frequency modulation systems.

If we combine only a small number of constant amplitude modulating currents, of different frequencies corresponding to the several channels, as might be done when frequency shift keying, or frequency modulation of a subcarrier current, is to be used in each channel, it is necessary to assume that the currents will at times add up to a peak combined current nearly equal to the sum of the peaks of all the currents. In this case the range of modulation current must be divided among the channels so that the effective power per channel is nearly inversely proportional to the square of the number of channels. At the same time the modulation frequency band is divided up between the channels so that the noise power is divided similarly. If each channel passes all the noise power in its share of the modulation frequency band, then the noise power per channel is equal to the total modulation frequency noise power divided by the number of channels. In this case of a few channels the final signal-to-noise power ratio, in a system designed for a peak overall phase modulation of plus and minus one radian, is equal to the effective or apparent radio carrier-to-noise power ratio divided by the number of channels.

By effective or apparent radio carrier-to-noise power ratio is meant the ratio of radio-frequency carrier current power to the amount of radio-frequency noise power contained within a frequency band twice as wide as the modulation frequency band. All noise outside this band, and further from the carrier frequency than the highest modulation frequency, even if present in the input to the demodulator, can not contribute to noise in the output of the demodulator on frequencies within the modulation band. All it can do is to modify the improvement threshold level.

If the number of constant amplitude current channels is made large, keeping the total modulation bandwidth constant by decreasing the width of each channel, it is no longer necessary to assume that the channel currents will add up to a peak value equal to the sum of their peak values. Instead, as the number of channels is increased the currents may be added on a root-mean-square or power basis so that the signal-to-noise power ratio in each channel remains substantially constant as the number of channels is further increased. In this case the ratio of peak to root-mean-square value of the combined modulating currents assumes a constant value of 4 to 1 in amplitude, 16 to 1 in power, or 12 decibels. The final result for a large number of channels operated at constant amplitude, then, is that the signal-to-noise power ratio in each channel will be 9 decibels lower than would be the signal-to-noise ratio if the whole modulation frequency band and amplitude range were occupied by only one constant amplitude modulating current having a 3-decibel peak-to-root-mean-square power ratio.

It is not possible to obtain full utilization of the modulation frequency band for the multiplexed channeling currents because of limitations of frequency selective filters and the possibility of interchannel interference. It may be reasonable to assume that, for the next several years, it would be practical to make effective use of half of the modulation frequency band in equipment of reasonable cost. In such a case reducing a large number of channel currents to half will allow each one that remains to be increased by two to one in power or 3 decibels, increasing the signal-to-noise power ratio to 6 decibels less than it would be if only one channel were used.

For frequency shift keyed printer telegraphy, using a constant amplitude subcarrier current in each channel, which is to be amplitude limited before demodulation, it is desirable to keep the peak value of effective or apparent noise current in the channel at least 3 decibels below the peak value of the subcarrier current. This requires an average root-mean-square subcarrier to noise power ratio of 12 decibels. Assuming that half the maximum number of channels is used, because of the limitations of frequency selective filters, the required radio carrier to apparent or effective noise power ratio then becomes $12 + 6 = 18$ decibels. In any case the radio carrier to noise ratio should not go below the improvement threshold level of 12 decibels.

For printer telegraphy carried by subcarrier currents which are keyed on and off, in which case thresholding and limiting may be used at the receiving terminal to reduce the final effects of noise, it is desirable to keep the peak value of the noise in each channel at least 3 decibels below half the peak value of the subcarrier current. This would require a 6 decibel better subcarrier to noise ratio. In this case, however, the fact that only half the channel currents are active at any one time will permit obtaining a 3 decibel gain in demodulating the radio carrier current to obtain the subcarrier currents so that the required radio carrier-to-noise ratio is $18 + 3 = 21$ decibels.

In the case of telephony, applied by transmitting in each channel only a single sideband of current equal to the modulation band, experience would indicate that a maximum of only about a quarter of the channels will be active at any one time. This permits an increase in the modulation in each channel as compared with the condition of constant amplitude subcarriers of about 6 decibels. There is a still further gain due to the crest factor of the modulating currents in each channel during the times when they are active. Because of the crest factor the average power in each active channel is low compared to the peak value but, when many channel currents are combined the resultant combination has a crest factor which approaches a limiting value of 12 decibels more or less regardless of the crest factor in each channel. For present purposes this gain due to crest factor, which varies according to the kind of communication which may be handled over the voice channels, will be assumed to have a normal value of 9 decibels. The net result is that, for equal peak modulation due to a large number of channels, the peak single side band modulation in each channel may be $6 + 6 = 12$ decibels greater than the peak modulation in each continuous current channel. As a consequence, the maximum root-mean-square signal-to-noise ratio in each channel becomes equal to the radio carrier-to-noise ratio, when half the theoretical maximum number of channels is used.

Assuming that 40 decibels maximum root-mean-square signal-to-noise ratio in each channel will provide for acceptable speech, then the root-mean-square radio carrier-to-noise ratio should not be less than 40 decibels. For broadcast material and music higher carrier-to-noise ratios would be required.

For the conditions outlined the suggested *minimum* radio carrier to effective noise power ratios in radio relay systems for various kinds of service are the following:

	Carrier/Noise Power Ratios
Printer telegraph (frequency shift)	18 decibels
Printer telegraph (on-off)	21 " "
Ordinary telephone service	40 " "
Ordinary broadcast material	50 " "
High grade musical programs	60 " "
Facsimile and television	50 " "

Allowances for fading and equipment deterioration must be added to these values.

Bandwidth Occupied by Phase Modulated Relay System

To a fair degree of approximation the frequency band occupied by a phase modulated carrier current having a peak deviation of plus and minus d radians may be taken as twice the modulation frequency band plus twice the peak equivalent frequency deviation. This assumes that the phase deviation in any one channel is less than one radian. To determine what the band is for the multiplex phase modulated relay system the equivalent frequency deviations of all the channels are added together, multiplied by two, and twice the modulation frequency band is added.

Let B be the modulation bandwidth and the highest possible modulation frequency, assuming the band starts at zero frequency. If the modulation current range is divided among n channel currents, assuming n is large, the peak phase deviation produced by all the channels will be four times greater than that produced by the root-mean-square sum of the channel currents. The root-mean-square degree of phase modulation per channel can then be $\dfrac{d}{4\sqrt{n}}$ radians.

The modulation frequency band B is assumed to be divided into n equal parts, each B/n in width, and a signal current of constant amplitude is assumed to be placed in the center of each band. The frequencies of the various currents are then:

$$\frac{B}{2n}, \frac{3B}{2n}, \frac{5B}{2n}, \frac{7B}{2n}, ---, \frac{(2n-1)\,B}{2n}$$

The root-mean-square frequency deviations in each channel corresponding to $\frac{d}{4\sqrt{n}}$ radians root-mean-square deviation of the radio carrier current by each channel current is equal to the root-mean-square phase deviation multiplied by the modulation frequency. The root-mean-square frequency deviations of the several channels are then:

$$\frac{Bd}{8n^{3/2}}, \frac{3Bd}{8n^{3/2}}, \frac{5Bd}{8n^{3/2}}, \frac{7Bd}{8n^{3/2}}, ---, \frac{(2n-1)\,Bd}{8n^{3/2}}$$

If now these frequency deviations are added on a root-mean-square basis the sum is:

$$S = \frac{Bd}{8n^{3/2}} \sqrt{(1)^2 + (3)^2 + (5)^2 + (7)^2 + --- + (2n-1)^2}$$

$$= \frac{Bd}{8n^{3/2}} \sqrt{\frac{4n^3}{3} - \frac{n}{3}}$$

Since $\frac{n}{3}$ is negligible compared with $\frac{4n^3}{3}$, when n is large, this reduces to the approximate formula:

$$S = \frac{Bd}{8n^{3/2}} \times \frac{2n^{3/2}}{\sqrt{3}} = \frac{Bd}{4\sqrt{3}}$$

This is the root-mean-square frequency deviation.

$$S\,(peak) = 4S = \frac{Bd}{\sqrt{3}}$$

From this it appears that the frequency band occupied by the phase modulated transmitter, with a peak phase deviation of d radians, produced by the combined effects of a large number of channel currents will be approximately:

$$\text{Radio Frequency Band} = 2B + \frac{2Bd}{\sqrt{3}}$$

Present Status of Radio Relay Development

At the present time there are a variety of types of radio relay equipment to choose from and many other variations are possible. The choice of a type will depend for some time very largely on availability of commercially developed equipment, the kind and volume of traffic to be handled, and the geographic location.

In general, it might be anticipated that short pulse types of equipment would have advantages for application where a relatively small volume of telegraph or telephone service is required and in locations where efficiency of utilization of radio channel space is unimportant. The high peak power of pulses may prove to be an advantage in some applications, such as rural telephone service, because the high peak power is a help in accomplishing ringing through a crystal rectifier and sensitive relay without the necessity of consuming power continuously at the called station.

Subcarrier continuous wave methods, as utilized in the system demonstrated in 1944-1945, have an advantage in that distortions and interference between channels are relatively easy to keep small and the repeaters are relatively simple. The subcarrier method increases the occupied frequency band but this is compensated by the ease with which diversity reception can be employed to reduce the effects of fading and thereby to hold down the required power levels.

Time division methods of channeling, of which that used in the AN/TRC-5 type of equipment is but one example, have advantages in respect to bulk, weight, and cost of channeling terminal equipment but have the disadvantage of being at variance with frequency selective channeling equipment which is standard in carrier current wire line systems with which the relay equipment often will be associated.

Ultimately, it is probable that all the channeling problems in record communications service will be solved or bypassed by the introduction of page-per-frame facsimile message handling, over radio relay systems designed to transmit television, and by the use of destination markings on the messages to accomplish automatic sorting and routing without the need for human handling from origin to destination. In television it is normal practice to transmit 108,000 complete images, or pages per hour.

Fortunately the present state of flux of equipment development need not be the cause of serious risk to investment in radio relay systems. Towers, auxiliary facilities, antenna systems, etc., represent a large portion of the total cost of the systems and the repeater equipment may be changed as frequently as necessary, or it may be paralleled with new types of repeaters, without incurring a major loss in investment.

As the action of the Western Union Telegraph Co. indicates, radio relays are already at a point in their development where they not only can compete on equal terms with wire lines and cables but they can replace the wire lines and cables over circuits where they have been firmly established for many years. It is quite possible that radio relays are the best answer to competition for the overland record communication business.

Even the air mail, with messages carried in jet planes traveling at speeds above the speed of sound will not be able to compete with messages transmitted over radio relay systems with the speed of light, at a rate of over 100,000 pages per hour per circuit, with messages automatically controlling their own routing as they pass through the system.

AN INFRARED IMAGE TUBE AND ITS MILITARY APPLICATIONS*†

By

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Summary—*The military value of the security obtained by the use of infrared for nocturnal vision was recognized even before the entry of the United States into World War II. A program for the development of infrared viewing devices employing electron image tubes was consequently set up by the National Defense Research Committee. Before the close of the war a number of types of infrared telescopes had been manufactured in quantity and had seen service in fairly large numbers.*

The 1P25 image tube is the essential element in the infrared electron telescope, and serves to convert the invisible infrared image into a visible image. The tube contains a semi-transparent photocathode which is processed to be sensitive to infrared radiation, and an electron lens for imaging the electrons from the photocathode onto a fluorescent screen which becomes luminous upon bombardment by electrons. When an infrared image is focused on the photocathode, a visible reproduction of this image is formed on the fluorescent screen.

Basically, the infrared telescope consists of the image tube, an objective for forming the infrared image on the photocathode and an ocular for viewing the reproduced image. Associated with the telescope is a battery operated vibrator power supply which furnishes the 4000 to 5000 volts and the several intermediate voltages required by the image tube.

A variety of types of telescopes was developed and produced for a number of different applications. These included a signalling telescope employing a large aperture reflective optical system as objective, the Sniperscope which is a carbine-mounted telescope and infrared source permitting aiming and shooting in complete darkness and the Snooperscope composed of the same infrared units mounted on a handle for short range reconnaissance work. Binocular telescopes, helmet-mounted driving and flying instruments, long-range reconnaissance units and other special night-seeing devices were also developed in the course of this project.

EVEN before the entry of the United States into World War II, it was recognized that many military operations would require the secrecy afforded by complete visual darkness. Therefore, the National Defense Research Committee, under Army and Navy directives, undertook the development of infrared viewing devices employing electron image tubes and an investigation of the applications

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* Decimal Classification: R138.31 × R800 (621.375).

† This paper is based in whole or in part on work done for the National Defense Research Committee under Contracts OEMsr-169 and OEMsr-440 with Radio Corporation of America.

of such devices. This work was carried out by these laboratories.

A variety of infrared telescopes was developed suitable for different tasks and a number of types saw considerable service during the war. Among the most widely used were the Navy infrared signalling equipment and the Sniperscope and Snooperscope procured by the Army. Figure 1 illustrates an infrared telescope, while Figure 2 shows the laboratory prototype of the Sniperscope.

Basically, all of these telescopes consist of an objective for forming an infrared image of the scene being viewed upon the photosensitive cathode of the image tube, the image tube itself, and an ocular for viewing the reproduced image. The general form of the electron tele-

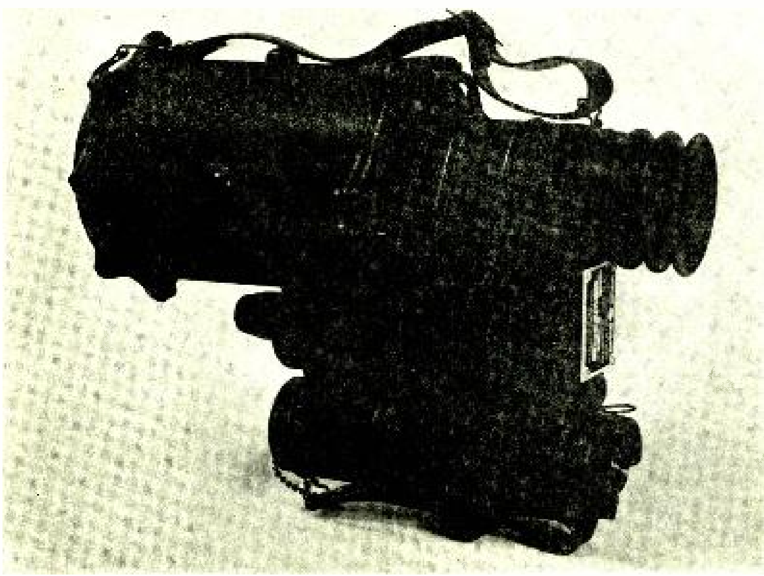


Fig. 1—Infrared telescope.

scopes using refractive and reflective optics is shown schematically in Figure 3.

The fundamental component of these infrared telescopes is the electron image tube. This tube consists of a semi-transparent photocathode processed so that it has high sensitivity in the infrared portions of the spectrum, a fluorescent screen and an electron optical arrangement for focusing the electrons onto the screen.

In undertaking the design of these instruments and tubes, the requirements of mass production as well as those relating to the particular application, were taken into consideration. As a result, the U. S.

Fig. 2—Laboratory prototype sniperscope.

Armed Forces were able to obtain these instruments in far larger quantities than could either the Germans or the Japanese whose instruments were not suitable for quantity production.

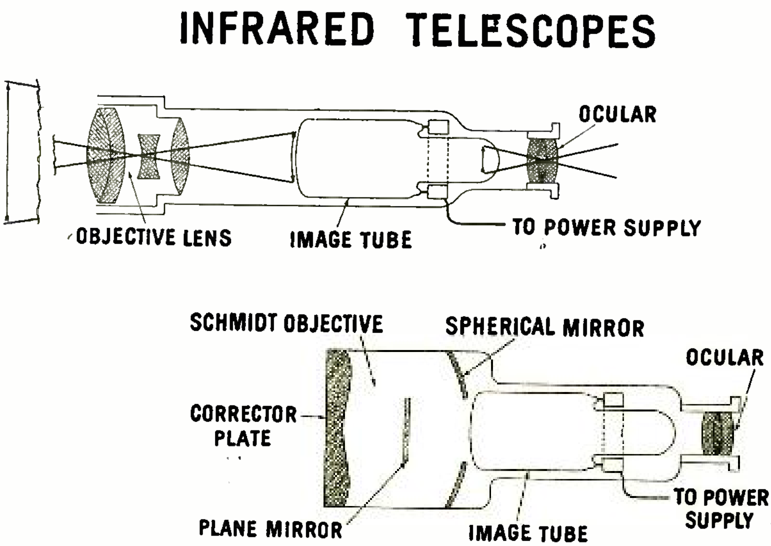


Fig. 3—Schematic diagram of two types of infrared telescopes.

THE IMAGE TUBE

An investigation of electron imaging dating back to the early 1930's had resulted in successful image tubes.[1,2] However, the requirements placed on an image tube for military applications were so very different from any heretofore encountered that it was necessary to re-examine the entire subject again.

The most important considerations were, of course, sensitivity of the tube and perfection of the image. These are properties of the activation, phosphor efficiency and electron optics, and will be discussed in greater detail. A second very important consideration was that the tube be of such a form that it could be produced quickly in fairly large numbers. Finally, it should be so designed that a single type of tube could be used for all of the various applications envisaged.

Tube dimensions selected as being the best compromise between the very small size which would be desirable for portable instruments, and the larger tube suitable for fixed units, were 4½ inches length and 1⅞ inches maximum diameter. This size was found convenient from the production standpoint, and useful in a wide variety of instruments. Consideration of power supply design, cable insulation and tube stability dictated an overall voltage range of 4000 to 6000 volts.

The first decision which had to be made concerned the most practical way of imaging the electrons from the cathode onto the fluorescent screen. There are essentially three systems which may be used, namely:

(1) uniform field between cathode and screen;
(2) magnetic lens; and
(3) electrostatic lens.

The first was rejected because of the close spacing between cathode and screen and high field strength necessary in the vicinity of the cathode. This makes the activation difficult and the tube prone to cold discharge. Also, the image produced in this way is erect where preferably it should be inverted. Magnetic focusing was also rejected from the standpoint of weight and complexity, and because of the difficulty of obtaining an inverted image.

An electrostatic lens system is capable of a sharp, clear image over a wide range of magnifications. The image is inverted making it unnecessary to use an inverting ocular for viewing the reproduced image. It is necessary to curve the photo cathode in order to produce an undistorted image over a large angular field. Where a reflective optical system is used as objective, the curvature of the cathode can be made

[1] V. K. Zworykin and G. A. Morton, "Applied Electron Optics", *Jour. Opt. Soc. Amer.*, Vol. 26, No. 4, pp. 181-189, April, 1936.

[2] G. A. Morton and E. G. Ramberg, "Electron Optics of an Image Tube", *Physics*, Vol. 7, No. 12, pp. 451-459, Dec., 1936.

to match that inherently present in the image surface of these optics. It is, however, sometimes necessary to use an optical field corrector lens when an ordinary refractive objective is employed, if the field of view is to be flat. However, since the electrostatic lens is also free from the objections mentioned in connection with the magnetic and uniform field systems, it was selected as the most satisfactory for the purpose.

