BEAM TRANSMISSION OF ULTRA SHORT WAVES*

By

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Summary—*Part I of this paper is devoted to a description of various experiments performed at wavelengths below 200 cm. Curves are given to show the effect of the earth and various types of inductively excited antennas called "wave directors." Part I is concluded with a discussion of beam and horizontally polarized radiation.*

Part II is devoted chiefly to the magnetron tubes used for the production of very short wavelengths (as low as 12 cm.) and the circuit arrangements employed. It is shown that the geometry of the tube and its external connections are of great importance.

The effect of variation of plate voltage, magnetic field strength and other factors on the high-frequency output, is described.

Introduction

THE general term "short wave" loses much of its lucidness when the range of frequency involved is considered. For this reason, the term "ultra short waves" will apply to only those electro-magnetic waves whose length is less than ten meters.

One of the simplest ways of generating short waves by means of vacuum tubes is to use the push-pull circuit developed by M. Mesny. This connection has been fully described by Mr. Englund in the PROCEEDINGS of the Institute.

Waves shorter than ten meters may be produced with stability, but it is difficult to make ordinary tubes operate satisfactorily below two meters. While electro-magnetic coupling is successfully used in the method referred to above, it seems much better to resort to electrostatic coupling in circuits used for the generation of waves of the length described in this paper. Fig. 1 shows a circuit which has been used in the generation of waves shorter than 100 cm.

Stable oscillations were successfully produced using ordinary tubes in this circuit. Such waves have been utilized to determine the natural frequencies of the various forms of metallic bodies. The characteristics of "wave directors", which will be fully described later in the paper, were thoroughly studied with the short waves produced using this type of generator. However, it was

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impossible to generate waves shorter than 60 cm. even with this circuit using electrostatic coupling within the tubes.

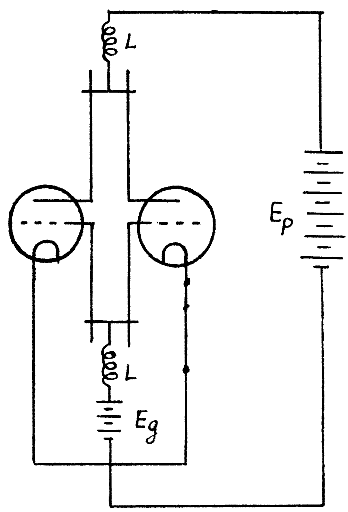


Fig. 1—Circuit Diagram of Oscillator; 60-200 cm.

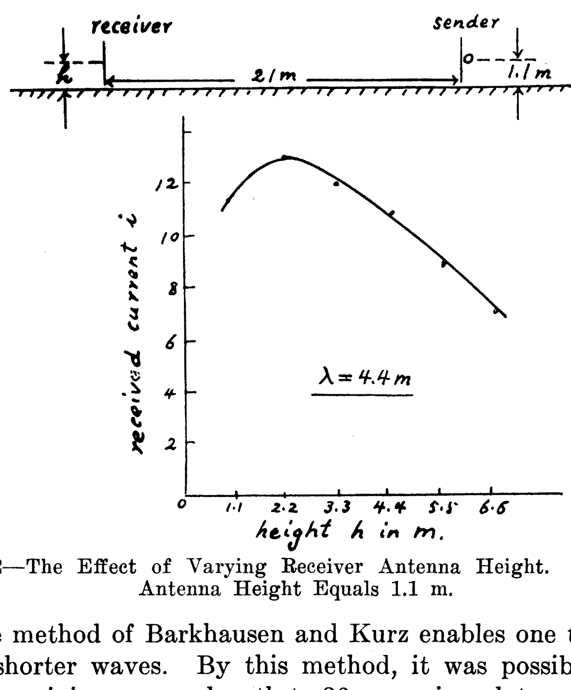


Fig. 2—The Effect of Varying Receiver Antenna Height. Sending Antenna Height Equals 1.1 m.

The method of Barkhausen and Kurz enables one to obtain much shorter waves. By this method, it was possible to reduce the minimum wavelength to 36 cm. using plate voltages in the order of 300 volts. Schafer and Merzkirch obtained waves of the order of 34 cm. with a plate voltage of 350 volts, and Scheibe has reported a stable minimum of 30 cm. With somewhat less stability, he has produced waves 24 cm. long.

Mr. K. Okabe, assistant professor at the Tohoku Imperial University, has succeeded in generating exceedingly short, sustained waves by introducing certain modifications in the so-called magnetron. These waves are the shortest which it has been

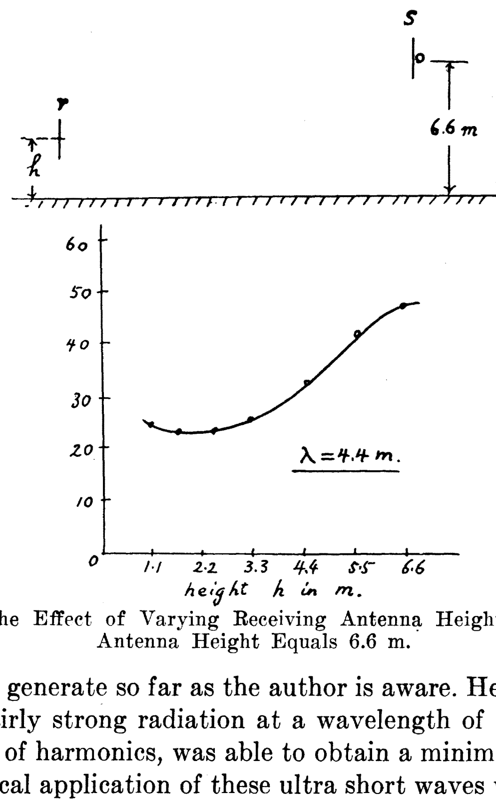


Fig. 3—The Effect of Varying Receiving Antenna Height. Sending Antenna Height Equals 6.6 m.

possible to generate so far as the author is aware. He was able to produce fairly strong radiation at a wavelength of 12 cm. and, by the use of harmonics, was able to obtain a minimum of 8 cm. The practical application of these ultra short waves will be dealt with in Part II of the paper.

