Transmission and Reception of Centimeter Radio Waves

Progress in the field of electronic oscillations—Description of transmitting and receiving equipment—Transmitter modulation—Operation and results—Uses and applications

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THIS article will outline a new system of transmitting and receiving centimeter radio waves—that is, wavelengths from 1 to 10 centimeters. It should be considered merely as a progress report in the very complex and as yet little understood field of electronic oscillations. In all pioneer fields, we have to get along as best we can without a complete theory or accurate quantitative measuring devices.

Transmitter

Historically we start from Zacek's[1] discovery that electronic oscillations may be produced in Hull's[2] simple cylindrical Magnetron tube. In the present case the electronic oscillations are generated in a specially designed, long, single-anode Magnetron tube with short concentric axial filament. FIG. 1 shows the construction and principal dimensions of the latest water-cooled tube of this type.

The field structure, shown in FIG. 2, consists essentially of a pair of truncated conical iron pole pieces with axial holes through the center to house the tube. This construction provides the necessary axial magnetic field over the active central portion of the Magnetron filament. It has a further important feature, namely, that the field is released beyond the useful central portion, which means that the spiralling electrons will go to the plate and not give puncture trouble at the ends of the tube. The desired airgap flux density is here obtained from large Alnico permanent magnets as shown. A 3 to 1 variation in air gap flux density is provided by the magnetic shunt.

The cooling water is circulated in the annular space between the copper anode and pole pieces. A flange gasket is provided at the back end and a soft rubber expansion gasket at the front end of the tube.

The small iron ring shown around the air gap is used to improve the flux distribution in the active part of the field, thereby greatly increasing the output

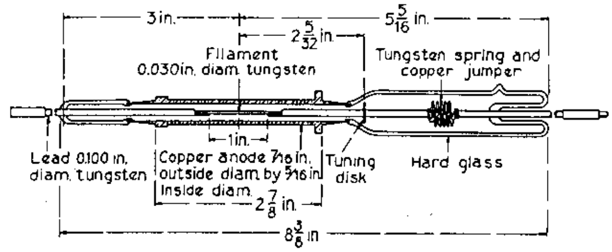

Fig. 1. Cross-section of Magnetron tube for centimeter radio waves

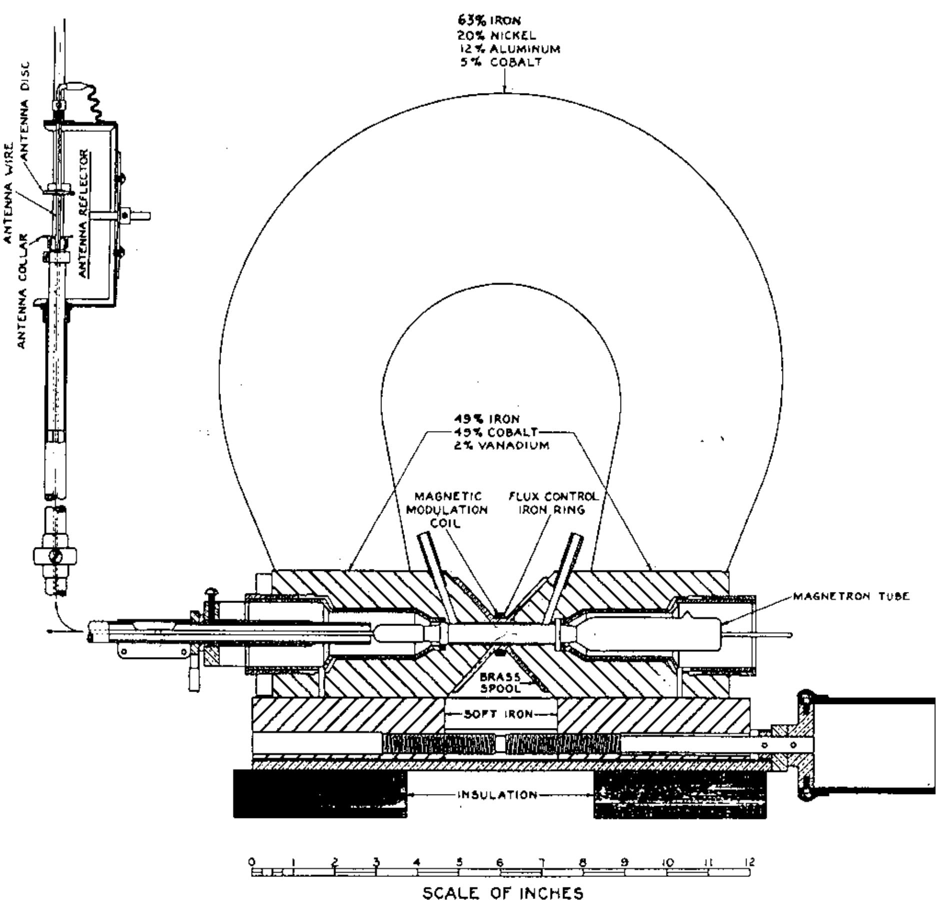

Fig. 2. Sketch of transmitter for centimeter radio waves

(1) A. Zacek: Casopis pro Pestovani Mathematiky a Fysiky (Prague), vol 53, 1924, p. 378. (Summary in *Zeit. fur Hochfrequenz-technik*, vol. 32, 1928, p. 172)

(2) "The Effect of a Uniform Magnetic Field on the Motion of Electrons Between Claxial Cylinders," by A. W. Hull, *Physical Review*, vol. 18, no. 1, July 1921, pp. 31-57.

and efficiency of the tube. For example, a 13-fold increase in output was made possible when the small iron ring was inserted.