The magnification of the image tube has an important bearing on its performance. This is because the brightness of the reproduced image varies inversely with the square of the magnification. Thus, if a telescope with a given overall magnification employing an image tube

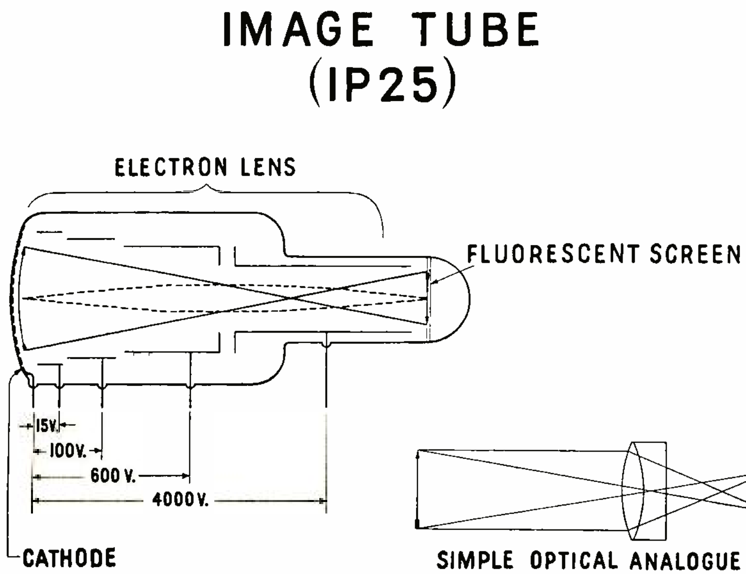


Fig. 4—Schematic diagram of 1P25 Image Tube.

with unity magnification and an X5 ocular is compared with one using an image tube with magnification ½ and an X10 ocular, the image in the latter will be four times brighter. However, for a given size of image tube and angular field of view, the magnification cannot be decreased indefinitely because as the power of the ocular increases the size of the exit pupil decreases until a point is reached where the pupil of the dark adapted eye is not filled. Beyond this point, the brightness of the retinal image does not increase with decreasing magnification of the image tube. For many applications, it is also essential that the exit pupil be much larger than the pupil of the eye, so that the observer's eye does not have to be located too exactly with respect to the instrument. Experiment showed that for a tube the size of the image tube under discussion, the magnification should not be less than one-half. Figure 4 illustrates schematically the construction and action of the image tube adopted.

Electron Optical Considerations

The electron optical system of the image tube consists essentially of a strong main lens as the principal imaging means and a series of relatively weaker correcting lenses between the cathode and main lens. The potential distribution along the axis of the tube is shown in the upper portion of Figure 5. Two electron paths, one of an electron

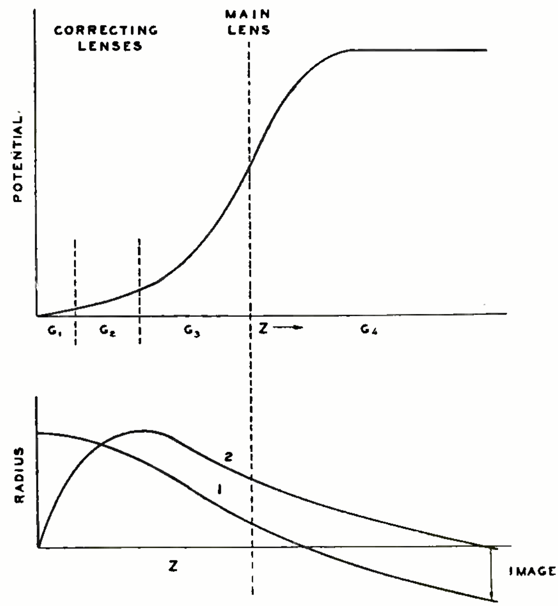


Fig. 5—Potential distribution and electron paths in the Image Tube.

originating from the cathode on the axis of symmetry with radial initial velocity, the other originating off the axis with no initial velocity, are illustrated in the lower part of the figure. These two paths are sufficient to determine the first order imaging properties of the system.

A detailed theoretical study of this type of system leads to the following conclusions:

(1) Curvature of the image field and pincushion distortion can only be eliminated by the use of a curved cathode (or a radial potential gradient on the cathode).

(2) Curvature of the image surface and astigmatism limit the off-axis definition.

(3) Chromatic aberration due to the spread of initial velocities of the photoelectrons establishes the limit of resolution at the center of the image.

(4) Spherical aberration and coma play a negligible role in limiting the definition.

The radius of curvature of 2.38 inches selected for the cathode was a compromise between that required for a flat electron image surface and optical considerations of the objective. With this curvature very little pincushion distortion remained, and a definition of 350 lines (television nomenclature) or better could be obtained near the margins of the picture.

At the center, the diameter (Δ) of the circle of confusion due to chromatic aberration is given approximately by:

$$\Delta \cong 2m\,V/E \tag{1}$$

where E is the gradient near the cathode and V the initial electron energies in electron volts. Evaluating this from the gradient known to exist in the tube and from the initial velocities expected near the infrared threshold, the limiting definition at the center is 2000 or more lines. Definitions of 1000 lines were realized in laboratory tubes, and of 450 lines or better in production tubes. In general, the difference in definition between the theoretical estimated definition and that achieved in practical tubes is due to misalignment of the electrodes, inhomogenities in the photo-cathode and granularity of the fluorescent screen.

Photo-Electric Cathode

The photo-sensitization of the cathode is one of the critical steps in the preparation of the image tube. Research to date has lead to the conclusion that a complex surface involving caesium, oxygen and silver yields the highest infrared response of any of the surfaces yet studied. This surface is formed by evaporating a thin layer of silver on the cathode disk, oxidizing it completely, then adding alternately silver, caesium and silver while subjecting it to an appropriate thermal treatment. The completed surface is semi-transparent so that, when illuminated from the outside, electrons are emitted from the inner surface. The photoemission from a well activated surface of this type will be 30 to 50 microamperes per lumen for whole light (visible + infrared) from a tungsten source at a color temperature of 2870 degrees Kelvin.

Figure 6 illustrates the spectral response of this type of emitter.

Fluorescent Screen

The requirements of the fluorescent screen are the following:

(1) It must have a high efficiency of conversion of electron energy into visible light of a color suitable for scotopic vision.

(2) It should have a fine grain structure capable of giving high definition.

(3) Its time constant must be short so that moving images do not blur.

(4) It should be inert to the chemical action of caesium.

Synthetic willemite was found to satisfy these requirements fairly well, although its phosphorescent decay time is somewhat longer than

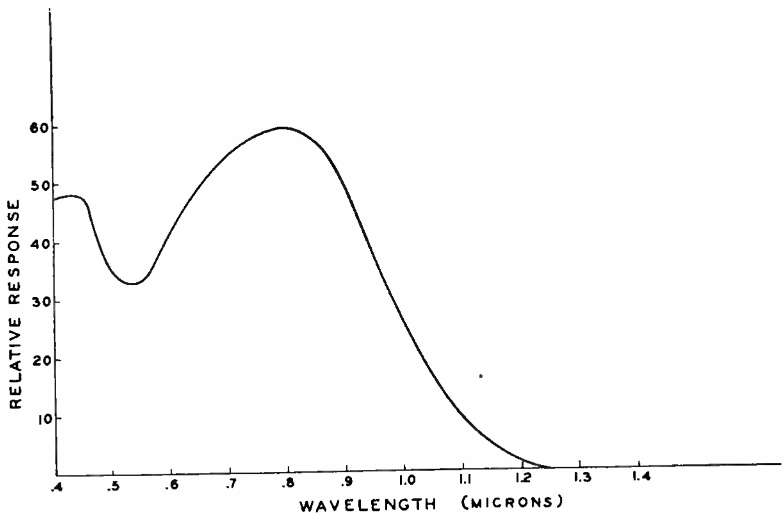


Fig. 6—Spectral response of 1P25 Image Tube.

might be desired. In spite of its shortcoming as far as persistence is concerned, it was selected as the phosphor most suitable for the 1P25 because of its availability and ease of handling together with its chemical stability.

The efficiency of this phosphor in the vicinity of 5000 volts is between 1 and 3 candles per watt. Its color is green or yellow-green which is quite satisfactory from the standpoint of scotopic vision. With a little care, the grain and aggregate size can be made small enough so that the screen does not limit the definition of the image. The decay characteristic of the material cannot be expressed by a single time constant. However, for the brightness involved in such applications of the tube as night driving, reconnaissance, and sniperscopes, the relation:

$$B = B_o \varepsilon^{-60t} \qquad (2)$$

where t is the time in seconds after excitation ceases and B_o is the brightness at $t = o$ is entirely adequate. The expression for phosphorescent decay indicates that the image brightness falls to 10 per cent of its initial value in 0.04 secs. While rapid enough for most purposes, it causes some loss in definition for rapidly moving objects. At very low brightness levels, the decay becomes less rapid than is indicated by this expression. This long low-level afterglow is of consequence in the detection of an infrared marker and signal light near the visual threshold.

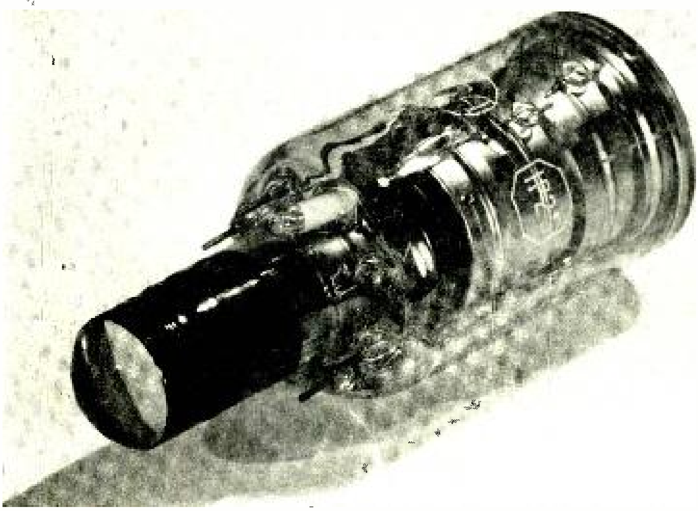


Fig. 7—1P25 Image Tube.

Image Tube Performance

The performance of the 1P25 image tube may be summarized as follows: The light output per lumen of light incident on the photocathode, or conversion, is in the neighborhood of 0.5 to 1 lumen. In conjunction with an infrared filter, the conversion is reduced by the corresponding filter factor. It has been customary to express this filter factor in terms of the ratio of the image-tube response for whole light from a given incandescent source at color temperature 2870 degrees Kelvin to the response from the same source when filtered.

The central definition of the image is 450 lines or more and the peripheral definition 300 lines. This definition is such that for most brightness levels encountered in practice, the eye rather than the instrument is the limiting element.

A photograph of the finished tube is shown in Figure 7.

During the later stages of the research program, a number of new types of tubes were developed to meet special problems. One of these was a single-voltage tube, contained in an envelope identical to that of the 1P25, but requiring no intermediate or focusing voltages. This tube is interesting in that it employed an electron optical system with an unconventional departure from circular symmetry. A second tube operated at an overall-voltage of 16 kilovolts employing a multiple lens anode.

INSTRUMENTS EMPLOYING THE 1P25

During the course of the investigation, many different types of infrared instruments were developed employing the image tube. The number is so large that only a small fraction of them can be described in this paper. Therefore, a few representative instruments have been selected which will be described and their performance indicated.

Signalling Telescopes

One of the widest and at the same time most exacting use of the electron telescope is for the observing of infrared signal and marker lights. Here, since the object observed is an unresolved luminous point, the considerations involved in determining the sensitivity of the instrument are quite different from the case of an extended image. The two primary optical factors are the area of the objective and the magnification, while for the image tube the conversion and background only are involved. It will be noticed that the f-number of the objective and magnification of the image tube do not affect the sensitivity. However, if a lens with a large f-number or an image tube with high magnification is used, the angular field of view will be small which is undesirable for a marine signalling or search instruments. For these reasons the signalling telescope was designed with an objective having a short focal length and large aperture. The only practical way of achieving such a system is by the use of reflective optics, as illustrated in the lower part of Figure 3. The corrector plate and spherical mirror were of transparent plastic, assembled as a unit in a plastic barrel. The system was arranged so that the image was folded back by means of a plane mirror onto the cathode of the image tube. The focal length of this objective was 2.4 inches and its effective f-number was about 0.9. The image on the fluorescent screen was viewed through an X11 ocular. A hemisphere, which was an integral part of the image tube bulb, was a component of the ocular system. The telescope and power supply were assembled in a light, weatherproof and hermetically sealed magnesium casting. A discussion of power supplies for this type of instrument will be postponed until a later section.

A much larger reflection-type telescope was also developed having a 7-inch focal length and approximately the same effective numerical aperture. This instrument was very much more sensitive as a signalling telescope but had a much smaller angle of view. Because this instrument was also designed for reconnaissance, its optical focus was made variable through an adjustment which moved the plane mirror in and out.

Reconnaissance Telescope

With the exception of the large reflective-type telescope mentioned in the preceding paragraph, the reconnaissance instruments were in general of the small portable variety. In order to give them greater depth of focus than could be obtained with a reflective optical system, these telescopes employed refractive optics with f-numbers down to about 2.0. With an f/2.0 lens and an image tube having a conversion of 1.0 the ratio of brightness of the image of an object illuminated with whole light as seen through the telescope to brightness as seen directly is about 0.10. This ratio is reduced by the appropriate filter factor when a filtered source is employed.

In their simplest form, these instruments consist of a barrel (usually of mu-metal or other high permeability alloy for a shield) containing the image tube, to which are affixed the objective and ocular, both in focusing mounts. Tests indicated that objective focal lengths in the range 2½ to 3½ inches and ocular magnification of X8 to X12 were most satisfactory. For example, when used as the basis of a driving telescope, as will be discussed below, an instrument with a 2½-inch objective and an X8 ocular giving an overall magnification of unity and a 24-degree field of view gave best results, while for devices such as the Sniperscope and Snooperscope a 3½-inch focal length objective and a X8 or X12 ocular were to be preferred.

Power for the image tube was supplied through a three wire, insulated cable providing ground, the overall voltage and the variable focusing voltage. A resistance voltage divider at the image tube socket provided the other voltage steps for the 1P25.

Other instruments were designed with the power supply an integral part of the telescope. One unit employs a 2½″ focal length f/2.0 plastic objective and an X12 ocular. A model is illustrated in Figure 8. Its size and weight is only about one third that of the telescope shown in Figure 1.

For general purpose observation, these simple in-line monocular telescopes served as very useful tools. For example, this type of instrument was frequently carried by an observer during night driving. Also, it was used to supplement the large reflective-type telescopes as general orientation instruments, and for many other supporting operations. Under these circumstances, the illuminator providing the infrared radiation was a separate unit over which the user of the telescope had little or no direct control.

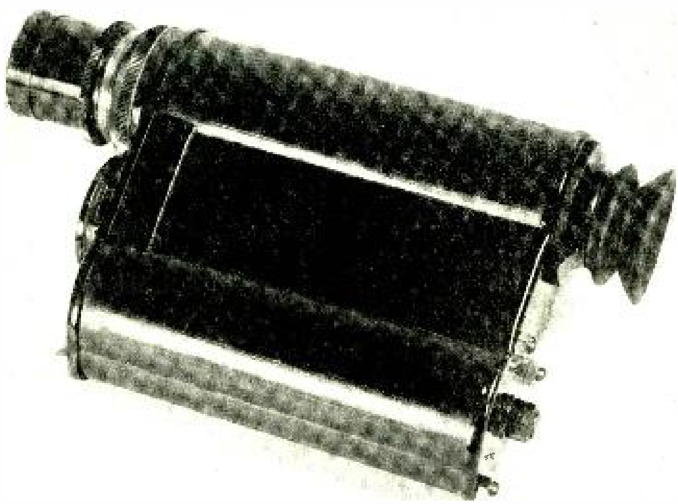


Fig. 8—Experimental telescope.

Frequently it is advantageous to have a portable light source to use in conjunction with the telescope. Therefore, a study was made of instruments involving source-telescope combinations. In particular, two instruments of this class were developed, namely, a monocular telescope and a light source mounted on a handle for relatively short range reconnaissance (see Figure 9) and a similar telescope and source mounted on a carbine in such a way that the telescope could be used for aiming in complete visual darkness. These instruments were christened Snooperscope and Sniperscope respectively and were later named Molly and Milly by members of the Armed Forces.

The telescopes used in the laboratory prototypes of these units were essentially the same as the monocular telescope described in earlier paragraphs. The objectives were 3½-inch focal length f/2.0 lenses while an X8 ocular was used for viewing the screen. A chevron was placed on the surface of the field-corrector lens to serve as the aiming index for the Sniperscope. This chevron was accurately aligned with the direction of fire of the piece. By placing the aiming index at the objective, distortion or deflection of the electron image had no effect on the accuracy of aiming.

Tests were made to determine whether the telescope, including the image tube, was sufficiently rugged to withstand the rough usage involved in this application. No particular difficulties were encountered

Fig. 9—Laboratory prototype Snooperscope.

in the case of the Snooperscope. In the Sniperscope, a certain percentage of tubes were found to fail as a result of the shock of firing, due to minute particles of the phosphor becoming dislodged from the fluorescent screen and settling on the lens electrodes and causing flashing in the tube because of cold discharge. This made it necessary to shock-test production tubes before employing them for this purpose.

The selection of the size and form of light source was a result of compromises in a number of directions. These included angular field, range, operating life for the allowable battery weight, and considerations of security. The source chosen for the laboratory models was a special General Electric sealed beam lamp with a 12 to 15 degree spread and a maximum beam candle power of 80,000. Various infrared filters were used including Corning 2540 heat transmitting glass and the Polaroid XRX series.

The high voltage power supply and storage batteries were carried in a knapsack with a cable from it to the instrument carrying both the image tube voltages and the current for the infrared source. The design of the power supply is discussed in a later section.

The weight of the telescope and source was about 5 pounds while the power supply and batteries weighed approximately 13 pounds. The unit was capable of 3 to 4 hours continuous operation before it was necessary to recharge the batteries. The Snooperscope and Sniperscope were manufactured on a fairly large scale, the production design being carried out by the Engineer Board of the Army for the Corps of Engineers.

Driving Instruments

In some applications, particularly vehicle driving, it is advantageous to have binocular vision. It is interesting to note that while the observer feels a very definite need of being able to use both eyes it makes very little difference whether or not he has stereovision.

The first experimental driving instruments were in the form of a single large barrel carrying the objective and eyepiece, and enclosing an image tube which was much larger than the 1P25. The eyepiece was so arranged that the virtual image of the fluorescent screen was at infinity and the observer saw this image with both eyes.

This type of driving telescope was found to be generally quite satisfactory, but suffered from two serious drawbacks. It was quite large and occupied considerable space in the vehicle and it was difficult to use on short turns.

To overcome these difficulties, a small binocular instrument was developed using two 1P25's. This instrument, illustrated in Figure 10 gave the observer true stereovision. The binocular consisted of a pair of in-line telescopes mounted parallel to one another by means of hinges so that the interpupillary distance could be adjusted to fit the user. In order to obtain satisfactory register of the images seen by the two eyes, it was necessary to provide means for moving the two images relative to one another. This was accomplished by mounting the ocular lenses in such a way that their axes were slightly displaced with respect to the axes about which the ocular fittings could be rotated. When the eyepiece fittings were turned the two virtual images seen by the observer moved in circles about two different centers. The points of intersection of these circles are the points of register of the images.

Separate focus of the two objectives and two oculars was provided. The power supply was designed so that the electrical focus of the two image tubes was also independent.

These binoculars, with a suitable head rest, served as excellent driving telescopes, when supported on a pivoted arm in front of the driver. As designed the instrument not only gave the operator use of both eyes but also permitted true stereovision.

Some experiments were undertaken in helmet mounting the in-line binoculars. However, even when counterbalanced to neutralize the forward torque of the instrument, the moment of inertia was rather high which made it awkward to handle.