Part I

Beam Radiation for 4-Meter Waves

Mr. S. Uda, assistant professor at the Tohoku Imperial University, has published nine papers in the *Journal* of the I.E.E. of Japan on beam radiation at a wavelength of 4.4 meters. Several papers by Mr. Uda and the author have been presented at the Imperial Academy of Japan and the Third Pan-Pacific Science

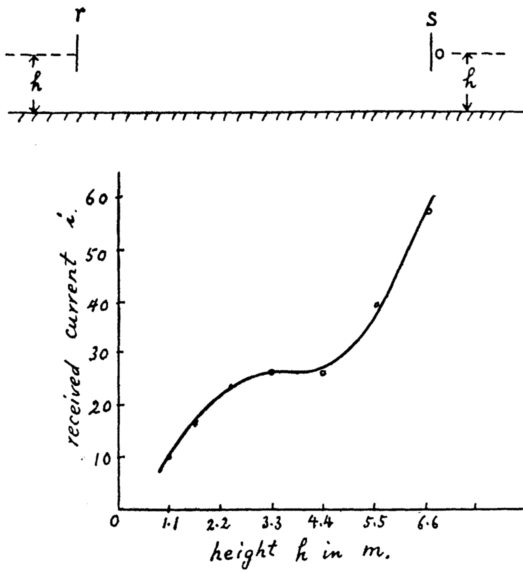


Fig. 4—The Effect of Varying Both Sending and Receiving Antenna Height Simultaneously.

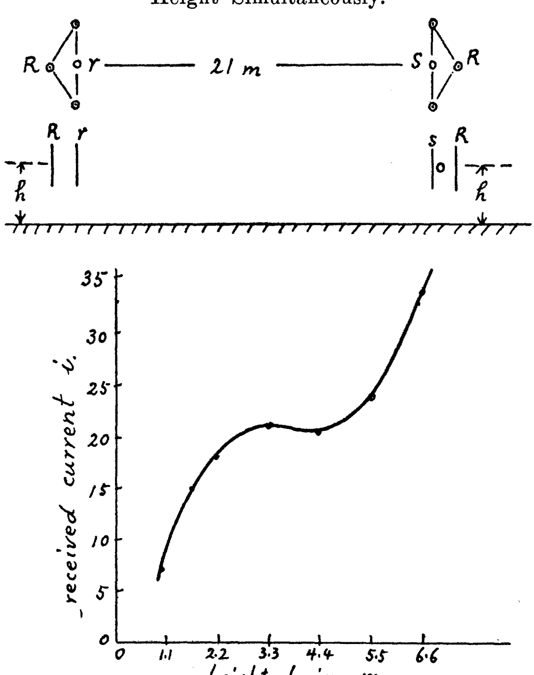


Fig. 5—The Effect of Providing Sending and Receiving Antenna in Fig. 4 with Trigonal Reflectors.

Congress held in Tokyo in 1926. In the following description, some of the much more notable points of the beam system used in this work will be explained. The photographs show some of the actual apparatus used.

WAVE REFLECTORS AND DIRECTORS

Suppose that a vertical antenna is radiating electro-magnetic waves in all directions. If a straight oscillating system, whether it be a metal rod of finite length or an antenna with capacities at

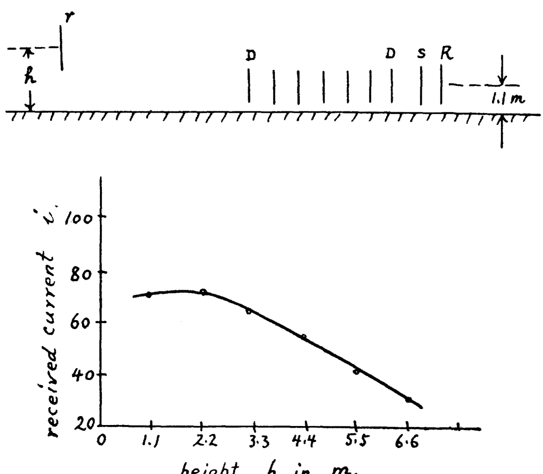


Fig. 6—The Effect of Varying Receiver Antenna Height When Wave Canal Is Applied at Sending Antenna. Sending Antenna Height Equals 1.1 m.

both ends and an inductance at the middle, is erected vertically in the field, the effect of this oscillator upon the wave will be as follows: If its natural frequency is equal to or lower than that of the incident wave, it will act as a "wave reflector." If, on the other hand, its natural frequency is higher than that of the incident wave, it will act as a "wave director." The field will converge upon this antenna, and radiation in a plane normal to it will be augmented. By utilizing this wave-directing quality, a sharp beam may be produced.