If the filament current, anode voltage, magnetic field shape and intensity are properly adjusted, strong electronic oscillations will appear on the filament and leads. The disk shown at the back end of the tube in FIG. 1 is provided to reflect the power and thereby eliminate back end losses. At the front end the power is transmitted out over the concentric transmission line formed by the concentric tube and filament lead extension. The front end seal is placed at an approximate potential node to reduce the loading effect and losses.

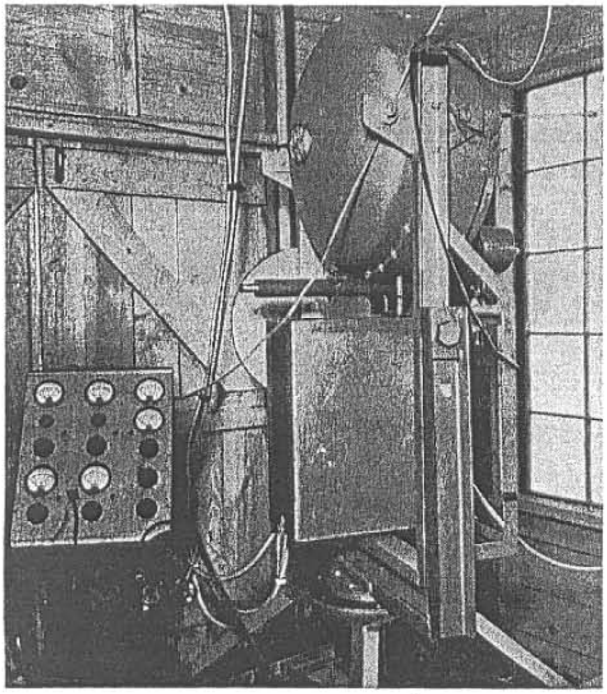

Fig. 3. The transmitter for centimeter radio waves in position for transmission

This *filament swing* circuit has been found very effective when excited by electronic oscillations produced by a Magnetron tube as outlined, as well as an ideal arrangement when excited by B-K[3] electronic oscillations. In the latter case, a long, sturdy grid and plate permit large heat dissipation without introducing detrimental capacity loading effects.

The high heat-dissipating properties, rugged simplicity, and ideal circuit conditions of the filament-swing circuit should appeal to those who have worked with the "see-saw" circuits required by split-anode Magnetrons and conventional B-K tubes. Here the problems of heat dissipation, inter-electrode capacities, and difficult mechanical constructions impose serious limitations on power output in the centimeter-wavelength band—that is, 1 to 10 centimeters.

The convenient type of radiator which is now being used is made as shown in FIG. 2 by ending the outer tube of the concentric transmission line and exposing approximately a quarter wavelength of the filament lead; the latter is terminated for the radio frequency by a tuning disk which slides on the filament lead. The antenna length is kept constant when tuning by means of a slide tube which fits the outer transmission-line tube and is coupled to the disk mechanically by insulation. The metal collar on the end of the slide tube was added to make the radiation-directive

(3) "Die kürzesten, mit Vakuumröhren herstellbaren Wellen," by H. Barkhausen and K. Kurz, *Physikalische Zeitschrift*, vol. 21, no. 1, 1920, pp. 1-6.

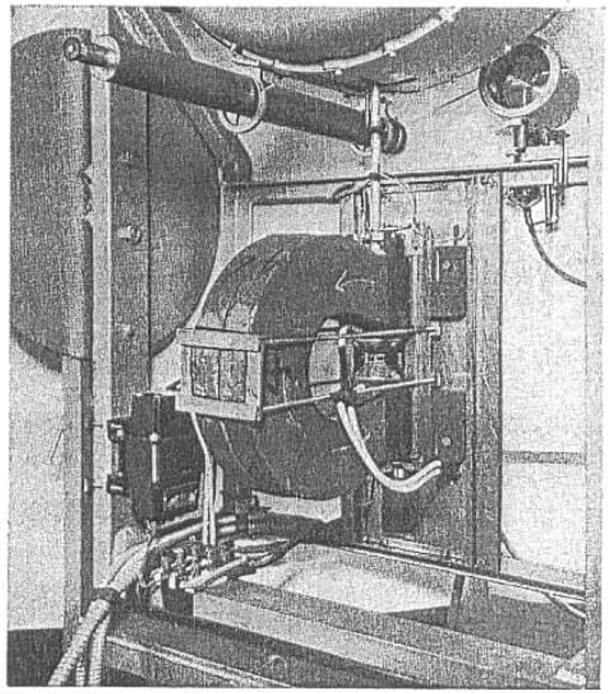

Fig. 4. The transmitter for centimeter radio waves showing the Magnetron tube field structure and the tube monitor