To overcome this, an investigation was made on a series of helmet-

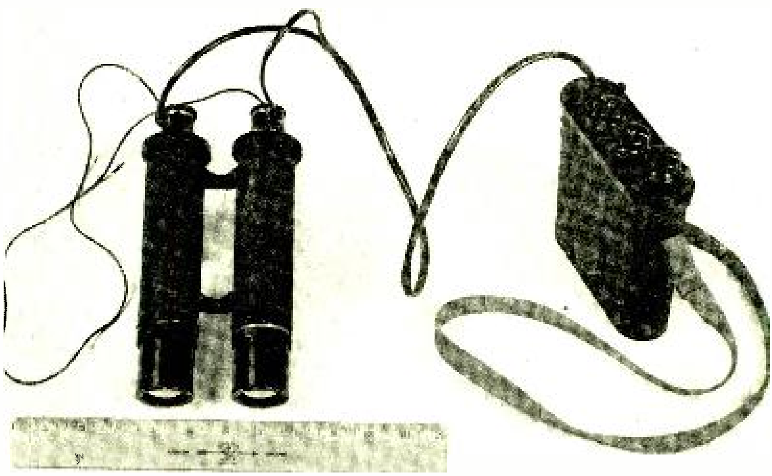


Fig. 10—Infrared In-line Binocular.

mounted instruments. Figure 11 illustrates an early right-angle periscopic unit. The results of these tests were so encouraging that the development of a light-weight, Z-shaped binocular suitable for night flying and driving, was undertaken in collaboration with the Johnson Foundation of the University of Pennsylvania. The completed instrument is illustrate in Figure 12. The unit was made of aluminum, and plastic optics were used throughout (except for the ocular lenses) to reduce the weight to a minimum. The folding was accomplished by means of plastic prisms. Again, independent optical and electrical focusing adjustments were provided for the two sides, the electrical focus being controlled by means of potentiometers mounted at the bases of the telescope barrels. Register of the image was effected by means of a pair of rotatable ring magnets mounted on each barrel just below an inner mu-metal shield which surrounded the image tube from cathode to main lens. The resultant field of these ring magnets, which could be varied in intensity and direction by rotating the rings, made it possible to deflect the electron images into exact alignment.

These helmet telescopes appeared to be a very adequate solution to the problem of infrared night driving, and were on the verge of going into production when the war ended.

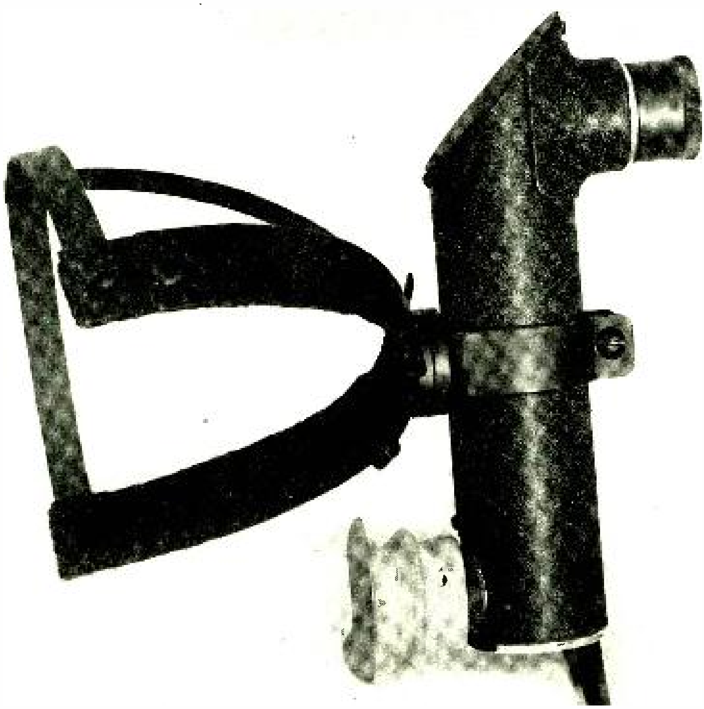


Fig. 11—Periscopic Helmet Monocular.

High Voltage Power Supplies

The 1P25 image tube requires a rather high voltage for its operation. Since portability was one of the aims of the development, it was essential that the power supplies be small and operate from a small primary battery source. At the same time, the battery life had to be above a certain minimum if the instrument was to be practical.

The design of a power supply meeting these requirements is possible only because of the fact that while a 4000 to 6000-volt output is required, the actual power needed is very small. The tube itself requires only a fraction of a microampere of current even under bright light conditions. The total power output required to supply the tube and the voltage divider necessary for the various focusing electrode voltages of the 1P25 is on the order of a tenth of a watt.

The only practical available means of converting the low voltage

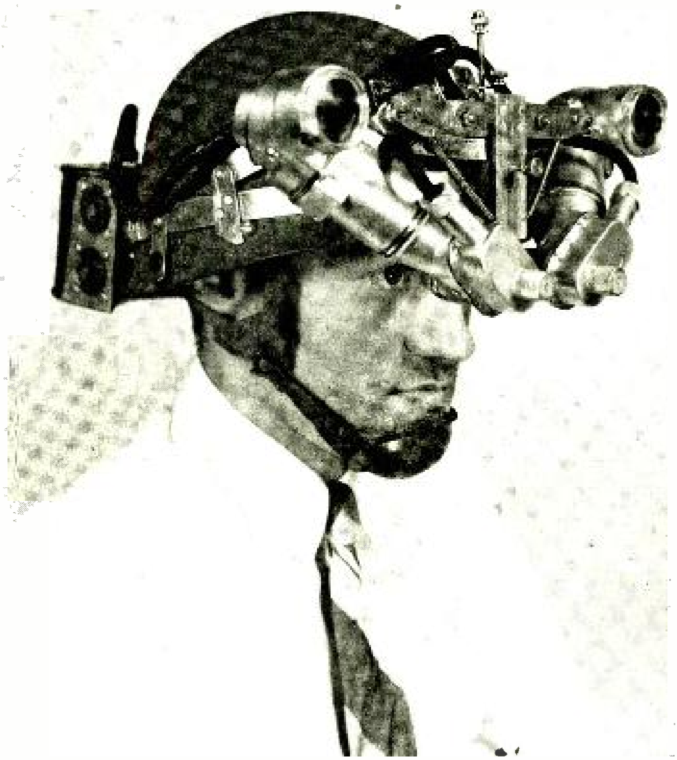


Fig. 12—Type Z Helmet Binocular.

from the batteries to the high potential necessary to actuate the image tube is a vibrator-transformer-rectifier combination. A typical vibrator power supply is shown in Figure 13. It differs from the conventional vibrator power units used in battery operated radios, in that, due to the low power requirement, use can be made of the relatively high voltage peaks appearing across the primary of the transformer when the magnetic field collapses as the primary circuit is broken by the vibrator. In addition the primary is tuned to resonate with the natural period of the secondary to obtain maximum transfer of energy. By this method an effective primary voltage of ten to twenty times the battery voltage is realized. This makes possible a great reduction in the size of the transformer required.

A standard automobile type vibrator was used because of ease of procurement. The frequency was of the order of one hundred interruptions per second and the power consumed was about 0.2 watt. A conventional rectifier circuit and capacity filter was used employing the special rectifier described later.

The design of the transformer was necessarily a compromise between light weight and efficiency. A light-weight transformer with

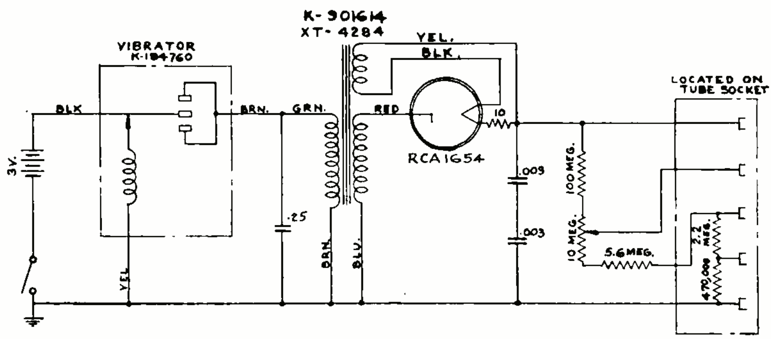


Fig. 13—Basic circuit of vibrator power supply.

somewhat lower efficiency means a larger battery or shorter battery life, while a heavier transformer will give a higher efficiency due to lower core losses. As a result, the optimum transformer is usually a design unique to the particular application. For an overall efficiency of 10 per cent, including vibrator power and rectifier filament, at an output of 4000 volts, the weight of the transformer is on the order of 20 ounces per watt of output. This means that in order to supply one-tenth watt at 4000 volts a two-ounce transformer would be required at an input of one watt. At somewhat higher power ouputs the efficiency may run as high as 20 per cent, since the power taken by the vibrator and rectifier will be constant.

A typical transformer design may be approximated by making the following assumptions:

Vibrator frequency—100 per second
Time of contact—.005 second
Battery voltage—3 volts
Maximum battery current (peak)—3 amperes
Peak output voltage—4000 volts.

Under the type of operation required, the secondary current is small and most of the power dissipated in losses. Therefore, as a first approximation the effect of the secondary circuit on the primary may be neglected except as it affects the resonant frequency.

If the time constant of the primary is made equal to the contact time, then

$$\frac{L}{R} = .005$$

Since the maximum current is to be 3 amperes and the voltage is 3 volts, the primary resistance is 1 ohm. Consequently,

$$L = .005 \text{ Henries.}$$

If the decay time of the primary current is now assumed to be one-tenth of the contact time as determined by the resonant frequency of the secondary to which frequency the primary is tuned, then

$$e = L \frac{\Delta i}{\Delta t}$$

$$= .005 \frac{3}{.0005} = 30 \text{ volts.} \qquad (3)$$

Since the peak output is to be 4000 volts, the turns ratio of the transformer becomes

$$\frac{4000}{30} = 133$$

To obtain the necessary primary inductance requires about 100 turns. Thus 13,300 turns will be required for the secondary.

The direct current from the 3-volt battery under these conditions is about 0.5 amperes with the secondary delivering about 50 microamperes. A core cross section of 0.25 square inch ordinary silicon steel with a 0.010 air gap was found sufficient.

Since no rectifier of small size and low filament power consumption was available, a special tube was developed. This tube, shown in Figure

14, is now in production as the 1654 and in the special circuit shown will deliver 100 microamperes at 5000 volts.

A typical example of this form of power supply is shown in Figure 15. This supply delivers 0.15 watts at 4000 volts with an input of one watt. The total weight including the battery, which will operate the instrument for 2½ hours, is 2½ pounds.

A high degree of stability of the overall voltage is not essential but the ratio of voltages on the various electrodes must be maintained to

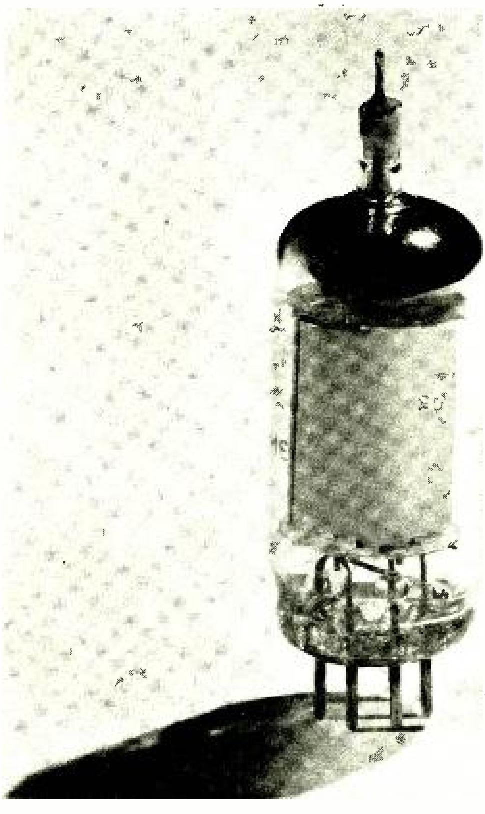


Fig. 14—1654 Rectifier Tube.

keep the image in good focus. The regulation of the power supply is not important since the load is essentially constant. As a matter of interest the equivalent resistance of the power supply shown in Figure 15 is approximately 40 megohms.

Since the overall voltage varies considerably as the batteries discharge and since the instruments may be subjected to wide ranges of temperature, behavior of the components of the voltage divider as regards temperature and voltage was a matter of considerable concern. It would be highly desirable to be able to maintain the proper voltage ratios over the range of temperatures and voltage encountered in the field. However, this is not always possible and occasional refocusing may be necessary although the variations can be greatly reduced by proper choice of components in order to balance their characteristics.

All of the available high value resistors (50 megohms or more) show considerable change of resistance with voltage. The voltage characteristics of a few of the best-known resistors are shown in Figure 16. Using dry cells as a source of power, a 2 to 1 change in overall voltage may be encountered from start to end point. Under these conditions, it is impossible to maintain focus without adjustment since a 50 per cent change in voltage represents a change of about 5 per cent in

Fig. 15—5-kilovolt vibrator power supply.

resistance of the best resistor. Therefore, unless compensation can be provided, it is necessary to refocus as the batteries deteriorate. In the case of storage batteries, about 10 per cent change in voltage may be expected over the operating life. This produces a negligible change in resistance of the No. 5 resistor and no refocusing is necessary.

Most resistors have a high temperature coefficient and in order to design a voltage divider which will maintain the tube focus independently of temperature, it is necessary to select components which either have the same coefficient, so that the ratio remains the same over the temperature range, or which have coefficients which tend to compensate for each other. Variation of resistance with temperature for a variety of resistors is shown in Figure 17.

In making up a divider, many combinations of resistors tending to compensate are possible. From the curves in Figure 17, two combinations were selected and the characteristics of the dividers plotted in Figure 18. In both cases, the G_3 voltage remained essentially constant over the entire temperature range, the small variations being in such a direction as to compensate for the variation in G_2. With divider No. 1 adjusted for focus at 20 degrees Centigrade, the voltage on G_2 remains in the region of good focus over the range from —10 degrees Centigrade to + 60 degrees Centigrade. Divider No. 2 remains in focus

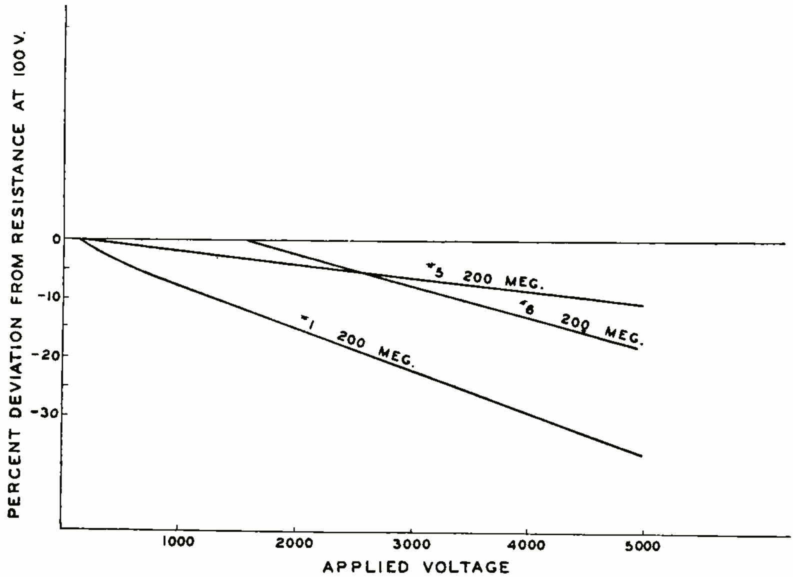


Fig. 16—Voltage characteristics of resistors.

from —40 degrees Centigrade to +75 degrees Centigrade. Therefore, using storage battery supply and selected components for the voltage divider, it is possible to build an instrument which will not require electrical focusing in the field under the range of conditions usually encountered.

The Type S_2 supply shown in Figure 19 is an interesting modification of the vibrator power supply. This arrangement is similar to the conventional voltage doubler circuit except that the two halves of the doubler are brought out separately. In this way, it is possible to place a voltage divider across one side without disturbing the other. In these vibrator supplies, the alternating-current wave is non-symmetri-

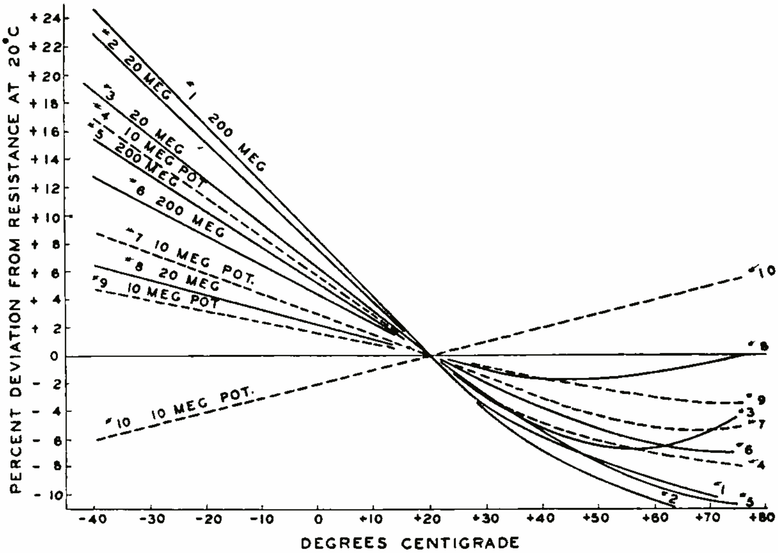


Fig. 17—Temperature characteristics of high-valued resistors.

cal, being in the nature of a damped oscillation, so that in the circuit shown, the voltage across the high voltage section, which is determined by the first loop of the wave, is about 4000 volts while the voltage in the opposite section, determined by the second or negative loop, is about 1000 volts. Therefore, by putting the voltage divider across

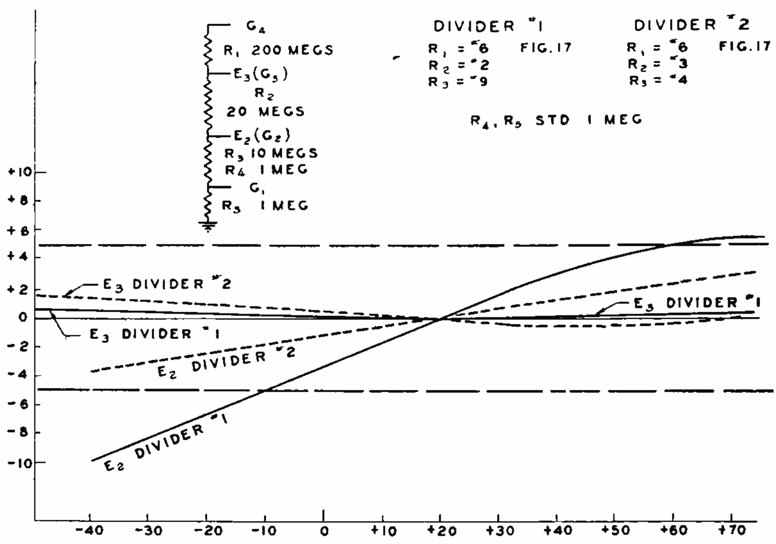


Fig. 18—Temperature characteristics of composite voltage divider.

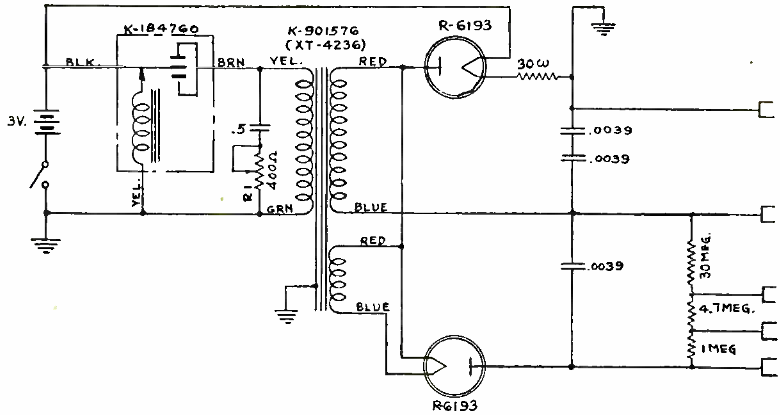


Fig. 19—Voltage doubler power supply (Type S-2).

only the low voltage section, the desired low voltages may be obtained without loading down the high voltage section. Another very interesting feature of this circuit is the fact that by introducing resistance in the tuned primary circuit, the damping of the circuit is increased which tends to decrease the second or negative loops and thus the low voltage without appreciably affecting the high voltage. This action is shown in the curves on Figure 20. This affords a means of varying the

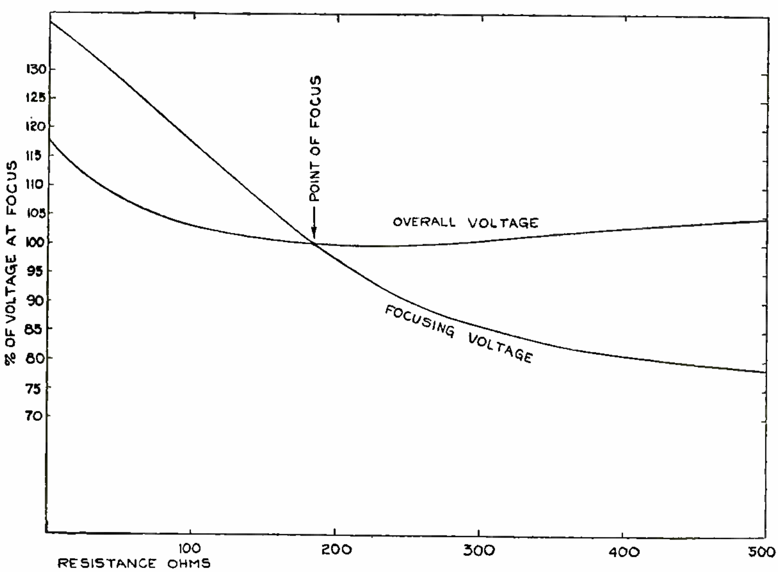


Fig. 20—Voltage control of type S-2 Power Supply.

focusing voltage by an element in the primary circuit which is a great advantage from the standpoint of electrical design.