A triangle formed of three or five antennas erected behind the main or radiating antenna will act as a reflector. This system will be called a "trigonal reflector." In front of the radiating antenna, a number of wave-directors may be arranged along the line of propagation. By properly adjusting the distance between the wave-directors and their natural frequencies, it is possible to transmit a larger part of the energy in the wave along the row of directors. Adjustment of the natural frequency of the directors is made by simply changing their length or by adjusting the inductance inserted at the middle of these antennas.

The number of wave-directors has a very marked effect on the sharpness of the beam, the larger number of directors producing the sharper beam. It has been found convenient to designate such a row of directors as a "wave canal."

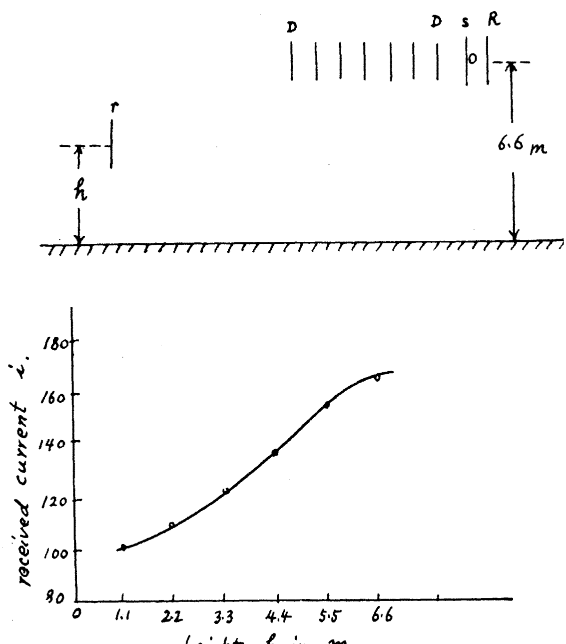


Fig. 7—The Effect of Varying Receiver Antenna Height When Wave Canal Is Applied at Sending Antenna. Sending Antenna Height 6.6 m.

The trigonal reflector and wave canal may also be employed at the receiving station. In this case, the reflector will be called "collector." Here again, the effect of the directors and the wave canal has been found to be considerable.

Radio Beacon

These principles may be used in a radio beacon, by which a beam may be projected in any direction. This is not done by altering the position of the antennas or by revolving the whole system. A number of antennas which are fixed in position are employed and so arranged that their natural frequencies may be altered between two values. Thus, it may be made either a reflector or a director, depending upon its natural frequency.

The main or radiating antenna is situated at the center, and the others which are used for reflecting or directing the beam are located on two concentric circles whose radii are 1/4 and 1/2

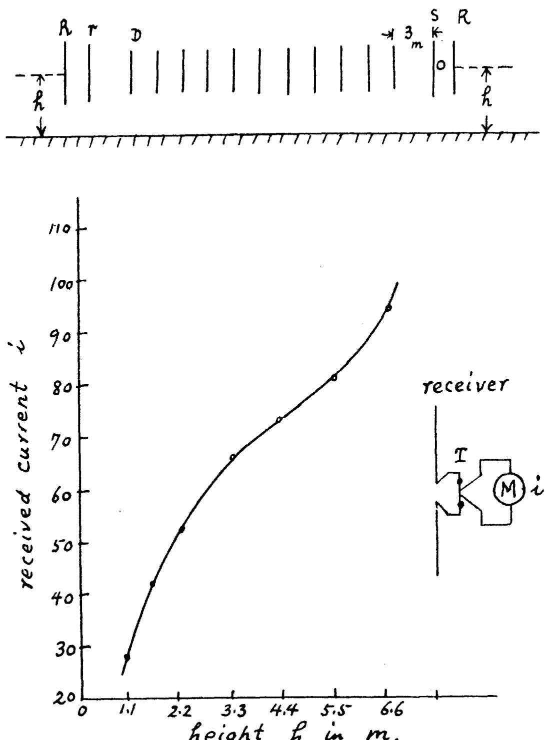


Fig. 8—The Effect of Varying Sending and Receiving Antenna Simultaneously When Wave Canal Is Located between Two Antennas.

wavelength respectively. The direction of radiation may be changed at will by properly controlling the functions of the antennas on these two concentric circles; that is, certain of them are made to act as reflectors while others are made to act as directors of the electro-magnetic wave.

Radio Beacon Transmission

If the sending and the receiving antennas are both surrounded by reflecting systems, and these two structures, which

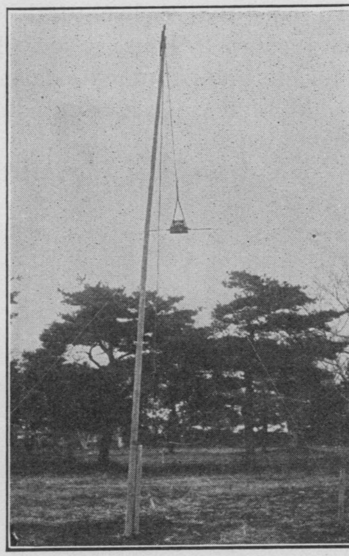


Fig. 9—Horizontally Polarized Wave Receiver in the Air.