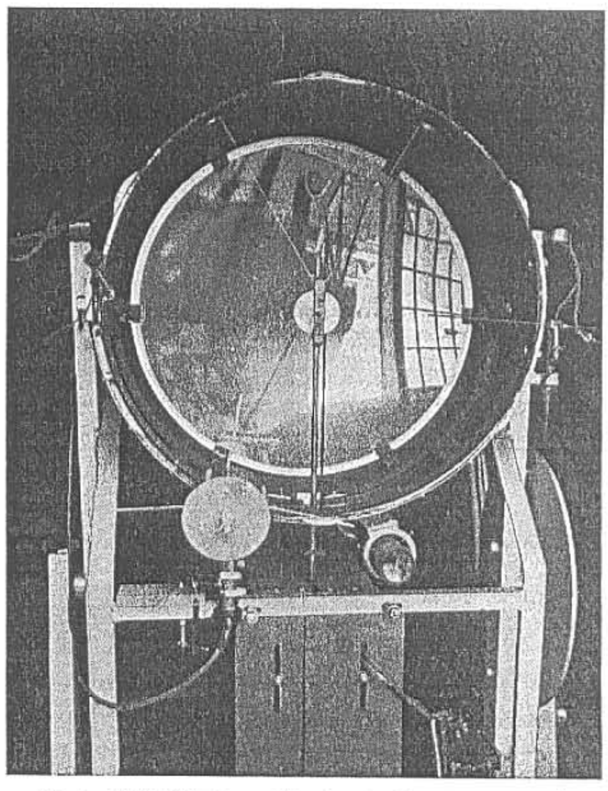

Fig. 5. View of the transmitter showing the antenna, crystal, and tube monitors

curve of the antenna more symmetrical. A small circular plane reflector is placed at approximately a quarter wavelength in front of the radiator to give it unidirectional characteristics. The metal frame which carries this circular plane reflector serves also to carry the filament current back down the outer tube of the concentric transmission line. This simple radiator is then placed approximately at the optical focus of a suitable parabolic mirror.