Another power supply of interest was developed for use with the single voltage tube. With this tube the only load on the power supply is the actual photocurrent and leakage. By careful design, the entire load resistance can be made as high as 10^{10} ohms. Using a relatively large capacity in the output, the time constant of the circuit can be made to equal several seconds so that a quite infrequent charging of the circuit is required. For this purpose, an interrupter was designed consisting of an electrically-driven balance wheel having a period of

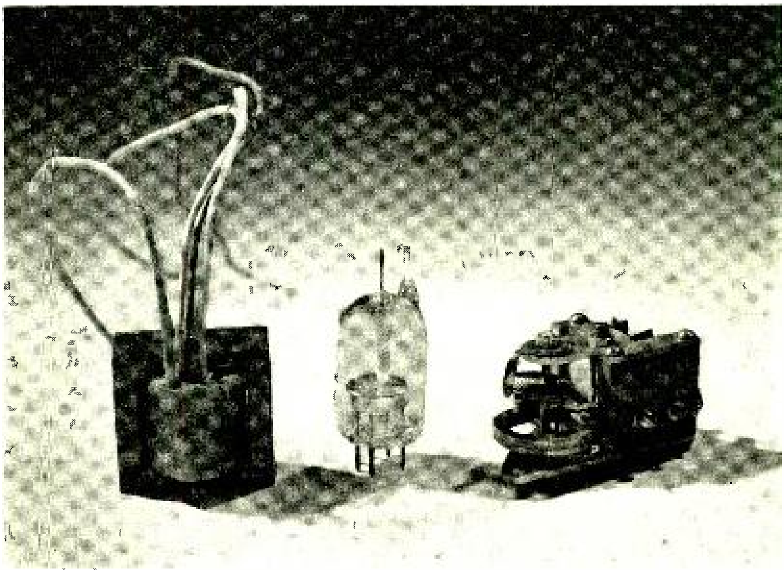


Fig. 21—Electrical components of pulsed power supply.

about ¼ second. The design was such that the transformer primary is open most of the time and is closed for a short time, to allow the current to build up, and immediately opened. In this way the drain on the battery is extremely small, the supply operating for as long as 50 hours on a single size D flashlight cell. A photograph of the interrupter, the 1-ounce transformer designed for the purpose and the special rectifier described below are shown in Figure 21.

Since the primary power required by this supply is so small, the power taken by the usual rectifier filament becomes very large in comparison. Consequently, a new type "filamentless" rectifier was developed, known experimentally as the KR-31.

This rectifier depends for its action upon a gas discharge in Helium, Neon, or other inert gas at about 0.5 millimeters pressure. The cathode is an aluminum cup, mounted so that its closed side faces the anode. The anode is a nickel rod or tube, over which is fitted a woven fibreglass sleeve. The entire anode is covered with the fibreglass; the sleeve fits down over the glass seal at one end and is closed by fusing the glass at the free end.

The peak inverse voltage of the KR31 is 6000 volts and the forward breakdown voltage is 300-600 volts. The peak current may be several milliamperes but the allowable average current is low. In the applications for which the tube was designed the average current is under 10 microamperes. An average current of 50 microamperes may not be exceeded except for very short periods due to sputtering and clean-up of the gas.

This tube has not been put into production and is not available commercially.

The power pack for the Snooperscope and Sniperscope involved some special considerations. A 6-volt, 25-ampere-hour storage battery was used to operate the infrared source so the power required to operate the high-voltage power supply was a negligible drain on the battery. It was necessary to silence the vibrator to a surprisingly high degree since the most obvious uses of the instruments were under conditions of extreme quiet and where the utmost in secrecy was essential. The usual rubber-mounted automobile radio-type mounting is effective for damping out the high frequencies, but the fundamental vibrator frequency (100 cycles) is not sufficiently suppressed. One method used in experimental models was to suspend the mounted vibrator by two flat spiral springs of at least one turn, coiled around the vibrator can, the inner ends being fastened to the vibrator can and the outer ends to the power supply chassis or box. By proper choice of spring thickness, a period of only a few cycles per second can be obtained with sufficient stiffness to support the vibrator adequately. By this means it was possible to silence the vibrator so that the user himself could not detect the vibration. Another method used, with some increase in bulk, was the addition of one or more stages of sponge-rubber cushioning around the usual vibrator can.

The type MA4, high-voltage image tube raised some special problems in power supply design. The overall voltage required is on the order of 15 to 20 kilovolts and in addition, a number of intermediate voltages are required. These intermediate voltages, particularly those over 4000 volts are difficult to obtain efficiently by conventional means because of the relatively large power which would be wasted in a voltage divider of sufficiently low resistance to be stable. Also, it is possible to obtain higher voltages from the previously described power supplies only by increasing the flux in the transformer. This in turn can be accomplished only by increasing the primary power, necessitating larger transformer and batteries. Lastly, if a conventional power supply is used, a rectifier tube capable of withstanding 20 to 30 kilovolts inverse voltage would be necessary. This type of rectifier is not available in small size and low filament power. Consequently, a cascade type (voltage-adding) power supply was designed which overcame most of the objections and automatically provided the necessary four steps of high voltage without a voltage divider.

A schematic diagram of the S-5 power supply making use of this circuit is shown in Figure 22. As can be seen, this supply is made up of four rectifiers which are essentially in parallel for alternating cur-

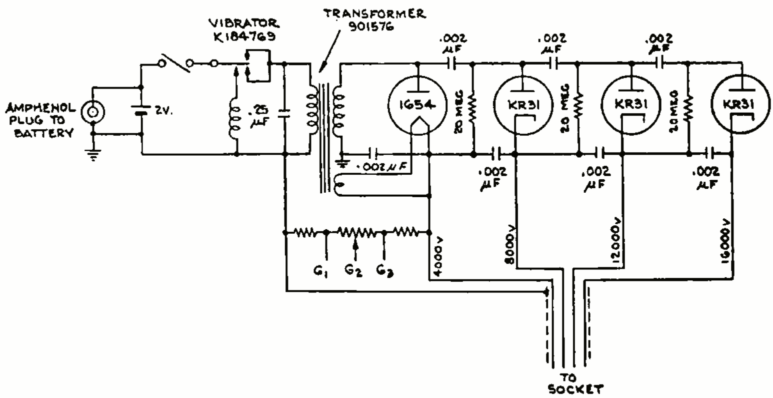


Fig. 22—Circuit of voltage quadrupler power supply (Type S-5).

rent. The direct-current voltages developed across the rectifiers, however, are added by means of the resistors which connect the anode of one rectifier to the plate of the next and thus place all the rectifiers in series for direct current. These resistors offer much higher impedance to the alternating current than do the capacitors so they do not affect the parallel alternating-current connection. Any number of stages may be cascaded in this manner, provided, of course, that the transformer will deliver the proper voltage to all the rectifiers in parallel. Four stages were chosen in this case because four steps of voltage are necessary for operation of the MA4 tube. The lower voltages required for the tube are obtained in the usual way by a voltage divider across the first section of the power supply. A thermionic rectifier (1654) is used in this stage in order to supply the divider current but the following stages make use of KR31 gas rectifiers, thus eliminating the need for filament supply circuits, with a high degree of voltage insulation. The current drain at the high voltages is very low so that the voltages shown are obtained with a total battery current of only 0.4 ampere at 2 volts. A photograph of the power supply is shown in Figure 23.

The chief problems in connection with this supply are leakage and corona. These must both be kept to a minimum since the internal resistance of the power supply is quite high (approximately 10^9 ohms at the 16-kilovolt tap). Leakage can be minimized by use of high-quality insulation and protection from humidity. Hermetical sealing, or other provisions for drying, are essential with this type of voltage supply.

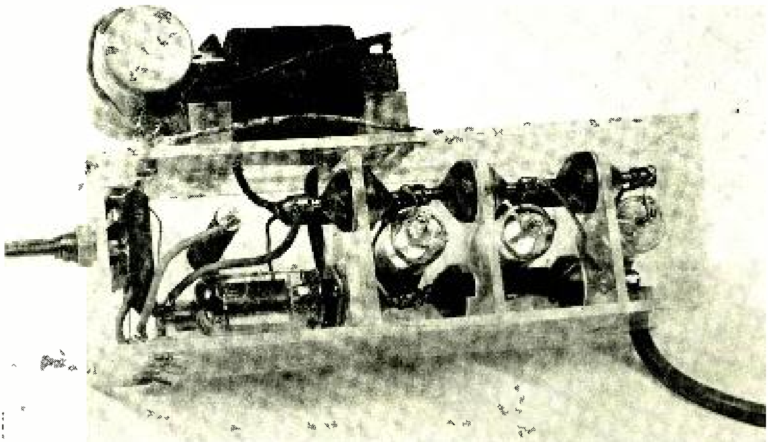


Fig. 23—16-kilovolt voltage quadrupler power supply.

Corona can be prevented by eliminating all sharp edges at the high voltage connections or by coating with a closely-adhering insulating material such as wax.

Conclusion

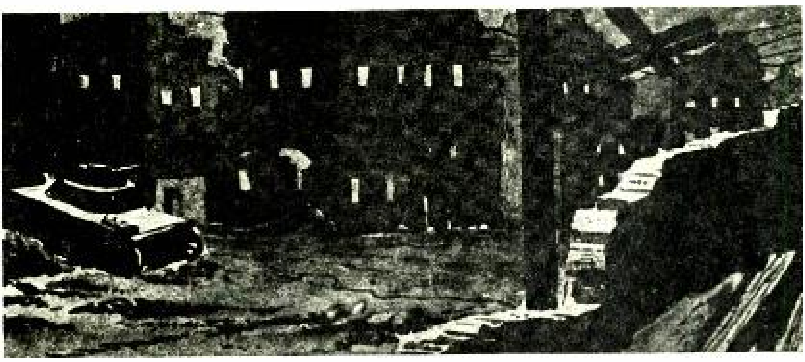
The above discussion stresses only the military application of infrared imaging equipment. There are, however, a number of peacetime uses for these instruments. Among these applications are their possible value in police work, their use in the field of medicine, the viewing of the usual types of photographic film during processing and production and for the inspection and control of a number of other industrial and scientific processes where visible light is undesirable.

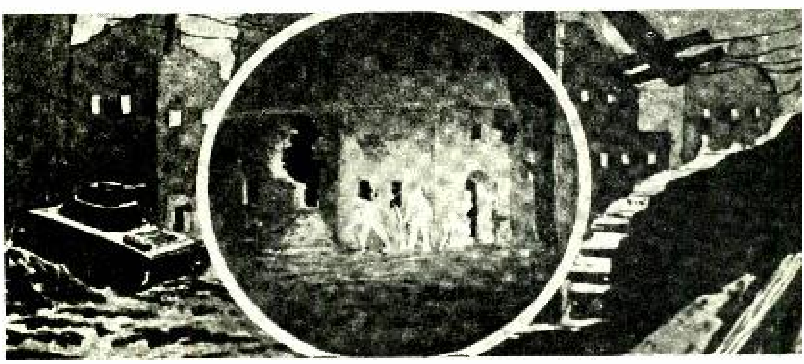
In closing, the authors wish to express their appreciation to Dr.

V. K. Zworykin, Director of Electronic Research, for his advice and encouragement during the course of this development and also their recognition of the contribution made by Dr. J. E. Ruedy, G. L. Krieger and Dr. P. Rudnick to this project. Credit should go to Dr. L. B. Headrick, Miss H. C. Moodey and Dr. R. B. Janes of the Lancaster plant for work on the production design of the image tube.

As an interesting example of the effectiveness of the infrared devices described in this paper, two illustrations of a war street scene at night are included below. The upper picture shows the scene as viewed by the unaided eye. The lower picture shows, in the circle, the details of the scene when viewed by the infrared devices.

The Manager, RCA REVIEW





WAVEGUIDE-OUTPUT MAGNETRONS WITH QUARTZ TRANSFORMERS*†

By

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Summary—*Design or space considerations frequently make it difficult to incorporate a "vacuum" transformer into waveguide-output magnetrons. This paper indicates how the use of quartz transformers may simplify the constructional problems. In tests at 1.25 centimeters, substantially identical results were obtained in tubes with quartz transformers as were obtained with those incorporating vacuum-filled transformers.*

INTRODUCTION

ONE method of coupling energy out of a multiple-cavity magnetron is to connect a waveguide or parallel-plate transmission-line transformer into one of the cavities, the other end of the transformer being connected to an output waveguide (Figure 1).

The dimensions of the transformer are determined by operating considerations of the magnetron. For instance, if the transformer width is too large, the external load will unduly affect the frequency of operation. On the other hand, if the width is too small, not enough power will be coupled into the external load.

In practice (particularly at higher frequencies), the width of the transformer opening is so small that the problem of machining the parts and assembling the tube is extremely difficult. It was realized that the use of a dielectric other than vacuum in the transformer would make the width greater and at the same time shorten the transformer, a factor which is desirable when space is of importance.

THEORY AND DESIGN

The characteristic impedance of a rectangular waveguide for the

* Decimal Classification: R355.912.1 × R382.11.

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This paper covers work completed while the authors were associated with Radio Corporation of America. Dr. Malter is now in charge of the Vacuum Tube Research Section of the Naval Research Laboratory, Washington, D. C.; Mr. Moll is at present taking graduate courses in Mathematics at Ohio State University.

TE_{10} mode is:[1]

$$Z_t = \sqrt{\frac{\mu\,\mu_o}{k\,\epsilon_o}}\ \frac{1}{\sqrt{1-\left(\frac{\lambda_m}{2\,a}\right)^2}}\ \frac{b}{a}\quad\left(\begin{array}{c}\text{Meter-Kilogram-}\\ \text{Second Units}\end{array}\right) \tag{1}$$

where a and b are the major and minor dimensions, respectively, of the guide.

λ_m is the wavelength in the medium

μ_o is the permeability of free space

μ is the ratio of the permeability of the medium to that of free space (a dimensionless constant)

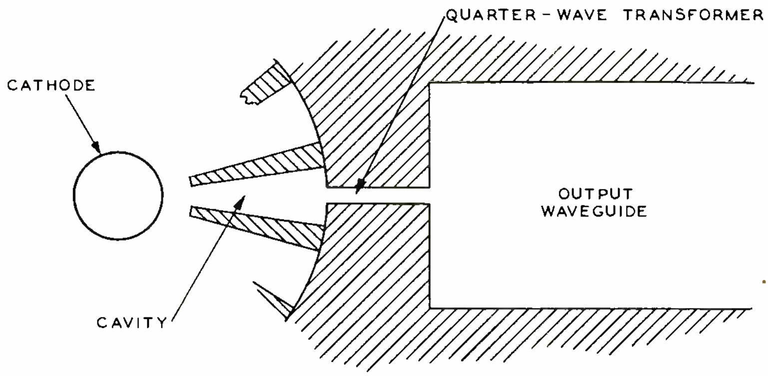

Fig. 1—Waveguide-output magnetron.

ϵ_o is the permittivity of free space

k is the ratio of the permittivity of the medium to that of free space (a dimensionless constant)

For all ordinary media $\mu = 1$

Then: $\lambda_m = \dfrac{\lambda_o}{\sqrt{k}}$

where λ_o is the free-space wavelength.

Then (1) becomes:

[1] J. C. Slater, MICROWAVE TRANSMISSION, McGraw-Hill Book Company, New York, N. Y., 1942. (p. 185).

$$Z_t = \frac{377}{\sqrt{k}} \frac{1}{\sqrt{1 - \frac{1}{k}\left(\frac{\lambda_o}{2a}\right)^2}} \frac{b}{a} \tag{2}$$

For this investigation λ_o was chosen to be 1.25 centimeters. In the case of a particular tube under investigation (one with a vacuum transformer), $b = 0.028$ centimeter and $a = 0.890$ centimeter. Then from (2), $Z_t = 16$ ohms.

It was desired to construct the tube with a quartz-output transformer. Since $k = 3.9$ for quartz $\lambda_m = \frac{1.25}{\sqrt{3.9}}$ centimeter $= 0.635$ centimeter. The value chosen for "a" was 1.09 centimeters. While this value of "a" is sufficiently great so that the TE_{20} and TE_{30} modes could be set up in the quartz-filled waveguide transformer no difficulties were experienced on this score. It is believed that this is due to the fact that geometrical symmetry made any coupling to the TE_{20} mode impossible and to the fact that even if some TE_{30} mode were set up in the quartz, none of it would be transmitted by the following external waveguide. Substitution of $a = 1.09$ centimeters, $Z_t = 16$ ohms, and $k = 3.9$ into equation (2) yields $b = 0.083$ centimeters for the quartz transformer. The transformer width is increased threefold over the equivalent vacuum transformer, thus greatly simplifying the mechanical problems.

The problem of transformer length requires more extended investigation. Because of "end effects", the transformer length is not necessarily one-quarter of the wavelength in the guide of which the transformer may be considered as being a section. This guide wavelength is given by

$$\lambda_{mg} = \frac{\lambda_m}{\sqrt{1 - \left(\frac{\lambda_m}{2a}\right)^2}} = \frac{0.635}{\sqrt{1 - \left(\frac{0.635}{2.18}\right)^2}} = 0.665 \text{ centimeter}$$

Then $\lambda_{mg}/4 = 0.166$ centimeters. This, however, is not the exact transformer length to be used because of the "end effects". The "end effects" may be determined in the following manner. The magnetron, transformer, and output waveguide may be represented by the equivalent circuit of Figure 2. L_t and C_t are the effective inductance and capacitance of the magnetron when "viewed" by the transformer; Z_a is the effective impedance of the "end effects" at the junction of the magnetron and transformer; Z_b is the effective impedance of the "end effects" at the junction of the transformer and output waveguide; Z_t is the characteristic impedance of the transformer; and Z_0 is the characteristic impedance of the output waveguide.

Work done at the M. I. T. Radiation Laboratory and at Columbia University has demonstrated the validity of the series representation

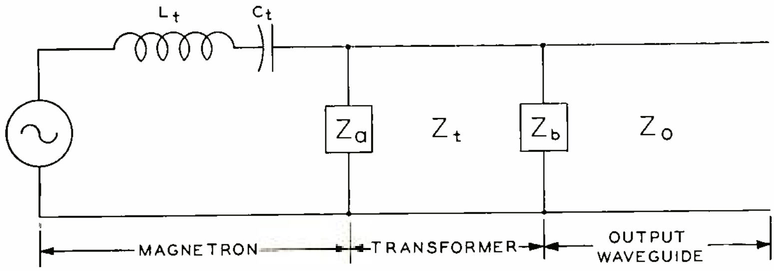

Fig. 2—Schematic diagram of waveguide-output magnetron.

for the magnetron.