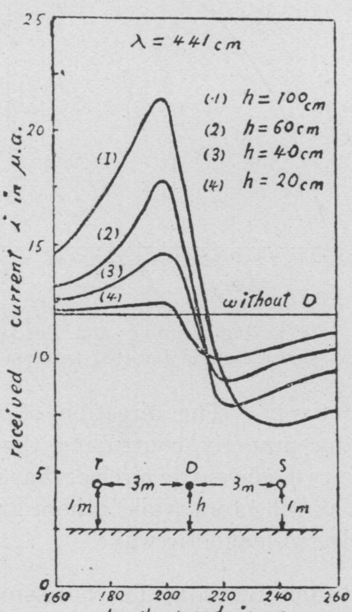
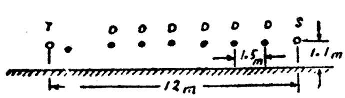


Fig. 10—The Effect of Varying Length and Height of Wave Director on Received Current.

are directed toward one another, are joined by a wave canal, the radio-frequency energy may be directed back and forth along this canal. All the directors forming the canal will have induced oscillations but the intensity and phase displacement will, in



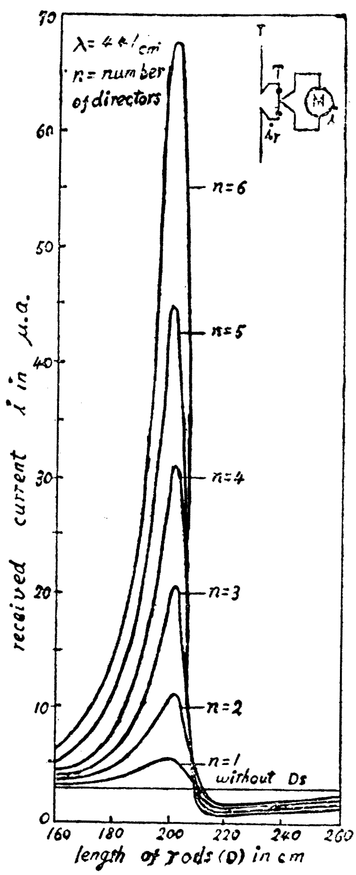


Fig. 11a Fig. 11b

The Effect of Varying Number and Length of Directors in Wave Canals on Received Current.

general, be different. A sort of standing wave will exist along the canal and the power will flow at a definite rate from the sending to the receiving station.

The wave energy received can be rectified by means of vacuum tubes or otherwise, and thus it may be used to charge a storage battery. It has been the experience of the author that rectification is very easily obtained even at very short waves.

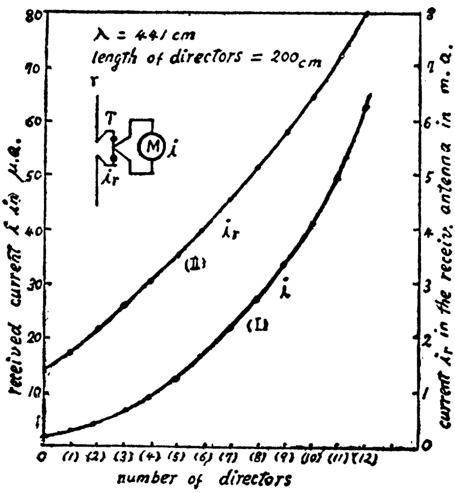


Fig. 12—The Effect of Varying Number of Directors on Received Current.

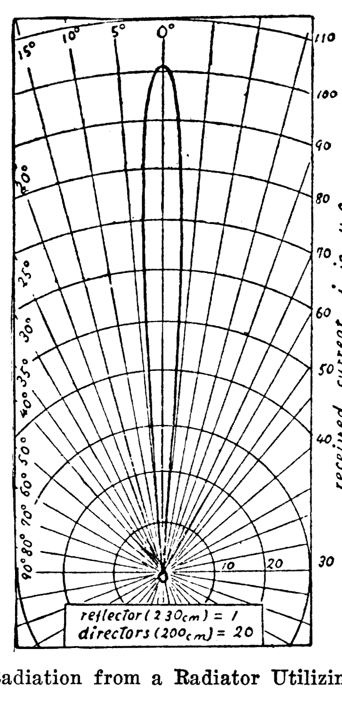


Fig. 13—Beam Radiation from a Radiator Utilizing a Wave Canal.

It appears that the wave collector at the receiving station may suppress to some extent the flow of energy from the sending antenna. It was found that in certain cases it was possible to transmit more power when a certain number of the directors in the middle of the wave canal were removed.

Effect of the Earth

In ultra short wave work, the effect of the earth is very considerable. Some of the experimental results are given below to illustrate this. Figs. 2 to 8, which are self-explanatory, are for various conditions of transmitter and receiver antenna height, with and without trigonal reflectors and wave canals.

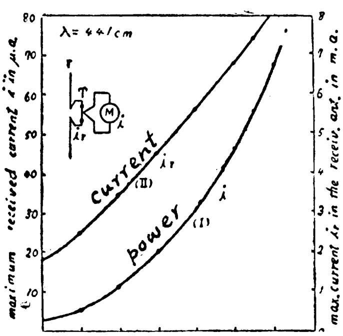


Fig. 14—The Effect of the Number of Directors on Received Current and Power.

It is interesting to note that the energy transmitted increases or is considerably increased when the height of the entire system is increased. As yet, no limit has been found for this effect.

Projector of Horizontally Polarized Waves

A radiating antenna placed horizontally with the earth is naturally directive. The wave is radiated chiefly in a vertical plane bisecting the antenna and perpendicular to it. Various polar diagrams were taken with such an antenna using a receiving antenna such as is shown in the accompanying photograph, Fig. 9. A thermocouple and micro-ammeter located at the middle of this antenna were used to indicate the magnitude of the received power.

The results of these experiments are shown in Figs. 10 to 14. In Fig. 10, *S* and *R* are the sender and receiver respectively, while *D* is a wave director. The effect of varying the length of *D* on received energy is very pronounced, and is a maximum of about 200 cm., whereas, in the case of vertically polarized waves, this maximum occurred between 190 and 195 cm.