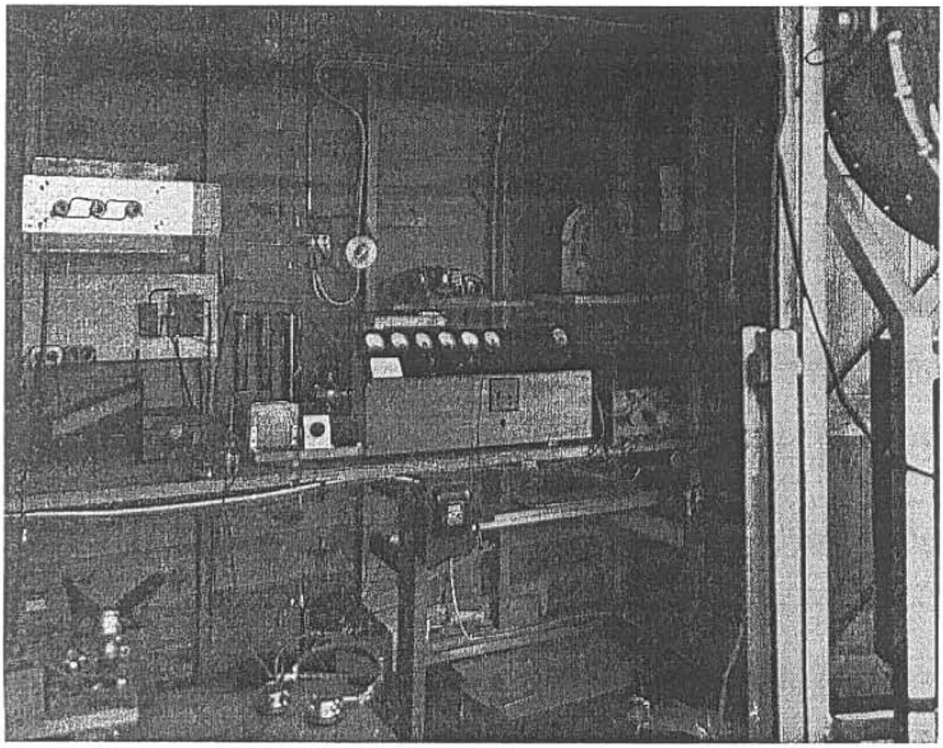

Fig. 6. The modulated power supply unit for the centimeter-wave transmitter

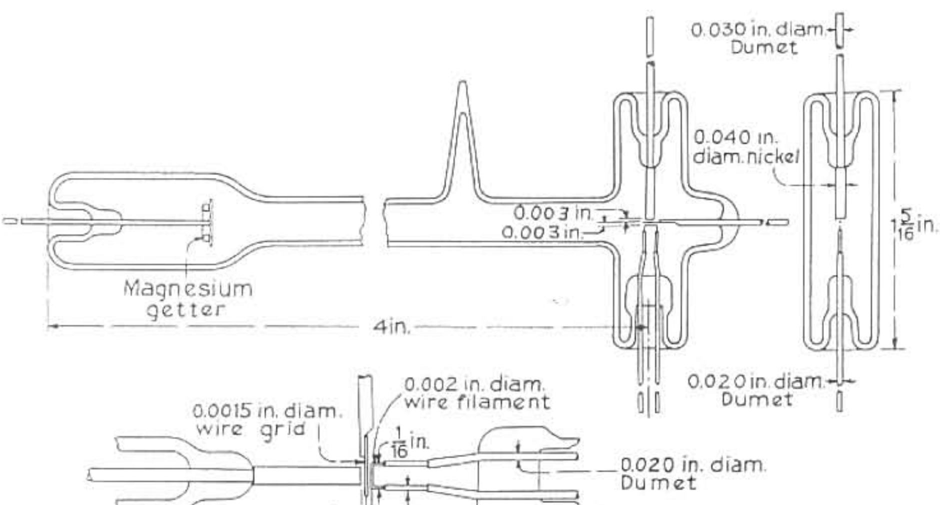

Fig. 7. Cross-section of three-element tube for centimeter-wave reception

The present set-up utilizes a 24-in. diameter, 10½-in. focal length, metal parabolic mirror mounted in a standard airport beacon.

FIG. 3 shows the transmitter as set up in a shack on top of the Research Laboratory at Schenectady (N. Y.).

FIG. 4 shows a close-up view of the transmitter with cover removed.

FIG. 5 is a view looking into the parabolic mirror.

FIG. 6 shows the modulated power supply.

Receiver

The receiving tube is a specially designed three-element tube which is capable of oscillating at the wavelength which is being received. The oscillations appear to be of the B-K electronic type. FIG. 7 shows the construction and principal dimensions of our present tube.

The filament consists of a 0.002-in. diameter U-shaped tungsten wire; the grid is a single 0.0015-in. diameter tungsten wire placed approximately halfway between the flattened bottom of the U-shaped filament and the plate. The plate is merely the flat end of a 0.040-in. diameter nickel wire. The grid and active portion of the filament—that is, the bottom of the U—are parallel. A long side tube with a getter bulb at the bottom is provided to take care of seal-off gas. This construction allows the getter to be well out of the focus of the receiving mirror. This tube, by reason of its mechanical arrangement, may be thought of as a wedge-shaped section of a conventional cylindrical B-K tube.

In operation the grid is made positive and the plate negative with respect to the negative end of the filament. The rectified output appears across an impedance which is placed in the grid circuit.

The two parallel filament leads pass straight through a press seal at one end of the tube and the plate lead passes out in line at the opposite end. The grid comes in at the side and is therefore perpendicular to the filament and plate leads. Tuning is accomplished by three small disks which slide on the filament, grid, and plate leads. One of the holes in the filament disk is brushed with insulation to prevent short-circuiting the filament.

The tube is supported on a convenient insulating frame which is arranged to place the active ends of the grid, filament, and plate at the approximate focus of a parabolic mirror. The present set-up is shown in Figs. 8 and 9.

For good reception of weak signals it is necessary properly to tune grid, plate, and filament leads with the small sliding disks and properly to adjust the values of grid and plate potentials and filament current. When thus adjusted the receiver appears to be working on the self-quenching super-regenerative principle.

If the transmitter antenna is vertical—that is, electric vector vertical—good reception is obtained with the grid of the receiving tube vertical. There are other angular relations which give good results when both the mechanical and electrical tunings are properly adjusted.

We first proved that these small B-K tubes were capable of oscillating at the fundamental of the wavelength to be received by listening to what we have called *hiss points*. For example, if we set up one of these tubes in its bakelite frame in front of a plane reflector, everything being first adjusted properly, and then move a second plane reflector back and forth in front of the tube a hissing is heard, which starts and stops at what we assume to be every half wavelength. We may also measure the wavelength without the use of the second reflector by finding a series of *hiss points* on the grid lead, for instance, as we slide the tuning disk out from the tube. Similar series can also be found on the filament and plate leads by careful adjustment of electrical and mechanical tunings.

The wavelengths measured in this way correspond roughly to those obtained from the simple B-K[3] equation $\lambda = 1000\ D_p/\sqrt{E_g}$, where D_p is taken as twice the distance from the center of the filament to the plate in centimeters, and E_g is the grid voltage in volts. Applying this equation to our present tube, we obtain λ calc. $= 3.5$ cm for $E_g = 104$ volts, whereas the wavelength determined by reception is $\lambda = 4.8$ cm. We have no wavelength data on this tube by the hiss-point method.