A test arrangement is shown in Figure 3.

The section between A and C consists of a parallel-plate transmission line having the height and width of one of the magnetron cavities at the end where it couples to the transformer; the waveguide section between B and A is the cross section of the transformer (quartz-filled),

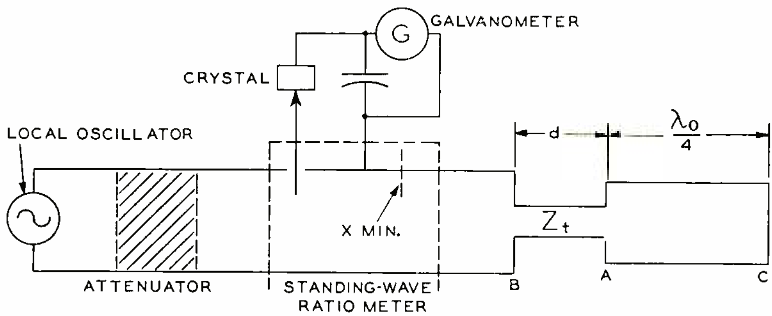

Fig. 3—Experimental setup for determining transformer "end-effects".

and the section to the left of B is a standard output waveguide. Then, the shunt impedance at A is Z_a and that at B is Z_b. $X_{\min 1}$ is the position of the standing-wave minimum when the parallel-plate line is shorted at C and $AC = \lambda_0/4$. The system is now shorted at B and $X_{\min 2}$ determined. Then d is varied until $X_{\min 2} = X_{\min 1}$. Since B is a low-impedance point for both these measurements, Z_b can be neglected for the moment. Assume $d = 0.23\,\lambda_{mg}$. Then, Z_a can be obtained by means of a "P. H. Smith Chart" in the manner shown in Figure 4. It is seen that in this case $Z_a = -8jZ_t$, indicating that the "end effects" at A are capacitative in nature. In the actual case under study $d = 0.25\,\lambda_{mg}$ indicating that $Z_a = \infty$. Thus, no "end-effect" correction need be applied for the conditions at A.

In order to determine Z_b, d is set $= \lambda_{mg}/4$, A is short-circuited, and

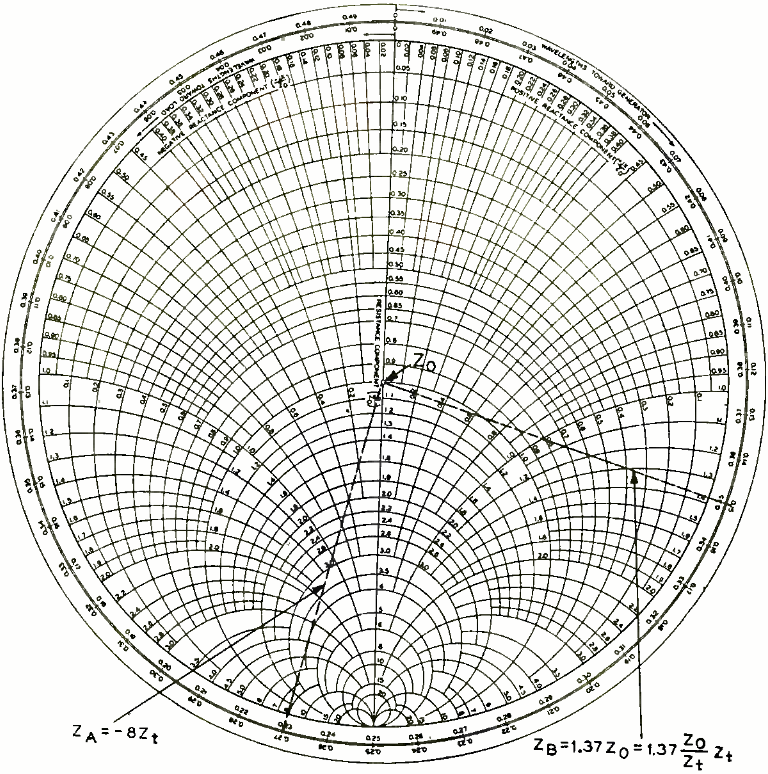

Fig. 4—Transformer "end-effect" reactances.

$X_{\min 1}$ measured. Then the system is short-circuited at B and $X_{\min 2}$ measured. If the distance between $X_{\min 1}$ and $X_{\min 2}$ *is* $\lambda_g/4$ (λ_g is wavelength in main guide), then $Z_b = \infty$. If the distance from $X_{\min 1}$ to $X_{\min 2}$ is less than $\lambda_g/4$, then Z_b is inductive, and can be found from the chart by rotating through an angle $(X_{\min 1} - X_{\min 2})/\lambda_g$. In the actual case $(X_{\min 1} - X_{\min 2})/\lambda_g = 0.15$, indicating that Z_b is inductive. Then, from Figure 4, it appears that $Z_b = 1.37jZ_o$.

$$Z_B = 1.37j\left(\frac{Z_o}{Z_t}\right)Z_t$$

$$\text{Since } \frac{Z_o}{Z_t} = 10.9 \qquad Z_B = 15jZ_t$$

The correct transformer length can now be determined. The nor-

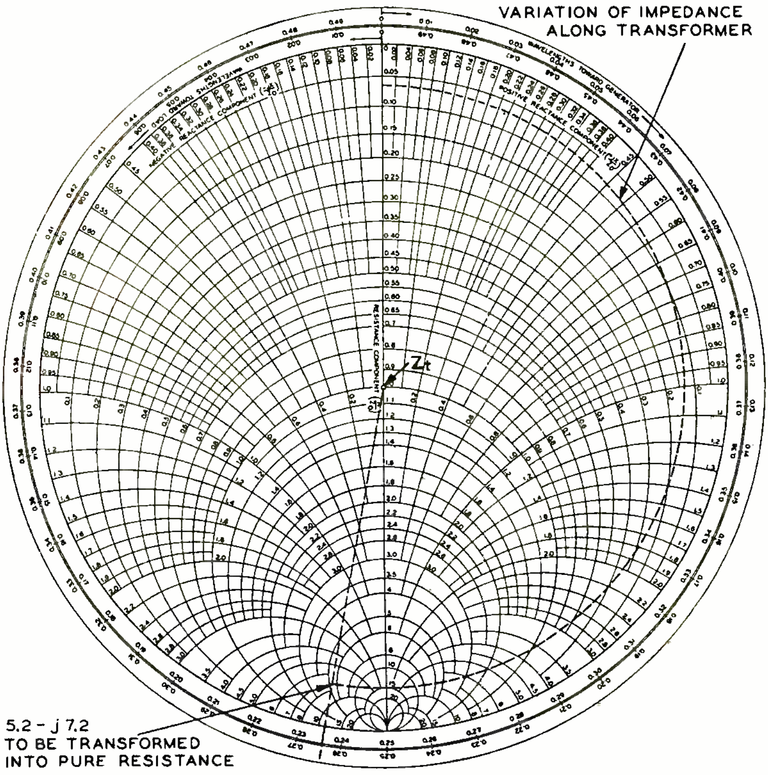

Fig. 5—Determination of correct transformer length.

malized impedance "seen" by the transformer looking to the left is then

$$\frac{\dfrac{Z_B}{Z_t}\,\dfrac{Z_o}{Z_t}}{\dfrac{Z_B}{Z_t}+\dfrac{Z_o}{Z_t}} = \frac{Z_o\,Z_t}{Z_o+Z_t} = \frac{15j\times 10.9}{15j+10.9} = 5.2-7.2j$$

This impedance is to be transformed into a pure resistance by the transformer. Figure 5 shows how the total length of the transformer is obtained. It is seen that its length is $0.264\lambda_{mg} = 0.264 \times 0.665$ centimeters = 0.175 centimeter.

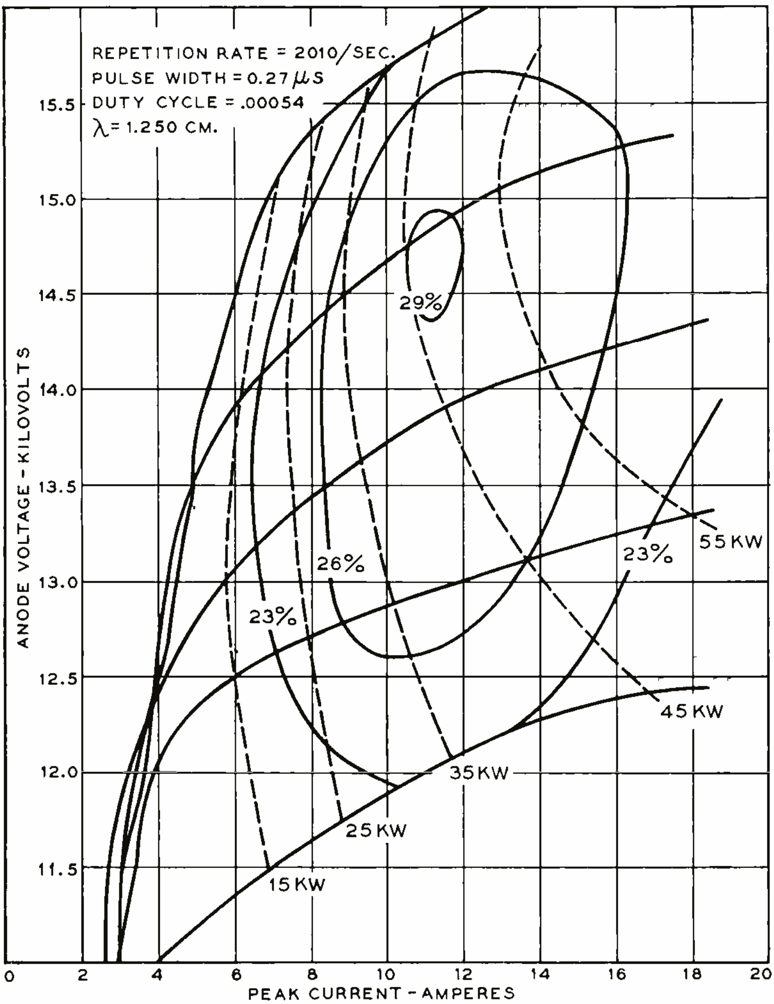

Fig. 6—Performance chart of quartz transformer magnetron.

Thus, by shifting to quartz, the width of the transformer is increased from 0.028 centimeter to 0.083 centimeter and its length is decreased from 0.32 centimeter to 0.166 centimeter. Each of these changes is desirable from a mechanical standpoint. In particular, the width increase is very desirable, as it is difficult to construct an enclosed slot 0.028 centimeter wide, with the strict tolerances set by the requirement that changes in external loads should not result in excessive changes in output frequency ("pulling" **figure).**

EXPERIMENTAL RESULTS AND CONCLUSIONS

Eight 1.25-centimeter magnetrons with rising-sun anodes of the type used in the 3J31 and with quartz transformers were constructed. In all cases, the results of "cold" tests were in concordance with the results predicted from the above design. A number of the tubes went gassy for reasons not connected with the transformer development. The results of "hot" and "cold" tests of three of the tubes are listed in Table 1.

Table 1

Test results of magnetrons with quartz output transformers.

	TRANSFORMER		HOT TEST				COLD TEST			
	Length	Width	λ	Peak Power	Anode Voltage	Efficiency	Cold Pulling Figure	Q_o	Q_{ext}	Hot Pulling Figure
Q1L2	0.068″	0.034″	1.249 cm	45 kw	14.5 kv	24%	36 Mc	865	279	
Q1L3	0.062″	0.0335″	1.254 cm	47 kw	14.6 kv	25.5%	29 Mc	740	343	27 Mc
Q1L6	0.067″	0.0275″	1.237 cm	50.8 kw	14.0 kv	25.7%	42 Mc	740	237	

A typical performance chart is shown in Figure 6.

A comparison of the results shown in Table 1 and Figure 6 with those obtained from average 3J31's indicates that the tube performance is practically the same for tubes with either type of transformer. One of the quartz-transformer tubes was operated for 200 hours with no essential change in its behavior.

It is thus indicated that where space or design considerations make it desirable, quartz may be employed as a transformer medium in waveguide-output magnetrons.

THERMAL AND ACOUSTIC EFFECTS ATTENDING ABSORPTION OF MICROWAVES BY GASES*

By

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Summary—As a result of an investigation of the absorption spectra of gases at microwave frequencies, it has been found that of the 50-odd materials that are gaseous at room temperature and a pressure of one atmosphere, 15 strongly absorb microwaves. The experimental techniques used in taking measurements are described and the theoretical interpretation of the observed absorption for some of the simpler molecules is given.

The energy absorbed by the gas from the microwaves reappears as heat and sound. Thermal conversion is demonstrated by confining an absorbing gas in a cavity resonator which communicates with a U-tube. The gas not only absorbs the microwaves but serves as the thermometric substance of a gas thermometer. A 12-inch deflection of the U-tube column is obtained when the average input power is ten watts. Acoustic conversion is shown by exposing a gas-filled balloon to a modulated microwave field; the sound frequencies generated depend on the modulation. The absorbing gas may be confined in an organ pipe closed at one end by a disk in contact with a piezo-electric crystal. This organ pipe is resonant electromagnetically to the impressed microwave frequency and acoustically to the modulation frequency. A detector of this type has a square law response and is sufficiently sensitive to detect 10 milliwatts of power.

THE infra-red spectroscopist and the physicist working with microwaves are at last on common ground. At a recent meeting of the American Physical Society an entire session was devoted to the absorption of microwaves by gases. Among other things, Van Vleck[1] pointed out that the absorption of 6 millimeter waves by oxygen and of 1.3 centimeter waves by water vapor is so large as to limit severely the use of these wave lengths in communication and radar involving long transmission paths in the earth's atmosphere. The absorption of 1.25 centimeter waves by gaseous ammonia has been known for some years[2]. This absorption is associated with the "turning-inside-out" of this molecule and is so intense that a plane 1.25 centimeter wave will lose one-half of its power on traversing a 3-foot

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* Decimal Classification: R110

[1] J. H. Van Vleck, "The Atmospheric Absorption of Microwaves", *Phys. Rev.*, Vol. 69, No's. 11 and 12, p. 676, June 1 and 15, 1946.

[2] C. E. Cleeton and N. H. Williams, "Electromagnetic Waves of 1.1 cm. Wave-Length and the Absorption Spectrum of Ammonia", *Phys. Rev.*, Vol. 45, No. 4, pp. 234-237, Feb. 15, 1934.

layer of ammonia at atmospheric pressure and room temperature. A systematic investigation into the field has been undertaken at these laboratories with the objective of determining whether other gases, both organic and inorganic, will show molecular absorption in the microwave region, and to study the scientific aspects of the problem and possible technical applications. It was presently found[3] that of the 50-odd substances which are gaseous at room temperature and atmospheric pressure, 15 are strong absorbers of microwaves. Moreover, the direct conversion[4] of microwave energy into both heat and sound was demonstrated. The purpose of this paper is to present a survey of results obtained in this field.

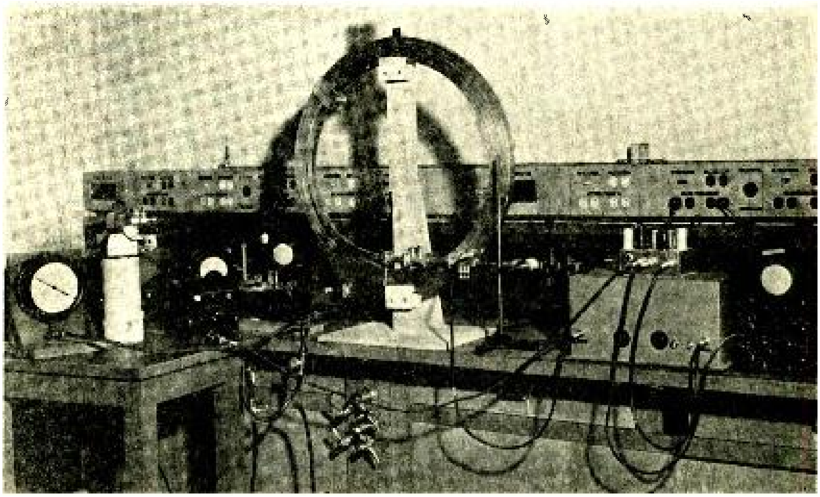

Fig. 1—Photograph of wave guide system.

The techniques used in taking measurements on the absorption of gases are borrowed very largely from the radar art. Figure 1 shows an experimental setup used in taking measurements at a wave length of 3.2 centimeters. A similar arrangement is used at 1.25 centimeters. A klystron is used as a source of power while a crystal detector is used in the receiver which is employed to measure the power transmission through a coiled-up 30-foot section of rectangular wave guide. This section is made vacuum tight by the use of mica windows, first, to permit evacuation of the guide and then the introduction of a gas

[3] W. D. Hershberger, "The Absorption of Microwaves by Gases", *Jour. Appl. Phy.*, Vol. 17, No. 6, pp. 495-500, June, 1946.

[4] W. D. Hershberger, "Thermal and Acoustic Effects attending Absorption of Microwaves by Gases", *Phys. Rev.* Vol. 69, No's. 11 and 12, p. 695, June 1 and 15, 1946.

under study to any desired pressure. Auxiliary components include a standing wave detector, tuners to eliminate standing waves in the test section of guide, pressure gauges, a linear amplifier, and an output voltmeter. In the experimental procedure a power reading is taken with the test guide evacuated, and then the diminution in power is noted as the absorbing gas is admitted to the guide. Under such conditions at 1.25 centimeters the power drops to less than 1/10 of 1 per cent of its initial value if one atmosphere of ammonia is used; if methyl chloride is used power falls to 41 per cent of its initial value. From the character of the curve in which absorption coefficient is plotted against pressure, one is able to draw inferences concerning the location of the absorption maximum on a frequency or wave length scale as well as to determine the parameters which permit this absorption curve to be constructed.

The simplest absorbing molecule which has thus far been studied is the linear molecule carbonyl sulphide: O = C = S. This molecule differs from carbon dioxide which has one carbon atom and two oxygen atoms and from carbon disulphide with two sulphur atoms substituted for these oxygens, in that it is dissymetrical, containing one atom of sulphur and one of oxygen. Hence unlike either carbon dioxide or carbon disulphide it possesses a permanent dipole moment. All of the molecules which are found to absorb, possess either an electric or a magnetic dipole moment which serves to couple them to the applied electromagnetic field. The motion imparted to the carbonyl sulphide molecule by the microwave field is envisaged as a pure end-over-end rotation, with the wave length in centimeters for absorption given by the simple equation:

$$\lambda = \frac{4\pi^2 c I}{h (J + 1)} \qquad (1)$$

c is the speed of light, I the moment of inertia of the molecule, h is Planck's constant, and J is the quantum number defining the rotational energy of the molecule. For this molecule, when J "jumps" from 0 to 1 we have either the emission or the absorption of 2.5 centimeter radiation, from 1 to 2 we have 1.25 centimeter radiation; from 2 to 3, 0.83 centimeter radiation and so on. The absorption for this molecule was actually measured at 1.25 centimeters and Figure 2 shows a plot of absorption against pressure. It is noted that the absorption curve rises very steeply at low pressures, then becomes almost independent of pressure above 0.1 atmospheres. The absolute value of the absorption coefficient for this molecule at one of its resonances ν_o is given by:

$$\alpha_J = \frac{\mu_o^2 \nu_o^2 (J+1) h}{3 c I (k T)^2} \frac{N}{\Delta \nu} \tag{2}$$

where μ_o is the dipole moment of the molecule
k is Boltzmann's constant
T is temperature
N is the number of molecules per cubic centimeter, and
$\Delta\nu$ is the half-width of the absorption line in cycles.