In Fig. 11a, a wave canal is introduced between the sending and receiving antennas and the effect of varying the length of all of the directors is more pronounced than was the case in Fig. 10.

In general, the effect of increasing the number of directors forming the canal is shown in Fig. 12, where i is the current in the indicating meter and i_r is the current in the antenna.

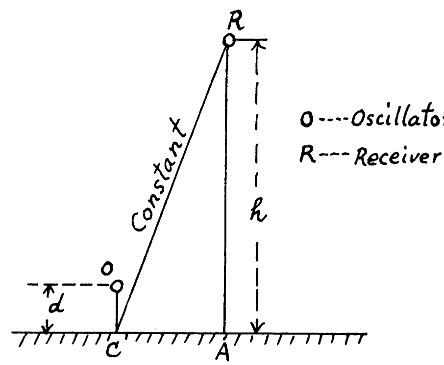


Fig. 15—Diagram Showing the Location of Antenna for Field Strength Measurements.

The length of the directors must be accurately adjusted; otherwise successful directing action will not be obtained. It has been found that the interval between adjacent directors must be adjusted to a suitable value. The most advantageous value for this interval seems to be approximately 3/8 wavelength.

A typical polar curve showing the beam radiation from such a projector is given in Fig. 13. The measurements were taken on a horizontal plane near the earth's surface. Here again, the advantage of utilizing the wave canal at the receiving station is demonstrated to be quite remarkable.

It has been found that power received increases nearly proportional to the square of the number of directors forming the canal. This effect is shown in the experimentally determined curves of Fig. 14.

High-Angle Radiation of Horizontally Polarized Waves

Some experiments were performed in which the field strength around the sending antenna O was measured by a receiving antenna R. The distance CR from R to a point on the surface of the earth directly beneath the sending antenna was kept constant. The wavelength employed was approximately 260 cm. and the length of the sending antenna O was 135 cm. Fig. 15 shows the arrangement.

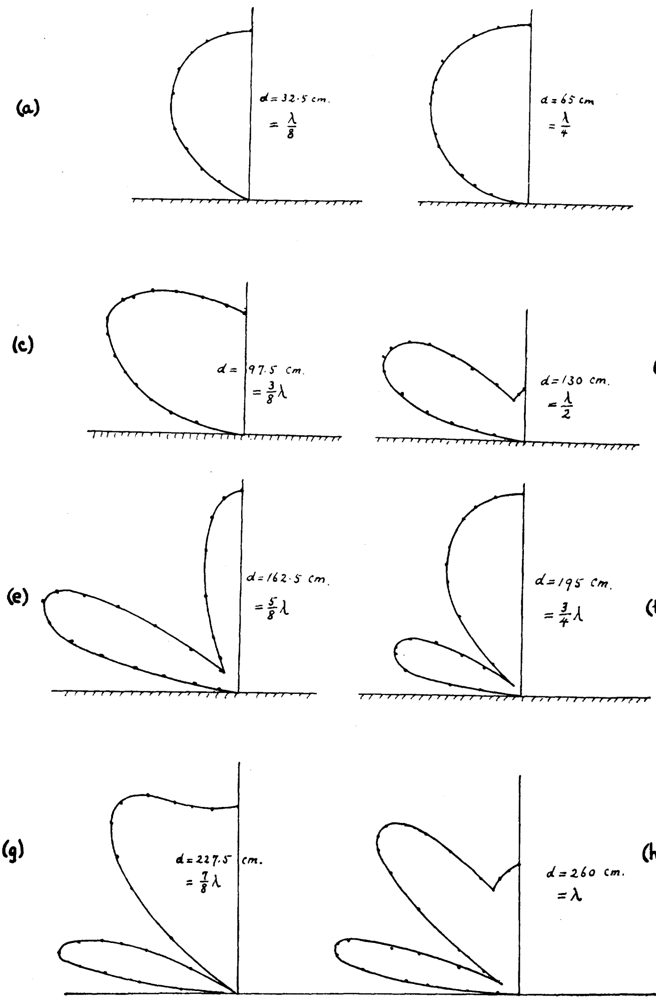


Fig. 16—Polar Diagrams.

The earth seems to act very much like a mirror to ultra-short waves, and reflection from its surface depends upon distance d between antenna and earth as shown in Fig. 15. The experimentally determined polar diagrams shown in Fig. 16, (a), (b), (c), (d), (e), (f), (g), (h), illustrate this fact very well.

The effect of a wave canal upon high-angle radiation of horizontally polarized waves was then studied. A canal was arranged parallel to the surface of the earth in the first case and

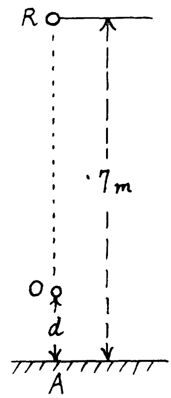


Fig. 17—Diagram Showing Location of Sending and Receiving Antenna for Fig. 18

along the line inclined 30 deg. to the horizontal in the second case. The actual set-up is shown in the two following photographs, Figs. 19 and 20.