Besides the *hiss points*, one will find also what we call *audio howl points*. These appear to be strong radio-frequency oscillations which start and stop at an audio-frequency period.

The receiver development was done in collaboration with Mr. Garret A. Hobart, 3d.

Transmitter Modulation

Good tone, voice, and music modulation can be obtained by modulating the Magnetron anode voltage. To obtain good quality with 100 per cent modulation it is necessary to have the transmission line and antenna properly adjusted as well as the correct values of mean anode voltage and filament current. Where very high quality is required it may be found desirable to compensate the impressed modulation voltage so as to correct some residual curvature in the Magnetron tube modulation characteristic.

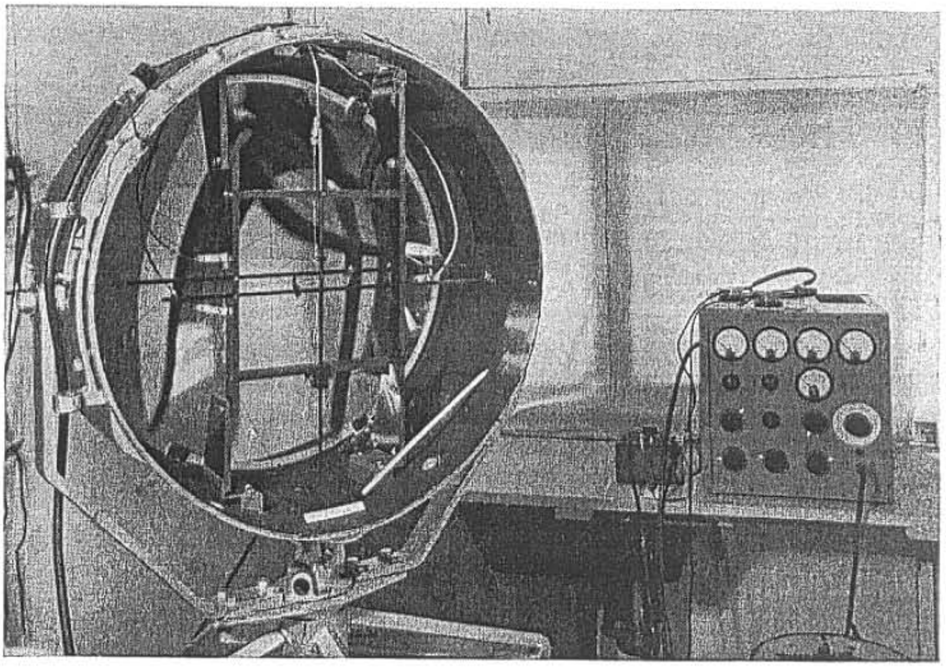

Fig. 8. Receiver for centimeter radio waves showing the tube and mirror

We have also found two types of *magnetic modulation*, that is, a variation in the radio-frequency output caused by a change in the air-gap flux distribution.

The first type occurs when the filament is excited from alternating current. That the effect was not due to mechanical vibration or heating was proved by the fact that when heating currents of different frequency were used (60 cycles to 400 cycles) the resulting percentage modulation remained constant when observed in the d-c amplified oscillographic output obtained from an untuned crystal detector. In our present tube, operating with a filament current of 35 amp, the peaks measured 16 mm and the valleys 11 mm or $2.5/13.5 = 18.5$ per cent modulation. If the effect had been due to mechanical vibration or heating we would expect to find that the percentage modulation would fall off at the higher frequencies.

The second type of magnetic modulation was obtained by winding a small 20-turn single-layer coil of 0.013-in. diameter insulated copper wire directly on the brass spool which spaces the pole pieces. The position of this modulating coil is indicated in FIG. 2 under the flux control iron ring. A 60-cycle current of 2 amp in this coil gave practically 100 per cent modulation. Modulation from WGY was surprisingly good in spite of the drooping frequency characteristic caused by the shielding action of the brass spool and thick copper anode. A great improvement in the quality and efficiency of this type of modulation could, of course, be obtained by using an insulating compound for the spool and a high-resistance anode material, such as german silver.

The sensitivity of our present set-up to the flux distribution in the air gap would appear to account for the ease with which magnetic amplitude modulation is obtained.