N varies directly with pressure and, to a good approximation, so does $\Delta\nu$; hence α is very nearly independent of pressure, after the plateau

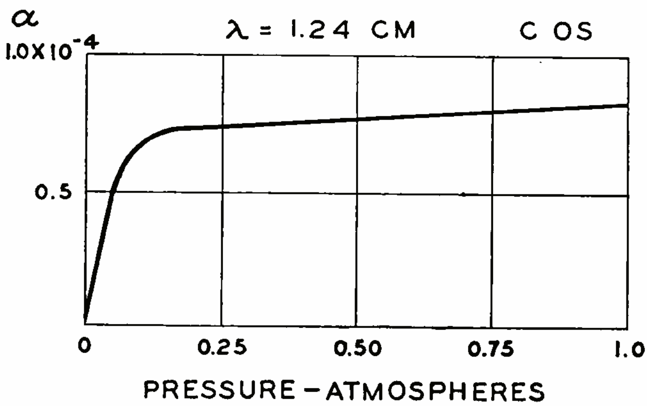

Fig. 2—Absorption of carbonyl sulphide.

in the absorption curve is reached. Addition of more gas has the effect not of increasing absorption at the center of the line but of increasing line width. The theoretical and measured absorptions agree within perhaps 35 per cent which for this type of calculation is considered quite a satisfactory agreement.

Molecules more complicated than the linear one just considered are the symmetrical tops, as ammonia and the methyl halides, all of which are good absorbers. The theoretical treatment is reasonably straightforward and gives results in quite good agreement with experiment. Ammonia is unique among these molecules in that the potential barrier involved in the so-called "tunnel" effect is so low that the energy levels of the molecule are measurably split. As a result, a fine structure is observed in its infra-red spectrum and there is pronounced absorption at 1.25 centimeters. For the methyl halides, the potential barrier involved in "tunnelling" is high, the energy level splitting is small, and the maximum in the absorption curve will come at some low frequency, possibly in the broadcast band. Pressure broadening—that is the broadening of a spectral line that arises from collisions between molecules—necessitates working at very low pressures if we wish to observe a spectral line at a low radio frequency. Observations of this character at the center of the line are made difficult if not impossible, not by the need for the low pressure, but because the absolute value of the absorption coefficient increases with the square of the frequency. At microwave frequencies we are taking observations on the high frequency wing of a spectral line whose center lies at some low and undetermined frequency. The Van Vleck theory referred to earlier

Table 1—ABSORPTION COEFFICIENTS

Material	Absorption Coefficient $\times 10^4$
Ammonia	78.0
Methyl Fluoride	10.0
Methyl Chloride	8.0
Methyl Bromide	6.2
Ethyl Chloride	15.0
Freon 21	10.6
Freon 22	12.0
Freon 12	3.1
Hydrogen Sulphide	0.3
Sulphur Dioxide	5.0
Carbonyl Sulphide	0.8
Dimethyl Ether	3.9
Ethylene Oxide	6.8
Methylamine	10.5
Dimethylamine	7.0
Ethylamine	10.2

permits us to calculate with reasonable precision the magnitude of the absorption, as well as to account for the experimental observation that absorption increases with the square of the gas pressure for this "non-resonant" type of absorption.

Table 1 gives the values of the absorption coefficients of 16 gases at 1.24 centimeters at one atmosphere. $\frac{1}{\alpha}$ is the path length in centimeters which suffices to reduce the power in a plane wave to $1/e$ or 37 per cent of its initial value. The accuracy of these results is on the order of 5 per cent. Dielectric constants of these gases were also measured at two wave lengths.

Eleven of the materials listed are unsymmetrical tops and for these the theory is most cumbersome and unwieldly. Ethylamine, for example, shows evidence of resonant absorption at 1.24 centimeters, but this molecule consists of 10 atoms, hence possesses 24 internal degrees of freedom as well as 6 external degrees.

The question very naturally arises: what happens to the energy abstracted by an absorbing gas from a microwave? Experiments designed to elicit the answer to this question show that this energy reappears as heat and sound. It should be emphasized that such effects

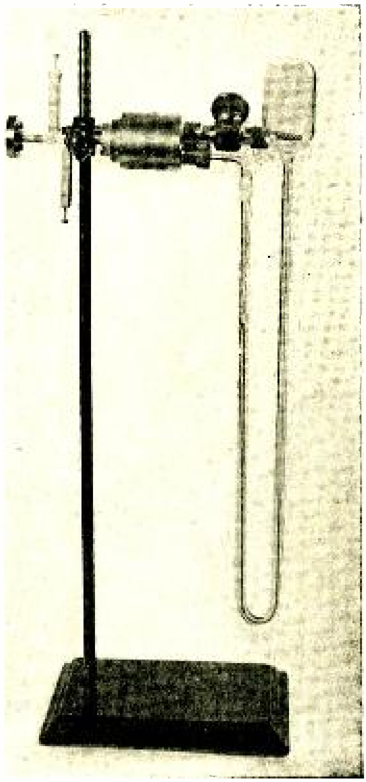

Fig. 3—Photograph wattmeter.

will not be obtained from atmospheric gases. The molecules listed in Table 1 have absorption coefficients larger than those for atmospheric gases by factors as large as 100 or 1000. For water vapor at usual New Jersey concentrations the loss in 1.3 centimeter propagation is of the order of 2 or 3 decibels per mile while for ethyl chloride the loss is 1000 decibels per mile. Thus, in the gases in Table I the energy is dissipated in a small volume of gas giving rise to measurable thermal and acoustic effects.

The device shown in Figure 3 serves to demonstrate thermal conversion and also may be used as a microwave wattmeter. The resonant cavity shown is made gas tight and filled with an absorbing gas such as one of the Freons in Table 1 or ammonia. The gas communicates with a U-tube filled with some light liquid, kerosene if ammonia is used, which will not react with the gas. The gas absorbs microwave power, thereby becoming heated, and the temperature rise is read from the change in level in the liquid in the U-tube. When a transmitter generating 10 watts of average power is used to feed this gas filled resonator the U-tube deflection is 12 inches and this deflection takes place in about one second. On cutting off the power the original level is reached in about a second. This speedy response is in sharp contrast to the sluggish deflection which results when the metal cavity itself is warmed—by placing a hand on it, for example. The microwave heating takes place throughout the volume occupied by the gas itself and the speed of response depends on the thermal capacity of the enclosed gas and the inertia of the liquid in the U-tube. Wattmeters of this variety operating at wavelengths of 1.25 and 3.2 centimeters have been built for use as microwave loads. The 12-inch deflection corresponds to a temperature rise of about 7 degrees Centigrade and since the device is an averaging instrument it may be employed with pulsed transmitters used in radar or with continuous wave generators equally well.

The process of heat conversion may be envisaged as follows: The molecule first abstracts energy from the field and this energy appears in one of its internal degrees of freedom or as rotational energy if a rotational transition is involved in the absorption. Such an "excited" molecule then collides with one of its neighbors, or perhaps only after many collisions, the molecule drops back to its "unexcited" state but in the collision process the colliding molecules pick up additional energy of translation. This increase in translational energy may be measured as an increase in pressure since the pressure of the gas depends on molecular velocities. This process of conversion may be fast or slow depending on such factors as gas pressure, temperature, and the collision cross section for the kind of process involved. In any event the lifetime of an excited state is at least as great and it may be greater than the time between collisions.

When modulated microwaves are absorbed by one of the gases in Table 1, in view of the above considerations, there is not only a steady increase in temperature and pressure, which depends on the average microwave power, but also alternating components of heat and pressure which depend both on the modulation envelope and on the slowness of exchange of energy between the internal and external degrees of freedom of the gas. This latter effect in another connection gives rise to the phenomena of dispersion of ultrasonic waves in gases, a subject on which there is an extensive literature.[5]

The alternating components of pressure and temperature just mentioned are of course sound, and the frequencies generated depend upon the modulation. The effect may readily be demonstrated by filling a balloon or other suitable rubber container with an absorbing gas and placing it at the exit of a horn or wave guide fed by a modulated microwave generator. When a microwave generator, pulsed in a manner suitable for radar, and having an average power of 10 watts was used in this manner, the audible sounds—most of the energy lies in

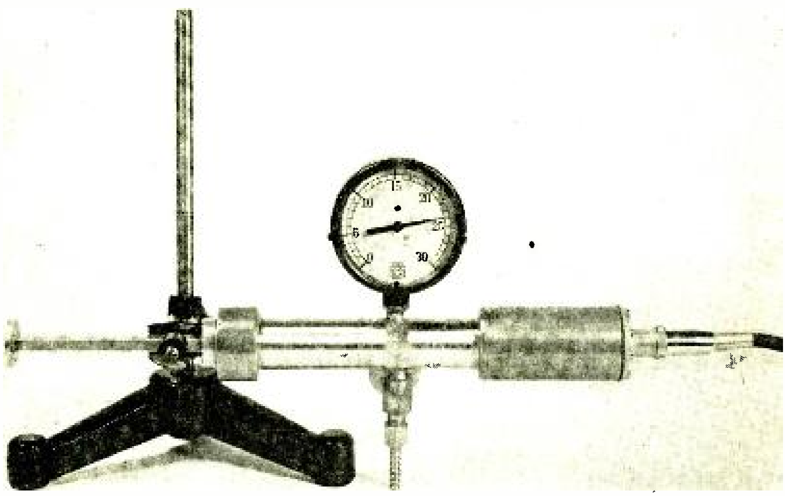

Fig. 4—Photograph of resonant receiver.

the ultrasonic region—may be heard in a quiet corridor 100 or more feet distant from the sound generator. In spite of the fact that the radio art is more than 50 years old, it is not unlikely that this gas-filled rubber balloon still has the distinction of being the first true "wireless" receiver. This receiver suggests the application of microwave techniques to the problem of the football coach who wishes to issue directions to his quarterback on the gridiron. The coach requires a narrow beam voice modulated microwave generator while the quarterback requires a helmet with a gas-filled ear piece.

A gas filled receiver which is simultaneously set in resonance electromagnetically and acoustically is shown in Figure 4. The length of

[5] W. T. Richards article on "Supersonic Phenomena" in *Reviews of Modern Physics*, Vol. 11, No. 1, pp. 36-64 includes a 384-title bibliography.

the gas column is chosen to resonate as an organ pipe closed at both ends at 540 cycles when Freon 22 was used as an absorber. The modulating frequency of a microwave generator is adjusted to resonate this column. One end is closed off by means of a glass disk permeable to the microwaves, while the other end is closed off by a 0.006-inch aluminum disk in contact with a Rochelle salt crystal. The electrical output of the device is then amplified and measured by conventional means. A portion of this output voltage may be coupled back to control modulating frequency, and since the acoustic column is readily made to be the most selective link in the feed-back loop, operation at the proper audio frequency is thus insured. The sensitivity of the device with the present acoustic pickup unit is sufficient to permit measurements on modulated carrier frequencies whose average power is 10 milliwatts.

The spatial factors involved in the production of heat for the excitation of a desired acoustic mode require critical attention. The ratio of the frequency of an acoustic mode to that of an electromagnetic mode is of the order of 10^6, namely, the ratio of the velocities of propagation.

For a slender resonator as in Figure 4 excited in its lowest transverse electric mode—TE_{11} mode—the situation is simple. The analysis is begun with the heat distribution function already known—because of the known electric field configuration—and for simplicity it is assumed that this function varies only along the axis of the resonator. This heat distribution function is resolved into its spatial Fourier components which are then employed to determine whether the coupling to the resonator is such as to excite effectively the desired acoustic mode of oscillation. These considerations led to the conclusion that the above resonator would be most effectively excited if the heat is generated in only one half of the resonator. This is accomplished by inserting a short length of cut-off guide at the mid-section of the resonator to confine the microwaves to one end of the resonator. The two halves are very closely coupled acoustically. Insertion of this section resulted in a many-fold increase in conversion efficiency when compared to the performance of a similar cavity without the cut-off section. When pulse modulation is employed the whole family of harmonics characteristic of the pulse and its repetition rate are generated and the acoustic column may then be designed to accentuate a desired harmonic.

The efficiency of the device as an electro-acoustic transducer depends upon $\Delta T/T$ where ΔT is the temperature rise experienced by the gas during the course of a pulse. $\Delta T/T$ is a small fraction of a percent. (Calculations of this sort were made in particular by John E. Walter in an unpublished memorandum.) Thus efficiency depends upon input power, and the acoustic power output of an electro-acoustic transducer of this variety varies with the square of the microwave power. The output voltage of the piezo crystal in the above device is proportional to sound pressure, so it was finally concluded that the voltage developed by the crystal is proportional to the modulated microwave power or the square of the microwave field strength. This conclusion is borne out by an experimental comparison using attenuators whose law is accurately known.

In conclusion, it is well to point out something of the significance of these studies. On the earth, the utility of microwaves for communication and radar uses becomes limited, as wave lengths become shorter and shorter. On Jupiter and Saturn whose atmospheres contain high percentages of ammonia under high pressure the centimeter and decimeter wave length region would be quite useless for applications involving transmission through their atmospheres. We need not expect to receive radar echoes from these particular planets similar to those received from the moon. But the very fact that microwaves lose their utility for conventional radio purposes due to absorption, molecular in character, makes them of especial interest to the structural chemist. These waves will prove very useful in studying extremley small differences between energy levels in molecules, atoms, or nuclei. The recent radio frequency experiments of Pound, Purcell, and Torrey[6] or of Bloch, Hansen, and Packard[7] in measuring the nuclear magnetic moments of protons are cases in point. Measurements on the conversion efficiency of the device in Figure 4 as dependent on frequency will be useful in studying the lifetimes of excited molecular states. Such a tool should find application in studies on chemical reaction rates in gases. The regularly-spaced rotational spectral lines of carbonyl sulphide may well serve as frequency standards in the microwave region. And finally, the use of molecular resonance in the detection of microwaves has already been demonstrated.

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[6] R. V. Pound, E. M. Purcell, and H. C. Torrey, "Measurement of Magnetic Resonance Absorption by Nuclear Moments in a Solid", *Phys. Rev.* Vol. 69, No's. 11 and 12, p. 681, June 1 and 15, 1946.

[7] F. Bloch, W. W. Hansen, and Martin Packard, "Nuclear Induction", *Phys. Rev.*, Vol. 69, No's. 11 and 12, p. 680, June 1 and 15, 1946.

TABLE OF THE INTEGRAL $\frac{2}{\pi}\int_0^x \frac{\tanh^{-1} t}{t} dt$*

By

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Summary—In the computation of either the real or imaginary component of a minimum-phase-shift network, having the other component given, the integral shown here is involved. This integral is tabulated over the range $x = [0.00(0.01)0.97(0.005)0.99(0.002)1;5D]$. *The methods of computation and checking are explained in detail.*

Introduction

When either the real or the imaginary component of a minimum-phase-shift-network characteristic is known for the entire frequency range, the other component can be computed, even though the actual form of the circuit may be unknown. For example, if the impedance of the circuit is known, the corresponding phase angle can be determined. If the reactance is known at all frequencies, the resistance can be computed at each frequency. These analytic relations have been given by Bode and he has shown how to make the computation by graphical approximation.[1] If the attenuation is constant on one side of a prescribed frequency ω_0 and has a constant slope thereafter, it is called a semi-infinite constant slope characteristic. Thus in Figure 1, if curve A is the attenuation in decibels, curve B is the corresponding phase shift in radians, where k is the attenuation slope. This corresponds to Figure 14.8 of Bode.[2] Curve B exhibits odd symmetry about the point $\omega = \omega_0$ when plotted on a logarithmic frequency scale, and the phase shift at this point is exactly one half the asymptotic value. If k is assumed to be unity, curve B is given by the relation:

$$B(x) = \frac{1}{\pi}\int_0^x \log\left|\frac{1+t}{1-t}\right| \frac{dt}{t} \qquad 0 \leq x \leq \infty \qquad (1)$$

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* Decimal Classification: R246 × R081.

[1] Hendrik W. Bode, NETWORK ANALYSIS AND FEEDBACK AMPLIFIER DESIGN, D. Van Nostrand Company, Inc., New York, N. Y., 1945, (Chapters 14, 15.)

[2] Bode, op. cit., p. 316.

$$= \frac{2}{\pi} \int_0^x \frac{\tanh^{-1} t}{t} dt \qquad 0 \leq x \leq 1 \qquad (2)$$

$$= \pi/2 - \frac{2}{\pi} \int_0^{1/x} \frac{\tanh^{-1} t}{t} dt \qquad 1 \leq x \leq \infty \qquad (3)$$

$$= \pi/2 - B\left(\frac{1}{x}\right) \qquad (4)$$

where $x = \omega/\omega_o$.

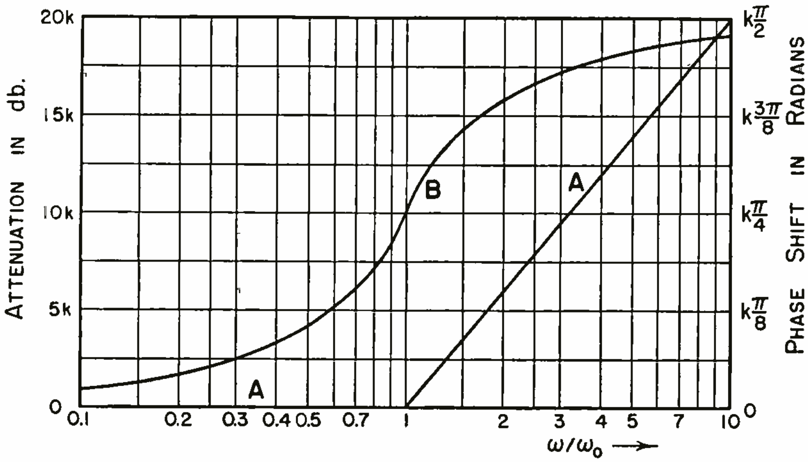

Fig. 1—Semi-infinite constant slope characteristic.

This integral for *B(x)* was computed in the following manner:

Method of Computation

If the inverse hyperbolic tangent is expanded in a power series about the origin, the integration can be carried out term by term. Thus,

$$B(x) = \frac{2}{\pi} \int_0^x \left\{ t + \frac{1}{3} t^3 + \frac{1}{5} t^5 + \frac{1}{7} t^7 + \cdots \right\} \frac{dt}{t} \qquad x^2 \angle 1$$

$$= \frac{2}{\pi} \left\{ x + \frac{1}{3^2} x^3 + \frac{1}{5^2} x^5 + \frac{1}{7^2} x^7 + \cdots \right\} \tag{5}$$

This series converges quite rapidly for $x < \frac{1}{2}$ but between ½ and 1 the convergence is too slow for rapid computation. If in equation 1 the transformation

$$\mu = \frac{1-t}{1+t} \quad , \quad y = \frac{1-x}{1+x} \tag{6}$$

is applied, the result is:

$$B(x) = \frac{2}{\pi} \int_1^y \log |\mu| \frac{d\mu}{1-\mu^2}$$

$$= \frac{1}{\pi} \left[\log |\mu| \log \left| \frac{1+\mu}{1-\mu} \right| \right]_1^y - \frac{1}{\pi} \int_1^y \log \left| \frac{1+\mu}{1-\mu} \right| \frac{d\mu}{\mu}$$

$$= -\frac{1}{\pi} \log |y| \log |x|$$

$$+ \frac{1}{\pi} \int_o^1 \log \left| \frac{1+\mu}{1-\mu} \right| \frac{d\mu}{\mu} - \frac{1}{\pi} \int_o^y \log \left| \frac{1+\mu}{1-\mu} \right| \frac{d\mu}{\mu} \tag{7}$$

Since, $\frac{1}{\pi} \int_o^1 \log \left| \frac{1+\mu}{1-\mu} \right| \frac{d\mu}{\mu} = \frac{\pi}{4}$,[3] (8)

equation 7 can be written:

$$B(x) + B(y) = \pi/4 - \frac{1}{\pi} \log |x| \log |y| \tag{9}$$

where $y = \frac{1-x}{1+x}$.

[3] D. Bierens de Haan, NOUVELLES TABLES D'INTÉGRALES DÉFINIES, Edition of 1867, Corrected, G. E. Stechert & Co., New York, N. Y., 1939, (Table 115, eq. 15, p. 165.)