It is evident from Fig. 21 that the canal is forcing the beam toward the horizontal direction. Thus, by the use of wave

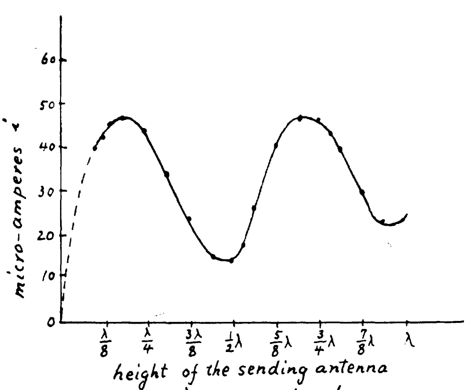


Fig. 18—The Effect of Height of Sending Antenna on Receiver Current.

canals, high-angle radiation may be propagated at various angles to the surface of the earth. This fact may find some practical application in long distance work.

Theory

Theoretical calculations concerning the various experiments described above are naturally involved. Some of the previously mentioned papers presented to the I.E.E. of Japan contain theoretical descriptions of the research. Certain fundamental theories are to be found in a paper which will be published at some later date by the I.E.E. of Japan. This paper will be in English.

Part II

Magnetron Oscillators

A diode is capable of producing oscillations if the anode is a circular cylinder and the cathode is a straight filament at the

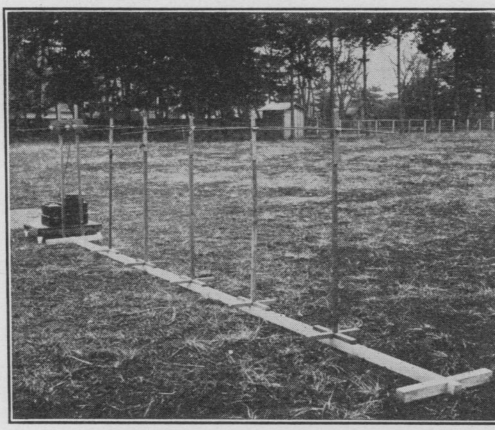


Fig. 19—Projector Horizontally Polarized Wave; 260 cm.

center, with the tube placed in a uniform magnetic field the direction of which coincides with the direction of the axis of the cylinder. When the strength of the magnetic field is increased past a critical value no current should flow through the vacuum tube because the electrons emitted from the filament and attracted by the anode describe circular orbits the diameter of which is less than the radius of the anode. However, when this is tried experimentally sometimes there is residual current flowing to the anode which can be detected by a hot wire instrument. This is evidence of the existence of high-frequency currents.

It has been found that any of the diodes or the triode shown in Fig. 23 can produce short-wave oscillations when sufficiently high anode voltage is applied and a magnetic field of appropriate intensity is employed. In order, however, that the oscillations be of extremely short wavelength with sufficient intensity, symmetrical construction and exact dimensioning are essential.

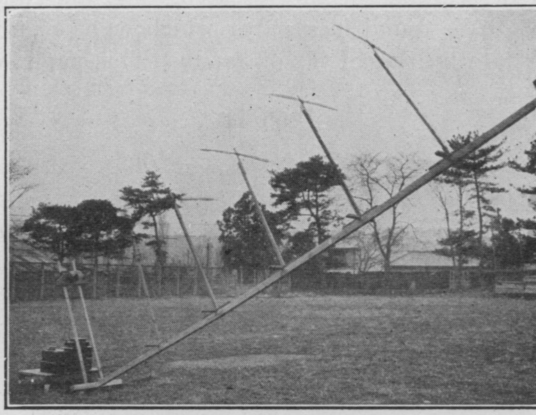


Fig. 20—High Angle Projector of the Horizontally Polarized Wave. 260 cm.

It has been found that the wavelength can be calculated roughly by the following semi-theoretical formula:

$\lambda_0 = 2\,ct$

$\lambda_0 =$ semi-theoretical wavelength

Where $c =$ velocity of light

$t =$ the time required by an electron for travelling across the space between the cathode and the anode

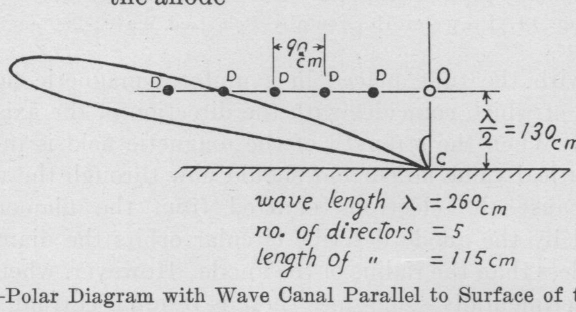


Fig. 21—Polar Diagram with Wave Canal Parallel to Surface of the Earth.

The results are given in the following tabulation. The second column gives the wavelength as measured by the Lecher wire method. The wavelength was practically independent of filament temperature.

MAGNETRON II

$D_a = 1.32$ cm. Vacuum:	$L_a = 2.5$ cm. 10^{-3}/bar.	$I_f = 3.5$ amp. Ni-Anode	$I_f = 3$ cm. W-Fil.
Anode-Voltage (Volts)	λ (cm.)	Intensity of the Oscillations	λ_0 (cm.)
190	150	Weak	87
230	122	"	79
280	88	Middle	72
450	63	Strong	58
500	.....	....	55
1000	32	Very Strong	38
1300	26.5	" "	35
5000	.....	....	17
20000	.....	....	8.5

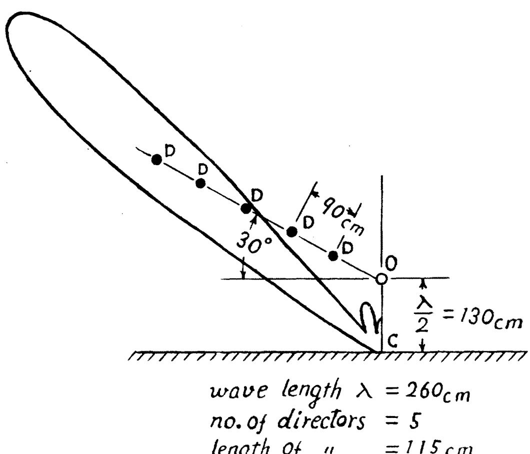


Fig. 22—Polar Diagram with Wave Canal at 30 deg. to Surface of the Earth.