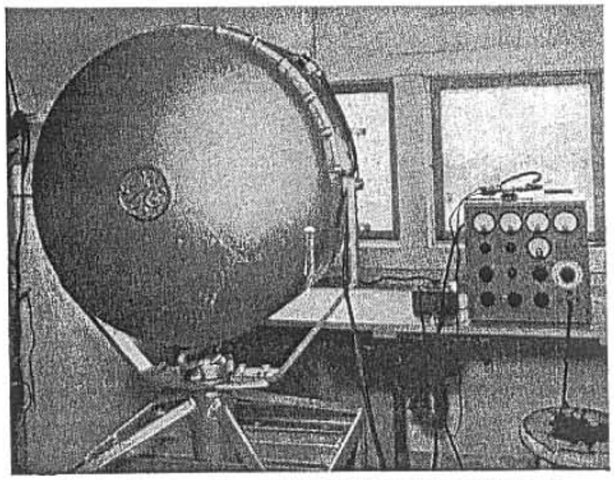

Fig. 9. Receiver for centimeter radio waves in position to receive 4.8-cm radio waves

Results

Line-of-sight propagation tests over a distance of 6½ miles, using 4.2-cm waves, have shown, as might be expected, that the signal strength is not materially affected by time of day, temperature, wind, fog, very heavy rain, sleet, or snow. We have not yet had an opportunity to observe the effect of hail, but presumably very large hailstones (a centimeter or more in diameter) which occasionally occur would appreciably scatter a 4.2-cm wavelength beam.[4]

Later, a new transmitter was designed for a wavelength of $\lambda = 4.8$ cm and gave about 10 times the power output. We chose the slightly longer wavelength in order to reduce the duty on our receiving tubes.

The following are the transmitter settings used to obtain high-quality modulation:

The air-gap flux density, measured ballistically by withdrawing a small single-layer coil ¼ in. diameter by ¼ in. long from the center of the air gap, is $B=$ 3300 lines per sq cm. If we insert this value of B in the simple wavelength equation[1] $\lambda H = \text{constant}$, we obtain $\lambda H = 15{,}850$. The plate voltage is 3050 volts; plate current, 0.115 amp; filament current when oscillating, 32.5 amp; modulation voltage for 100 per cent, 1000-cycle tone, is 1000 volts rms. The cooling water flow was approximately 1.3 gallons per minute and temperatures varied from 15 C to 20 C.

The mechanical settings were as follows: Antenna length between antenna disk and transmission line collar, 1.3 cm; antenna disk at 76.8 cm from center of Magnetron tube filament; small plate reflector 3 in. in diameter at 1.1 cm from center of 0.100-in. diameter antenna wire. Other mechanical settings are fixed in this tube and are given in FIG. 1. The center of the antenna was placed at 10½ in. from the center of a 24-in. diameter metal parabolic mirror as previously described.

We estimate that the radiated power, with the foregoing settings, is roughly three watts, which corresponds to a plate efficiency of about one per cent, and that the maximum power which we have obtained from this tube is about 10 watts. A small 400-ohm carbon-filament lamp (that is, a thermocouple heater with the couple burned off) can be lighted to full brilliancy of 0.4 watt when one of the leads is brought up to about 2.0 mm from the antenna wire. The radiation is not much affected by this additional load. The tip of one's finger gets uncomfortably hot if touched against the antenna wire. These rough power output estimates may be in error by 2 to 1 more.

The corresponding receiver settings for the present tube are: Grid voltage, 104 volts; grid current, 1.19 ma; plate voltage, −34.2 volts; filament current, 1.02 amp; grid lead tuning disk at 3.35 cm from center of filament; filament disk at 3.35 cm from end of filament; plate disk at 4.8 cm from end of filament. The filament of the tube was placed at 10¼ in. from the center of a 24-in. diameter metal parabolic mirror, as previously described. The other mechanical specifications of the receiving tube have already been given in FIG. 7.

In the recent tests the grid of the receiving tube was vertical and the transmitting antenna was also vertical. At present we are not using a small reflector in front of the receiving tube, although we have used it on previous occasions with beneficial results.

The voltage generated across the receiving tube grid circuit impedance was as follows:

Signal and noise 1000-cycle tone	= 0.05 volts
Noise (modulation removed)	= 0.0008 volts
Signal-to-noise ratio	= 62.5

Very good quality speech and music were obtained by rebroadcasting WGY over the beam system. With the stated noise ratio, there was practically no background noise present. Tone telegraph was readily obtained by keying the grids of the modulator tubes.

The divergence of the beam, obtained by swinging the transmitter sideways and up and down, was approximately 2½ deg either side of the center or a

(4) "The Effect of Rain and Fog on the Propagation of Very Short Radio Waves," by J. A. Stratton, *Institute of Radio Engineers*, vol. 18, no. 6, June 1930, pp. 1064-1074.

total divergence of 5 deg. The receiver was equally sharp by the same test.

The transmitter output was monitored by the small galena crystal detector, seen at the right in FIG. 5, or with one of our B-K tubes mounted in a shielded container, shown in the lower left-hand corner. The front view of the tube monitor is clearly seen at the upper right-hand corner in FIG. 4. Tuning disks are provided, as already described, on the leads. An adjustable plane reflector is provided back of the tube and the front is covered with a thin mica window and *polarized shield*, which can also be moved in and out for tuning purposes. This type of housing effectively shields the tube from all extraneous disturbances, permitting the entrance of only properly polarized centimeter waves.

When used as a monitor on strong signals we prefer to select one of the less sensitive low-voltage operating points. For example, we are now using the following values: grid voltage, 12.5 volts, plate at zero volts; grid current, 0.5 ma; filament current, 0.975 amp.