The table was computed from equation 5 for $0 \leq x \leq 0.45$ and from this series of values the remainder of the table was computed from equation 9 by interpolation with four-point Lagrangian interpolation coefficients.[4] All computations were made to eight decimal places. The computations were checked by constructing a table of horizontal differences and comparing the fourth differences with the differences computed from the derivatives of the function. Since an error of one unit in the last place will cause a maximum error of six in the fourth difference, it was assumed that if the fourth differences were within six of the computed values, the error was not greater than one unit in the last place. The horizontal differences were computed in the following manner.

Horizontal Differences in Terms of the Derivatives

Let a function be tabulated at uniform intervals such that

$$y_o = f(x_o)$$
$$y_1 = f(x_o + h)$$
$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$
$$y_n = f(x_o + nh) \tag{10}$$

Construct a table of horizontal differences:

y_{-2}	Δ^1_{-3}	Δ^2_{-4}	Δ^3_{-5}	.	Δ^n_{-2-n}
y_{-1}	Δ^1_{-2}	Δ^2_{-3}	Δ^3_{-4}	.	Δ^n_{-1-n}
y_o	Δ^1_{-1}	Δ^2_{-2}	Δ^3_{-3}	.	.
y_1	Δ^1_o	Δ^2_{-1}	Δ^3_{-2}	.	.
y_2	Δ^1_1	Δ^2_o	Δ^3_{-1}	.	.
. . .	. . .	. . .	. . .	.	.
y_m	Δ^1_{m-1}	Δ^2_{m-2}	. . .	.	Δ^n_{m-n}

where $\Delta^1_o = y_1 - y_o$, $\Delta^1_1 = y_2 - y_1$, $\Delta^2_o = \Delta^1_1 - \Delta^1_o$, etc.

By Taylor's theorem,

$$y_{-1} = f(x_o - h) = f(x_o) - \frac{h}{1!} f^{(1)}(x_o) + \frac{h^2}{2!} f^{(2)}(x_o) - \frac{h^3}{3!} f^{(3)}(x_o) + \cdots$$

$$y_1 = f(x_o + h) = f(x_o) + \frac{h}{1!} f^{(1)}(x_o) + \frac{h^2}{2!} f^{(2)}(x_o) + \frac{h^3}{3!} f^{(3)}(x_o) + \cdots$$

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[4] New York Mathematical Tables Project, TABLES OF LAGRANGIAN INTERPOLATION COEFFICIENTS, Columbia University Press, New York, N. Y., 1944.

$$y_2 = f(x_o + 2h) = f(x_o) + \frac{2h}{1!} f^{(1)}(x_o) + \frac{4h^2}{2!} f^{(2)}(x_o) + \frac{8h^3}{3!} f^{(3)}(x_o) + \cdots \qquad (11)$$

Let $a_n = h^n \dfrac{f^{(n)}(x_o)}{n!}$. Then equation 11 can be rewritten: (12)

$$\begin{aligned}
y_{-1} &= a_o - a_1 + a_2 - a_3 + \cdots \\
y_o &= a_o \\
y_1 &= a_o + a_1 + a_2 + a_3 + \cdots \\
y_2 &= a_o + 2a_1 + 4a_2 + 8a_3 + \cdots + 2^n a_n + \cdots \\
y_3 &= a_o + 3a_1 + 9a_2 + 27a_3 + \cdots + 3^n a_n + \cdots
\end{aligned} \qquad (13)$$

If these equations (13) are used to compute the horizontal difference table, the horizontal differences can be expressed in terms of the derivatives. Thus the differences with the most rapid convergence are:

$$\Delta^1{}_o = a_1 + a_2 + a_3 + \cdots = \sum_{n=1}^{\infty} a_n$$

$$\Delta^2{}_{-1} = 2\,!\,(a_2 + a_4 + a_6 + \cdots) = \sum_{n=2}^{\infty} \{1 + (-1)^n\}\, a_n \qquad (14)$$

$$\Delta^3{}_{-1} = 3\,!\,(a_3 + 2a_4 + 5a_5 + 10a_6 + \cdots)$$

$$= \sum_{n=3}^{\infty} \{2^n - 3 - (-1)^n\}\, a_n \qquad (15)$$

$$\Delta^4{}_{-2} = 4\,!\,(a_4 + 5a_6 + 21a_8 + 85a_{10} + \cdots)$$

$$= \sum_{n=4}^{\infty} \{(2^n - 4)\,(1 + (-1)^n)\}\, a_n \qquad (16)$$

$$\Delta^5{}_{-2} = 5\,!\,(a_5 + 3a_6 + 14a_7 + 42a_8 + \cdots)$$

$$= \sum_{n=5}^{\infty} \{3^n - (2^n - 5)\,(-1)^n - 5(2^n) + 10\}\, a_n \qquad (17)$$

$$\Delta^6{}_{-3} = 6\,!\,(a_6 + 14a_8 + 147a_{10} + 1408a_{12} + \cdots)$$

$$= \sum_{n=6}^{\infty} \{3^n - 6\,(2^n) + 15\}\,\{1 + (-1)^n\}\, a_n \qquad (18)$$

From these results, any desired order difference can be computed. It is usually best to use even-order differences since the odd-order derivatives are then not required.

After the difference test indicated that the computed values were all within one unit in the eighth decimal place, the values were rounded off to five places. It is therefore hoped that the table is free of error.

Table of $B(x) = \frac{2}{\pi}\int_0^x \frac{\tanh^{-1} t}{t}\,dt$

x	$B(x)$	x	$B(x)$	x	$B(x)$
0.00	0.00000	0.35	0.22599	0.70	0.47573
0.01	0.00637	0.36	0.23265	0.71	0.48365
0.02	0.01273	0.37	0.23932	0.72	0.49164
0.03	0.01910	0.38	0.24601	0.73	0.49970
0.04	0.02547	0.39	0.25273	0.74	0.50784
0.05	0.03184	0.40	0.25946	0.75	0.51605
0.06	0.03821	0.41	0.26621	0.76	0.52436
0.07	0.04459	0.42	0.27299	0.77	0.53275
0.08	0.05097	0.43	0.27978	0.78	0.54123
0.09	0.05735	0.44	0.28661	0.79	0.54981
0.10	0.06373	0.45	0.29345	0.80	0.55850
0.11	0.07012	0.46	0.30032	0.81	0.56730
0.12	0.07652	0.47	0.30722	0.82	0.57622
0.13	0.08292	0.48	0.31414	0.83	0.58526
0.14	0.08932	0.49	0.32109	0.84	0.59445
0.15	0.09573	0.50	0.32807	0.85	0.60378
0.16	0.10215	0.51	0.33508	0.86	0.61327
0.17	0.10858	0.52	0.34212	0.87	0.62293
0.18	0.11501	0.53	0.34919	0.88	0.63278
0.19	0.12145	0.54	0.35629	0.89	0.64284
0.20	0.12790	0.55	0.36343	0.90	0.65313
0.21	0.13436	0.56	0.37061	0.91	0.66368
0.22	0.14082	0.57	0.37782	0.92	0.67452
0.23	0.14730	0.58	0.38507	0.93	0.68569
0.24	0.15379	0.59	0.39237	0.94	0.69724
0.25	0.16029	0.60	0.39970	0.95	0.70926
0.26	0.16680	0.61	0.40708	0.960	0.72183
0.27	0.17332	0.62	0.41450	0.970	0.73513
0.28	0.17985	0.63	0.42197	0.975	0.74213
0.29	0.18640	0.64	0.42948	0.980	0.74942
0.30	0.19296	0.65	0.43705	0.985	0.75708
0.31	0.19954	0.66	0.44467	0.990	0.76527
0.32	0.20613	0.67	0.45234	0.992	0.76873
0.33	0.21273	0.68	0.46008	0.994	0.77236
0.34	0.21935	0.69	0.46787	0.996	0.77620
0.35	0.22599	0.70	0.47573	0.998	0.78036
				1.000	0.78540

ELECTRONIC COUNTERS*

By

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Summary—The use of resistance-coupled multivibrators is described and two types of electronic counter chains are discussed. The requirements of the "gate" circuits are given. The operation of the latest design of decade or a unit counter chain is described in detail and some applications are suggested.

Introduction

THE general principles of counting by means of electronic circuits have been known for some time. An electronic counter of one type or another has often been used either as a part of equipment in which it lost its identity, or as a useful tool of secondary importance in obtaining other information. The reason for its obscurity has lain in the fact that the electronic counters have not been able to single out a particular count; that is, the counter indication has been either average or approximate. This article deals with one particular type of electronic counter, which not only shows every individual count but, also, is capable of indicating the count as a number. A resistance-coupled multivibrator has been chosen as the basic unit counter because it provides the greatest convenience and reliability in operation and is economical in the number of component parts.

Multivibrator

The properties of the resistance-coupled multivibrator which make it useful for counter work can be briefly summarized by the following statements:

(a) The resistance-coupled or untuned multivibrator has two stable positions, which can be reversed by the application of a driving pulse (counting pulse).

(b) There is an upper limit in the frequency response (speed of counting) but no lower limit for a multivibrator having certain parameters.

(c) The multivibrator is equally responsive to either a periodic

* Decimal Classification: R621.375.2.

(constant) or a random rate of count.

(d) The multivibrator can store and indicate but one count, and only one meaning can be attached to that count.

Figure 1 shows several forms of resistance-coupled multivibrators, the difference being in the manner and the point of application of the counting information (Point A).

Multivibrator *a* is used in the ring counter chains. It receives the

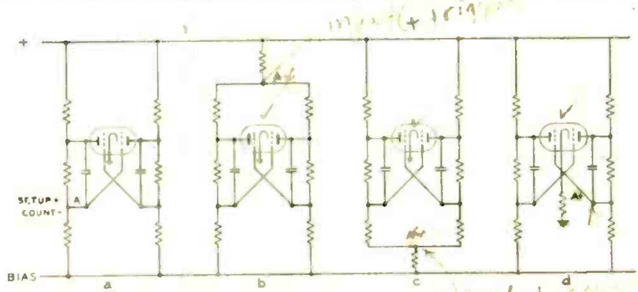

Fig. 1—Resistance coupled multivibrators.

counting information directly from the source and in parallel with other multivibrators in the same chain, but is set up in the receptive position indirectly by the count in the preceding multivibrator. It serves as the basis of the unitary system of counting.

Multivibrators *b*, *c*, and *d* are used in the series counter chains. They receive the counting information from each other, effectively

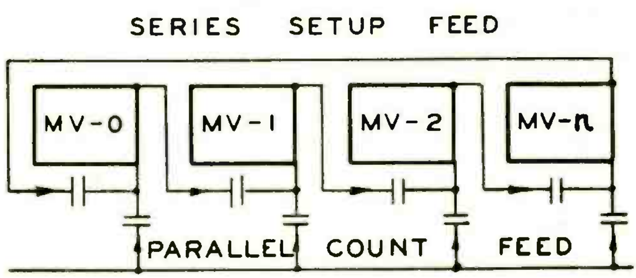

Fig. 2—Ring chain.

divide it by two, and thus serve as the basis of the binary system of counting.

Chains

The ring chain is made up of several multivibrators connected in parallel to a source of counting pulses and in a closed series circuit for the purpose of setting up. The chain is shown schematically in Figure 2. Here one multivibrator is energized in a sense opposite to the others. This is the one which would respond to the counting signal, trip over and set up the following multivibrator in a position to receive the next counting signal.

The capacity of a ring chain is limited to the number of multivibrators in it. A ring chain is usually arranged for a count of ten, thus forming the basis for a decimal system of indication. The count of ten also can be obtained by dividing the chain into two subchains, having capacities of two and five respectively.

The count of ten can be established by connecting the subchains in series and obtaining the answer by the process of multiplication

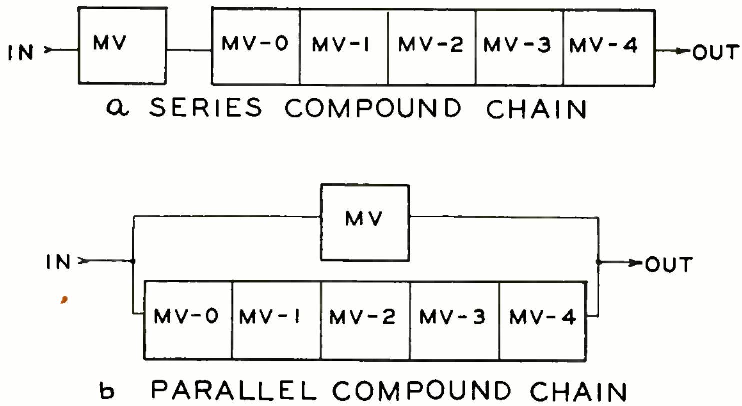

Fig. 3—Compound chains.

(two × five), or by connecting the subchains in parallel and obtaining the count of ten by coincidence of five two's and two five's (See Figure 3).

In a series chain each preceding multivibrator drives the following one at a half rate, the counting pulse being applied to the head multivibrator only.

The series chain is usually referred to as a binary counter (See Figure 4). Its capacity is 2^n where n is the number of multivibrators. The practical use of a binary chain is complicated by the necessity of transforming the binary indications into the decimal system. It will be shown that a binary chain can be broken up into sections corresponding to the places in the decimal system with direct indication of every digit.

Binary Decade

The decade consists of a binary chain of four resistance-coupled multivibrators. The multivibrators count by two's, each following multivibrator counting and storing two counts of the preceding one. Hence, the natural count of a chain of four would be sixteen.

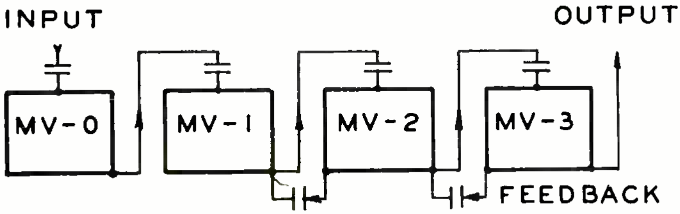

Fig. 4—Series of binary chain.

However, by feeding back it is possible to make certain multivibrators retain their instantaneous position which is, in effect, equivalent to advancing the count. By advancing the count by a total of six counts, the natural count of the chain is changed from sixteen to ten.

Whenever feedback is applied to a multivibrator it advances the count of the chain by the natural count of that multivibrator.

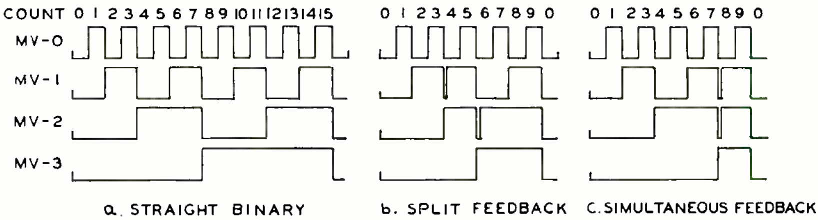

Fig. 5—Application of feedback to binary chains.

The operation of a binary decade can be readily understood by realizing that the count of ten contains only two factors: two and five. Factor two is taken care of by one multivibrator, preferably MV-0. Although MV-3 could be used, it is less desirable because in this case MV-1 would receive the feedback at a higher frequency of operation. The remaining three multivibrators MV-1, MV-2 and MV-3 reduce the count by the factor of five.

Figure 5(a) shows the progression of count in a binary chain. Figures 5(b) and 5(c) show two ways in which the application of the feedback produces a count of ten in the same chain. In the case of Figure 5(b), MV-1 receives the feedback at the count of four and MV-2 at the count of six. In Figure 5(c), MV-1 and MV-2 receive the feedback simultaneously at the count of eight. The scheme shown in Figure 5(b) is preferable because of the ease in which the indications can be obtained.

The count is indicated by means of neon lamps which receive the proper voltages through the resistance network (see Figure 6). The network is arranged in such a way that only one lamp corresponding to the count can be lighted. One side of each lamp is connected in five groups of two's as follows: 0-1, 2-3, 4-5, 6-7, 8-9 and the other side in

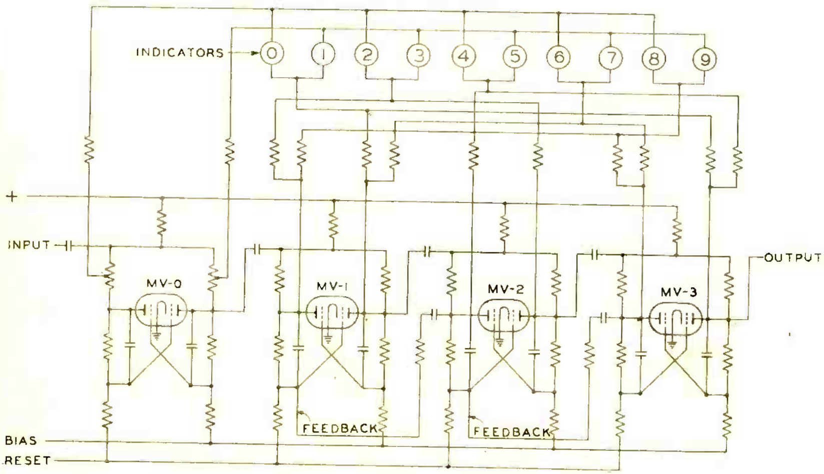

Fig. 6—Binary decade.

two groups of five's: 0-2-4-6-8 and 1-3-5-7-9. Selection of the odd or the even group is made by the head multivibrator MV-0, the selected group receiving the full positive plate potential, while the other group receives one half. The selection of groups of two's is accomplished by a combination of two plate voltages received from the plates of other multivibrators, the selected group receiving the full negative potential. Only one group of two's receives that potential for any combination of multivibrator positions. The voltage output of the resistance network for selection of indication is shown in Figure 7.

Figure 8 shows the potentials applied across lamp 0 for all the counts from 0 to 9. The solid line is the resultant potential derived from the plates of MV-1 and MV-3. The broken line suggests the half voltage gain obtained from a plate of MV-0. The shaded area shows the maximum voltage applied to the lamp. This voltage occurs only at a count of 0. Similar diagrams can be derived from the other lamps.

Gate

The gate is an electronic switch between the counter and the source of the signals to be counted. Functionally, the gate can be described

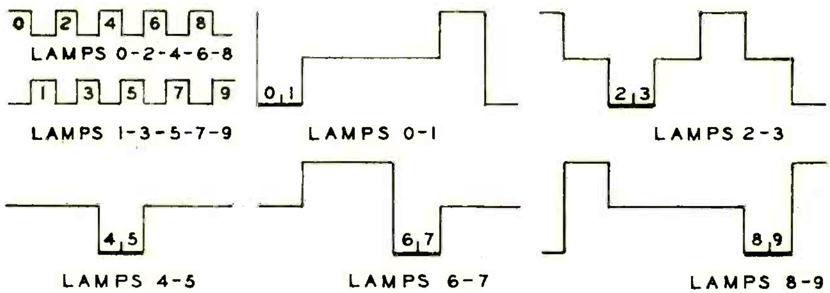

Fig. 7—Derivation of indications in binary decade.

as a mixer between two sets of unrelated signals, one set being the signals counted while the other set represents the time during which the count takes place. The time element at the gate is represented by an equivalent square wave. The gate may be one or more tubes. It is usually associated with some kind of switching circuit which opens and closes the gate in response to the timing signals.

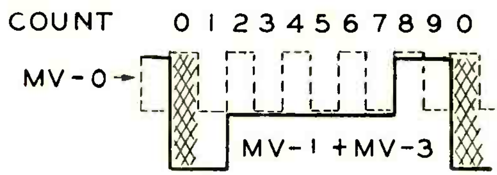

Fig. 8—Derivation of "0" indication in binary decade.

Switching Problems

The most important problem of switching is the reproduction of the desired time interval as a perfect square wave applied at a gate. Other problems, operational in nature, are: a provision for switching by signals originating from a single source, which involves interlocking; lockout features to prevent reopening of the gate; locking out of the "OFF" circuit for a period shorter than the anticipated time interval; and prevention of the switching signals from entering the counter.