The arrangement of the apparatus is shown in Fig. 24.

The variation of anode current with the magnetic field for a typical tube is shown in Fig. 25. Above the critical magnetic field strength there was still some current flowing which was a

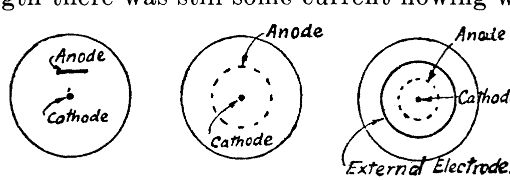


Fig. 23—Types of Diodes and Triode Used Experimentally.

result of the high-frequency oscillations. The most intense oscillation occurred at or near the critical field strength. The oscillations seemed to weaken with increasing magnetization.

When the anode diameter was kept constant larger diameter filaments seemed to give stronger oscillations. Moreover, with larger filament diameters, the anode current most favorable to the production of oscillations was smaller, which is decidedly an advantage.

To get the shortest waves, the anode diameter must be small. The result, however, is that the oscillations become less intense. It was found that the actual length of the anode must not be too short in proportion to its diameter, otherwise the oscillations were very feeble.

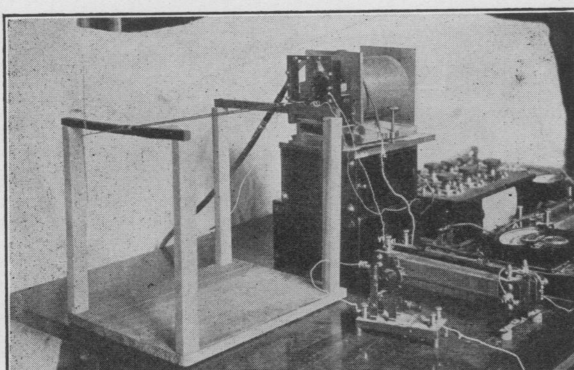


Fig. 24—Apparatus for 26.5-150 cm. Wavelength Production.

The position of the tube in the magnetic field is very important. It was found highly desirable to keep the tube in the most uniform portion of the field. As shown by Fig. 26, a slight deviation from the exact center of the magnetic field coil caused a marked decrease in the oscillation intensity.

Shortest Waves Obtained

Two special tubes of small dimensions were constructed and tried.

No. I $Da = 4.5$ mm. $Df = 0.14$ mm.

No. II $Da = 2.2$ mm. $Df = 0.07$ mm.

where Da = anode diameter and Df = filament diameter. For the test each tube was placed between the poles of a large electromagnet as shown in Fig. 27.

The relation between the anode voltage and the wavelength for tube No. I is shown in Fig. 28. Tube No. II gave a wave of 19 cm. with 840 volts on the anode and a minimum wavelength of 12 cm. with 1250 volts on the anode. These values of

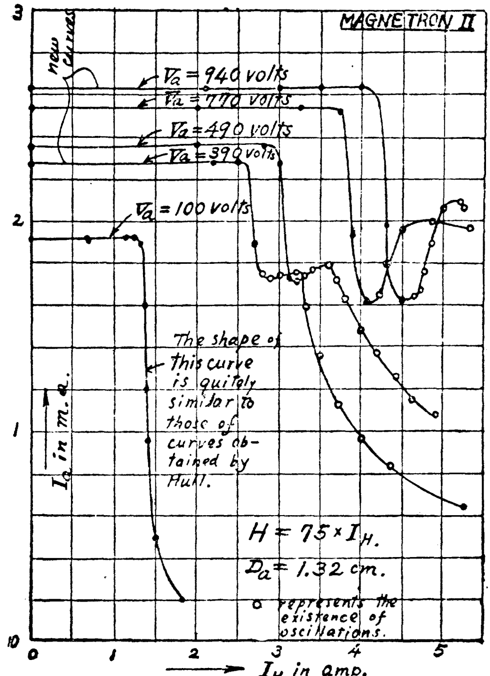


Fig. 25—Variation of Anode Current with Strength of Magnetic Field.

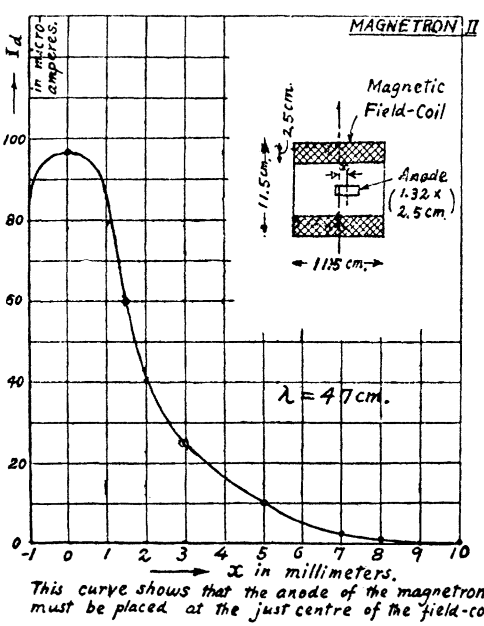


Fig. 26—Variation of Oscillation Intensity with Tube Position in Magnetic Field.

wavelength, however, do not agree very well with the semi-theoretical formula.