Wolf, Linder, and Braden[5] state that, when properly adjusted, their split-anode Magnetron tube can be used as a sensitive detector for centimeter waves. We also found, early in our work, that our filament-swing-type of Magnetron tube constituted a very sensitive type of receiver.

FIG. 10 shows the arrangement of one of our early trough set-ups which was used for transmission and reception experiments. Here, a half-wave antenna of the conventional type is coupled to the trough tank circuit. Air- and radiation-cooled Magnetron tubes which were symmetrical at both ends, except for a small jumpered filament spring at one end, were used. The field was excited dynamically and a heavy copper short-circuiting spool was provided to steady the air-gap flux density.

FIG. 11 shows the Magnetron transmitter and Magnetron receiver. Because of fluctuations of the field currents, which caused the signal to drift in and out, this set-up did not give good results. Later, excellent results were obtained when two permanent-magnet machines were used.

The action appears to be the same as that obtained with the three-element B-K tubes, namely, a self-quenching super-regenerative action.

Our next series of tests was to bring the transmitter and receiver together for the purpose of working on *radio searchlight* problems—that is, the detection and location of stationary or moving objects by reflected and scattered radiation. We also contemplate measuring distances by *radio echoes*. The transmitter and receiver were mounted side by side in the small shack on top of the Research Laboratory, a height of approximately 135 ft. From this position we were able to locate moving automobiles on a neighboring road at distances up to 1¼ miles by the Doppler effect. Some interesting field fluctuations produced by moving bodies have previously been recorded by other observers.[6] *Doppler detection* results from the beats produced between the outgoing transmitter frequency ν and the reflected or scattered radiation which comes back from the moving object with the frequency $\nu_1 = \nu\left(\frac{1 \pm 2\ v \cos\alpha}{c}\right)$ where $v \cos \alpha$ is the component of

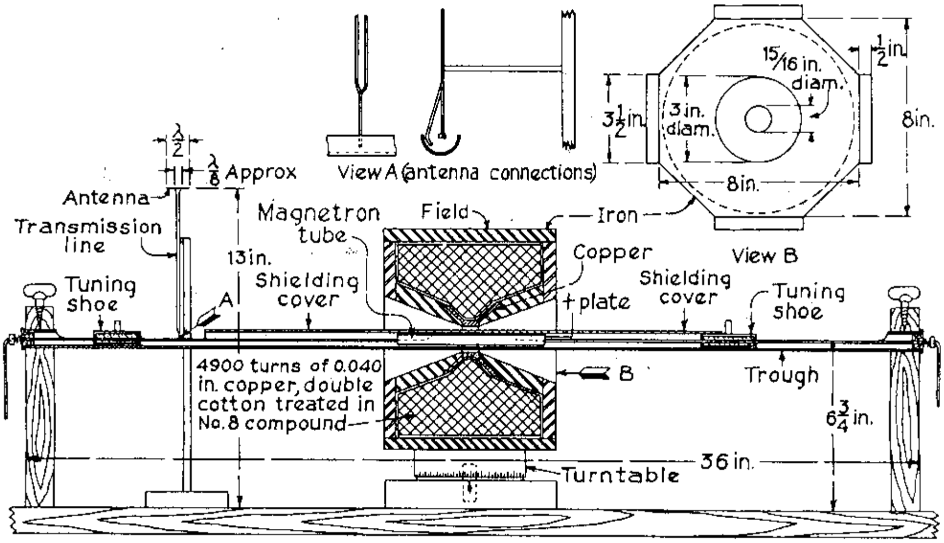

Fig. 10. Trough set up for transmission and reception with centimeter radio waves

velocity along the line of sight between the transmitter and receiver and c is the velocity of light. The resulting beat frequency f produced in the receiver is $f = 2\ v \cos \alpha/\lambda$. In the case of an automobile moving on the road at 30 miles per hour and making an angle of 45 deg to the normal, we have for our wavelength of $\lambda = 4.8$ cm, $f = 2 \times 1340 \times 0.707/4.8$ or $f = 395$ cycles.

The amount of transmitter-frequency power supplied to the receiver was adjusted by varying the sizes and positions of small reflectors which were arranged to feed power from the transmitter to the receiver. When working with Doppler detection the transmitter is, of course, not modulated.

The detection of stationary objects can be accomplished by modulating the transmitter and then adjusting the compensation so as to neutralize the stray modulation when the distant object is out of the field. If, now, a distant object is brought into the field, its presence will be evident because of a reappearance

[5]"Transmission and Reception of Centimeter Waves," by I. Wolff, E. G. Linder, and R. A. Braden, *Institute of Radio Engineers*, vol. 23, no. 1, January 1935, pp. 11-23.

[6]"Some Results of a Study of Ultra-Short-Wave Transmission Phenomena," by C. R. Englund, A. B. Crawford, and W. W. Mumford, *Institute of Radio Engineers*, vol. 21, no. 3, March 1933, pp. 464-492.
Taylor, Young, and Hyland, U.S. Patent No. 1,981,884, filed June 13, 1933; issued November 27, 1934.

of the modulation due to the change in the amount and phase of the reflected and scattered radiation.