Method of Producing the Square Wave

The leading and trailing edges of the square wave are produced independently by means of two multivibrators which are tripped in

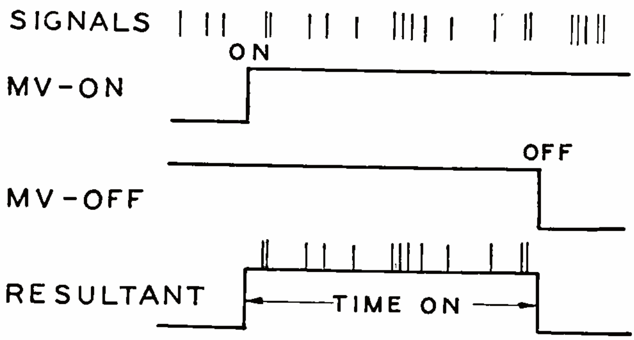

Fig. 9—Method of mixing timing and count signals.

response to the timing signals. The action of the multivibrators is not reversible in the sense that they remain in the newly assumed position until reset for the next operation. Figure 9 shows the components of the square wave contributed by the "ON" and "OFF" multivibrators.

The output of the "ON" and "OFF" multivibrators may be conveniently represented as in Figure 10 by means of plus and minus

	STANDBY	ON	OFF
MV-ON	$-$	$+$	$+$
MV-OFF	$+$	$+$	$-$
RESULTANT	$\mp$	$\overset{+}{+}$	$\pm$

Fig. 10—Potentials for opening and closing the gate.

signs, two plus signs representing the counter in a running position. The output of the multivibrators may be applied to one or two points along the counter amplifier, but always in such a way as to produce no extra count.

Methods of Combining the Output of Multivibrators

One of the early switching circuits shown in Figure 11 made use of a duo-diode to combine the output of the "ON" and "CFF" multivibrators, the grid of the mixer being brought up to the cutoff voltage, permitting the counted frequency signals to appear at the plate of the mixer, but not producing any extra counts. Later, a double triode was used (Figure 12) to obtain the same results. Capacitors connected to the grids are used to compensate for the time dissymmetry arising from the production of positive and negative potentials in the multivibrators and circuits. This dissymmetry eventually places a limit on the shortest time interval that can be resolved by a switching circuit.

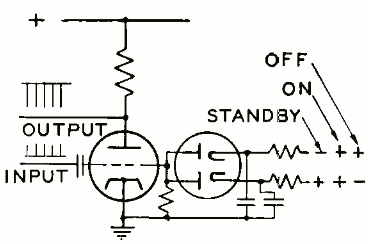

Fig. 11—Duo-diode method of switching.

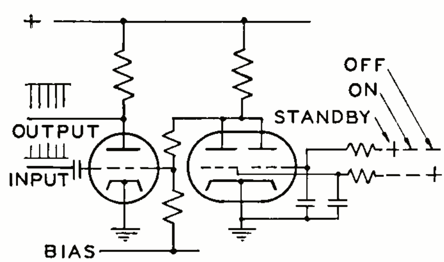

Fig. 12—Double triode method of switching.

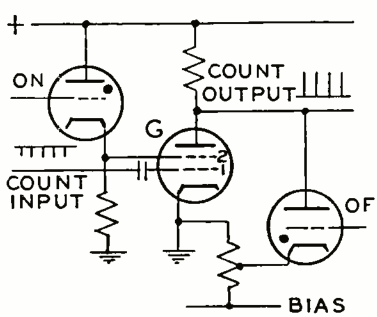

Fig. 13—Switching by gas tubes.

The speed characteristics of switching circuits can be greatly improved by substituting gas tubes in place of multivibrators as shown in Figure 13. The gate tube "G" is biased off by grid 2 until the gas tube "ON" establishes conduction, and the negative count pulses at grid 1 appear as positive at the plate. Gas tube "OFF" stops the count pulses from getting through the gate by shorting its plate to ground. Both "ON" and "OFF" signals received by "G" from the gas tubes appear as negative pulses at the output. Therefore, they do not affect the count.

Applications of Electronic Counters

The applications of electronic counters can be roughly divided into three groups. In group one, an electronic counter is used as a time measuring device. Group two deals with straight counting. Group three is a combination of groups one and two.

An electronic counter excited from a source of constant frequency has been successfully used as a chronograph for measuring short time intervals to a high degree of precision. The same counter can also be used for production of a controlled time interval. By appropriate selection of exciting frequency the counter can be applied to systems such as Loran or Shoran for direct indication in units of distance.

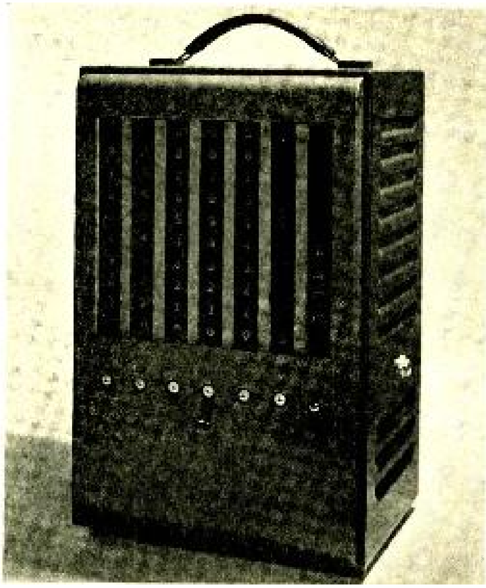

Fig. 14—A current model of the electronic counter.

An electronic counter can be used for speeds higher than those obtainable from electro-magnetic or mechanical devices and can be made to send a signal after a definite number has been counted off.

By combining a measuring device (such as a photocell, microphone, pressure gage or the like) with a variable frequency oscillator, an electronic counter can be used as an integrator for evaluating a variable function. Again, by selecting the proper frequency, the counter can be made to indicate in any desired units.

A combination of a counter producing a time interval, together with a straight counter can be used as a frequency meter.

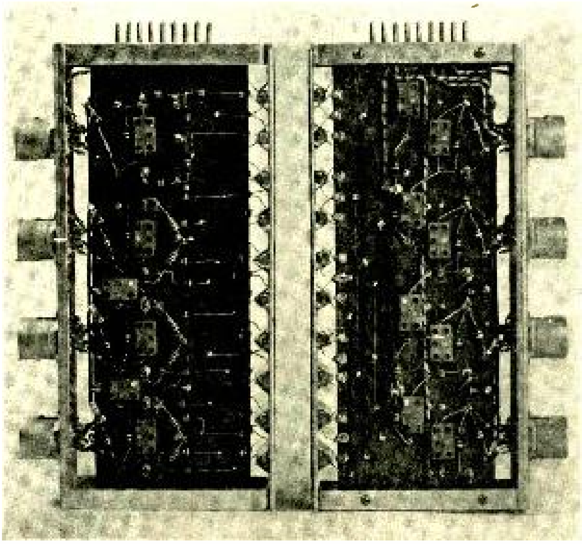

Fig. 15—Binary decade, view of both sides.

Figure 14 shows a current model of the electronic counter. Figure 15 is a view of both sides of a binary decade used in the model shown.

TECHNICAL PAPERS BY RCA AUTHORS†

Second Quarter, 1946

Any requests for copies of papers listed herein should be addressed directly to the publication to which credited.

T. J. Boerner—"Filament Supply in the BTA-50F Transmitter", *Broadcast News*, June, 1946.

C. H. Brereton—see J. B. Knox, "A Multi-Channel VHF Radio Communications System".

G. H. Brown and W. C. Morrison—"The RCA Antennalyzer", *Broadcast News*, June, 1946.

D. G. Burnside—see R. R. Law, "Development of Pulse Triodes and Circuit to Give One Megawatt at 600 Megacycles".

T. J. Buzalski—"A Method of Measuring the Degree of Modulation of a Television Signal", RCA REVIEW, June, 1946.

R. O. Drew and S. W. Johnson—"Preliminary Sound Recording Tests with Variable-Area Dye Tracks", *Jour. Soc. Mot. Pict. Eng.*, May, 1946.

G. L. Fredendall—see R. D. Kell "An Experimental Color Television System".

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D. B. Langmuir with (OSRD—formerly with RCA Laboratories Division) —see L. Malter, "Methods of Minimizing Lead Loss in Emissivity and Resistivity Determinations".

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S. M. Zollers—see R. G. Picard, "A Reliable High Vacuum Gauge and Control System".

NOTE—Omissions and errors in these listings will be corrected in the yearly Index.

Correction:

On page 243 of the June 1946 issue, Reference 9 should read as follows:

[9] "Present and Proposed Allocations Channels 30-40 Mc band 250 Channels 40 Kc Wide", RTPB Panel 13 Document dated March 12, 1946.

CONTRIBUTORS TO THIS ISSUE

ELIZABETH TAYLOR BUSH (Mrs. Robert R. Bush) received her B.A. in chemistry at Mount Holyoke College in 1944. In that year she joined the research staff of RCA Laboratories Division in Princeton, N. J., where she has been working in the field of microwave spectroscopy.

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LESLIE E. FLORY received his B.S. degree in Electrical Engineering from the University of Kansas in 1930. In the same year he joined RCA Manufacturing Company at Camden, N. J., conducting research on television tubes and related electronic problems. In 1942, he transferred to RCA Laboratories Division at Princeton, N. J., continuing work on electronic tubes and special circuit applications. Mr. Flory is a Member of Sigma Xi and a Senior Member of Institute of Radio Engineers.

STANLEY V. FORGUE received his B.S. degree in physics in 1939 and the B.E.E. and M.S. degrees in 1940 from Ohio State University. He was a graduate assistant in the Physics Department of this university from 1939 to 1940. While taking additional graduate work, he was a research engineer at the Ohio Engineering Experiment Station from 1940 to 1941 and a research fellow in the Ohio State Research Foundation from 1941 to 1942. Since then he has been with Radio Corporation of America at Harrison and Princeton, N. J. Mr. Forgue is a Member of the Institute of Radio Engineers, the American Physical Society, Sigma Xi, Tau Beta Pi and is a Registered Professional Engineer.

IGOR E. GROSDOFF received the degree of E.E. in 1926 from Columbia University. From 1927 to 1930 he was with the Westinghouse Company in East Pittsburgh, Pa. In 1930 he joined RCA Manufacturing Company at Camden, N. J. In 1932 he was with the Franklin Institute in Philadelphia as physicist, returning to Radio Corporation of America in 1936. He is at present with RCA Laboratories Division in Princeton, N. J. Mr. Grosdoff is a Member of Sigma Xi.

CLARENCE W. HANSELL received the B.S. degree in electrical engineering from Purdue University in 1919. He was employed by the General Electric Company in 1919-1920. He joined Radio Corporation of America in 1920 and in 1929 was associated with RCA Communications, Inc., in connection with the development and design of radio transmitting equipment. In 1942, he was transferred to the Radio Systems Research Laboratory, RCA Laboratories Division at Rocky Point, L. I., N. Y. Mr. Hansell was the recipient of a "Modern Pioneer" Award from the National Association of Manufacturers in 1940. He is a Member of the American Institute of Electrical Engineers, Franklin Institute, Electrochemical Society, the American Association for the Advancement of Science, and a Fellow of the Institute of Radio Engineers.

WILLIAM D. HERSHBERGER received the A.B. degree in 1927 from Goshen College, the A.M. degree in 1930 from George Washington University and the Ph.D. degree in physics from the University of Pennsylvania in 1937. From 1927 to 1931 he worked on supersonics at the Naval Research Laboratory, and from 1931 to 1936 at the Signal Corps Laboratories, where he was responsible for the work on target detection with microwaves. He was a Harrison fellow in Electrical Engineering at the University of Pennsylvania in 1936-1937 and joined the Radio Corporation of America in 1937, where he has been associated, first, with the work on radio altimeters and airborne radar and, more recently, on topics in spectroscopy at microwave frequencies. Dr. Hershberger is a Member of the American Physical Society, a Senior Member of the Institute of Radio Engineers and a Member of Sigma Xi.

RAY D. KELL received his B.S. degree in electrical engineering from the University of Illinois in 1926. From 1927 to 1930 he was engaged in television research in the radio consulting laboratory of the General Electric Company. From 1930 to 1941 he was a member of the research division of RCA Manufacturing Company, and since 1941 he has been with RCA Laboratories Division. He received the "Modern Pioneer" Award from the National Association of Manufacturers in February, 1940, for inventions in television. Mr. Kell is a member of Sigma Xi and an Associate Member of the Institute of Radio Engineers.

HAROLD B. LAW received the B.S. degree from Kent State University in 1934, and at the same time, the B.S. degree in education. In 1936, he was granted the M.S. degree, and in 1941 the Ph.D. degree in physics from Ohio State University. He taught elementary mathematics at Maple Heights, Ohio, in 1935 and in Toledo, Ohio, in 1937 and 1938. In 1941, he joined Radio Corporation of America, and at present is associated with the RCA Laboratories Division in Princeton, N. J. Dr. Law is a member of the American Physical Society and Sigma Xi, and a Senior Member of the Institute of Radio Engineers.

GEORGE W. LECK received his education at the Drexel Institute of Technology, taking courses in Electrical Engineering. He joined the Radio Condenser Corp. of Camden, N. J., in 1932 and was in charge of calibrating test equipment. From 1936 to 1941 he was a Member of the research division of the RCA Manufacturing Company. Since 1941, he has been with RCA Laboratories Division. Mr. Leck has been an active amateur radio operator for many years and is a Member of Sigma Xi.

LEWIS MALTER received the B.S. degree from the College of the City of New York in 1926 and the M.A. and Ph.D. degrees in physics from Cornell University in 1931 and 1936, respectively. He taught physics at the College of the City of New York from 1926 to 1928. He was with the Acoustic Research and Photophone Divisions of Radio Corporation of America from 1928 to 1930, and during the summer of 1931. From 1933 to 1942, he was with RCA Manufacturing Company at Camden, N. J., and from 1942 to 1943 with RCA Laboratories Division at Princeton, N. J. From 1943 to 1946, he was in charge of the Special Development Division of RCA Manufacturing Company at Lancaster, Pennsylvania. Since May, 1946, he has been in charge of the Vacuum Tube Research Section of the Naval Research Laboratory, Washington, D. C. Dr. Malter is a Fellow of the American Physical Society, a Senior Member of the Institute of Radio Engineers, a Member of the American Association for the Advancement of Science, and a Member of Sigma Xi.

LEROY MOFFETT received his B.S. degree in Electrical Engineering from the University of Oklahoma in 1929. He was employed by the S. W. Bell Telephone Company, and then as radio engineer by Station WKY. In 1931, he became a Studio Engineer for Station WENR. He transferred to the Development Group of the National Broadcasting Company in March 1937, to engage in television development. In November 1942, he entered the Navy to engineer television projects for the Aircraft Radio Section of the Bureau of Ships in Washington, D. C. Lieut. Comdr. Moffett was the Officer-in-Charge of Project RING, and other RCA developments for the Navy. He returned to the Development Engineering Group of NBC in February, 1946. He is an Associate Member of the Institute of Radio Engineers, a licensed Professional Engineer in the State of New York, and has held amateur and commercial radio operators licenses since 1920.

JOHN L. MOLL received the B.S. degree in Engineering Physics from Ohio State University in 1943 and joined the RCA Victor Division the same year. At present, he is doing graduate work in mathematics at Ohio State University. He is a Member of Tau Beta Pi and the American Mathematical Society.

GEORGE A. MORTON received his B.S. in Electrical Engineering in 1926; his M.S. in 1928 and his Ph.D. in Physics in 1932 from Massachusetts Institute of Technology. From 1927 to 1933 he was research associate and instructor at Massachusetts Institute of Technology. In 1933 he became a Member of the research division of RCA Manufacturing Co., working in the field of electronics and television, and from 1941 to the present time has been with RCA Laboratories Division. During the war, he also served as a Section Member of the National Defense Research Committee and consultant for the AAF Scientific Advisory Group. Dr. Morton is a Member of Sigma Xi and the American Physical Society, and Member of the Institute of Radio Engineers.

ROBERT E. SHELBY received his B.S. degree in electrical engineering and B.A. and M.A. degrees from the University of Texas. He joined the National Broadcasting Company, Inc., in 1929 in the Engineering Department, serving in various positions connected with television. He is now the Director of Technical Development on all technical phases of the company's activities in AM and and FM sound broadcasting, transcription recording, acoustics and television. He is a member of Tau Beta Pi and Phi Beta Kappa, and Associate Member of Eta Kappa Nu and Sigma Xi, a Senior Member of the Institute of Radio Engineers, and Member of the American Institute of Electrical Engineers and of the Society of Motion Picture Engineers.

FRANK J. SOMERS received the degree of B.S. in electrical engineering, from the University of Santa Clara in 1930. From 1930 to 1932 he was a Member of the Technical Staff of the Bell Telephone Laboratories. From 1932 to 1933 he attended the Graduate School of Electrical Engineering at Stanford University and from 1933 to 1938, he was employed as a development engineer on electronic television systems by Farnsworth Television, Inc. In 1938, he became a member of the television Development Group of the National Broadcasting Company. During World War II he worked on several military research and development projects undertaken by the National Broadcasting Company and was Project Engineer on the RING television reconnaissance equipment. In July 1945, he was appointed a Staff Engineer of the National Broadcasting Company assigned to television systems development. Mr. Somers is an Associate Member of the Institute of Radio Engineers and is a licensed Professional Engineer in the State of New York.

GEORGE C. SZIKLAI was born in Budapest, Hungary, on July 9, 1909. He received his absolutorium (equivalent to the M.S. degree) in 1930 from the Pazmany University of Budapest. He was an exchange student at the Technische Hochschule in Munich, Germany, in 1920. In 1931 he joined the Aerovox Corporation, where he became assistant chief engineer. He was the chief engineer of the Polymet Manufacturing Corporation from 1932 to 1935. During 1934, Mr. Sziklai spent a half year in Europe providing consultation to Electrical Component Manufacturers in London and Paris. From 1935 to 1939 he was on the research staff of the Micamold Radio Corporation. He joined the industry service division of Radio Corporation of America in 1939, and later transferred to the Bloomington plant. Since 1942, he has been in the television research section of the RCA Laboratories Division at Princeton, N. J. Mr. Sziklai is a Senior Member of the Institute of Radio Engineers, a Member of the American Physical Society and of Sigma Xi, and an Associate Member of the Optical Society of America.

PAUL K. WEIMER received the B.A. degree from Manchester College in 1936, the M.A. degree in physics from the University of Kansas in 1938, and the Ph.D. degree in physics from Ohio State University in 1942. While at Ohio State University, he was a graduate assistant in physics. During 1936 and 1937, he was a graduate assistant in physics at the University of Kansas. From 1937 to 1939, he taught physics and mathematics at Tabor College, Hillsboro, Kansas. Since 1942, he has been engaged in television research at RCA Laboratories Division at Princeton, N. J. Dr. Weimer is an Associate Member of the Institute of Radio Engineers, a Member of the American Physical Society, and a Member of Sigma Xi.

VLADIMIR KOSMA ZWORYKIN received the degree of electrical engineering from the Petrograd Institute of Technology in 1912, was a student in Coll. de France, Paris, from 1912 to 1914, received the Ph.D. degree from the University of Pittsburgh in 1926, and the D.Sc. degree from the Brooklyn Polytechnical Institute in 1938. In 1920, he joined the Research Division of Westinghouse Electric and Manufacturing Company, and since 1929 has been associated with Radio Corporation of America as Director of Electronic Research with RCA Manufacturing Company from 1929 to 1942, and, from 1942 to 1946, with RCA Laboratories Division in Princeton, N. J. In 1934, Dr. Zworykin was awarded the Morris Liebmann Memorial prize for contributions to the development of television. In 1940, he received a "Modern Pioneers" Award from the American Manufacturers' Association, and in 1941, the Rumford Medal, awarded by the American Academy of Arts and Sciences. Dr. Zworykin is a Fellow of the following societies: Institute of Radio Engineers, American Institute of Electrical Engineers, American Physical Society, American Association for the Advancement of Science, Franklin Institute, Electron Microscope Society of America, and Sigma Xi. He is a Member of the National Academy of Sciences, the American Academy of Arts and Science, and the French Academy of Science.

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