In the case of moving objects, there is, besides the modulation due to the Doppler effect, what might be called *chopper modulation*—that is, a variation of scattered and reflected radiation. We observed this effect very clearly when listening to a small 6-bladed paddle wheel or Soroco type of fan which was mounted on the top of a nearby building. The fan was run at 1750 rpm and had the following approximate dimensions: Outside diameter of blade circle, 8 in.; inside diameter of blade circle, 5 in.; blade length parallel to shaft, 4 in. The radial blades were almost flat. The chopper frequency of $f = 1750 \times 6/60 = 175$ cycles was about equal in loudness to the Doppler frequency caused by the linear blade velocity, namely, $f = 2\pi \times 6.5 \times 2.54 \times 1750/60 \times 4.8$, or 632 cycles.

Our next test was to see how far we could pick up a small open Waco biplane which ran toward and away from us. The plane had the usual fabric construction and a two-bladed metal propeller. The pilot ran at 1750 rpm or 90 miles per hour air speed. The day was calm. The Doppler frequency of 1680 cycles was clearly detected out to about one mile. We did not hear the propeller *chopper frequency* of 58 cycles. The fact that we did not hear the low frequency was probably due to the low phone sensitivity at this frequency, combined with the presence of some low-frequency background interference due to transmitter vibration.

Applications

In conclusion it may be of interest to list some of the applications which become possible with the advent of *radio optics*.

(*1*). Point-to-point beam communication.
(*2*). Wide side-band communication over a chain of automatically repeating beam stations spaced 15 to 20 mi apart. This might be termed a *radiation transmission line.* This type of line would appear to be a practical way of distributing television.
(*3*). *Fog light* for navigational purposes.
(*4*). Airplane landing beams and direction markers.
(*5*). All-weather airway beacons.
(*6*). Radio-beam protection of drawbridges, harbors, etc.
(*7*). *Doppler detection* of moving objects including relative line-of-sight velocity and distance.
(*8*). Airplane ground speed indicator using Doppler detection.
(*9*). Radio searchlight using modulation.
(*10*). Radio-echo altimeter.
(*11*). Radio-echo locator for navigation.

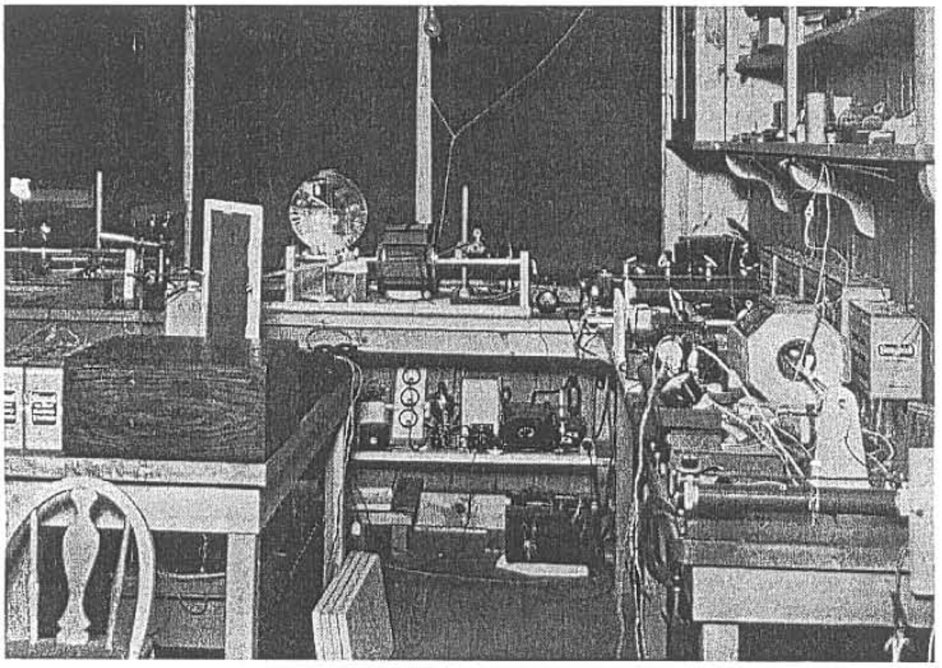

Fig. 11. Magnetron tube transmitter and receiver for centimeter radio waves

ACKNOWLEDGMENTS

Dr. J. D. Tear collaborated with the writer in the early part of the transmitter development. He was able to obtain 1-cm waves by using a filament-swing Magnetron tube with dynamic field excitation.

The early receiving tube work was done jointly with Mr. Garret A. Hobart, 3d. More recently Mr. W. C. Hahn has joined the writer in further studies and improvements of both the transmitting and receiving apparatus.

We also wish to acknowledge the skill and helpful suggestions contributed by many members of the Research Laboratory and of the Vacuum Tube Engineering Department.