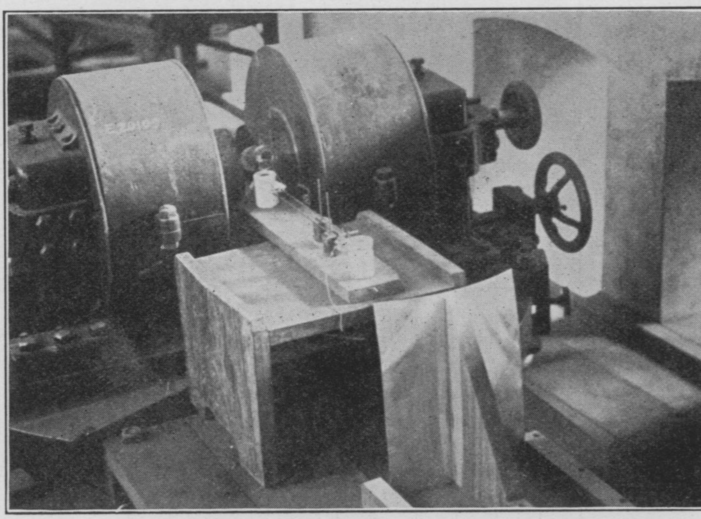


Fig. 27—Apparatus Set-up for the Shortest Waves Obtained (14-15 cm.).

The measurement of the wavelength on Lecher wires was not easy. Too strong a magnetic field seemed to disturb the

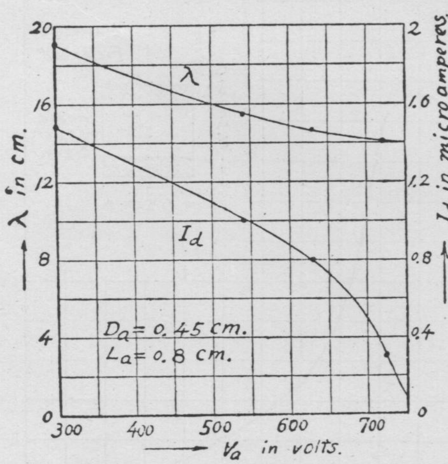


Fig. 28—Variation of Wavelength with Voltage.

steadiness of the oscillations and it was difficult to obtain the shorter waves as a fundamental oscillation. The stronger magnetic field had a tendency to produce oscillations rich in harmonics.

The most fruitful improvement made was to split up the cylindrical anode into two or more segments by narrow slits cut parallel to the axis of the cylinder. Fig. 29 shows the two-segment type and Fig. 30 the four-segment type of tube. Instead of bringing only one anode lead out of the tube a lead was brought out for each segment. These leads were then

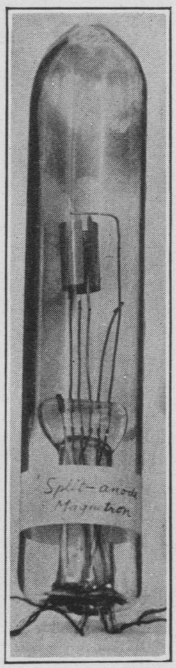


Fig. 29—Split-Anode Magnetron; 2-segment type.

brought together outside of the tube without directly touching each other and brought close to the cathode lead at a point *B* in Fig. 31. After that the leads were all connected and led to the positive terminal of the high-voltage anode battery.

Each anode segment with its leads seems to form a resonant circuit, the natural frequency of which may vary with the length of the lead and the capacity of the segment.

The distance between the anode leads and the cathode lead must also be adjusted at the point *B*, so that maximum oscillation intensity may be obtained. Now, owing to the tuning action of these resonant circuits, the change of wavelength, due to the change of anode voltage, became inappreciably small. The

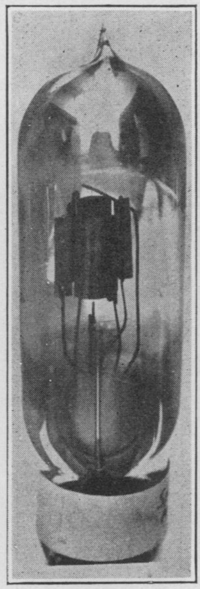


Fig. 30—Split-Anode Magnetron; 4-segment type.

wavelength was determined either by a Lecher system or by a receiving set used to indicate standing electromagnetic waves formed before a sheet metal screen.

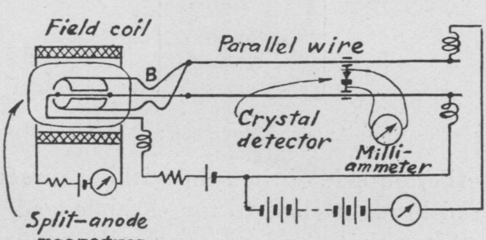


Fig. 31—Circuit Connection for Short Wave Oscillating Magnetron.

40 cm. Waves

A split anode magnetron was found to be especially well suited for the production of very intense oscillations of about 40 cm. wavelength. A typical case is given in the following table.

$Da = 14$ mm. $La = 26$ mm.

$Df = 0.14$ mm. $Lf = 30$ mm.

where La = length of anode and Lf = length of filament.

Anode Voltage	Wavelength	Intensity (Arbitrary)
951	34.5	5.3
724	41.5	15.5
670	42	16
500	42.5	6.7
400	42.5	4
320	42.5	1.8

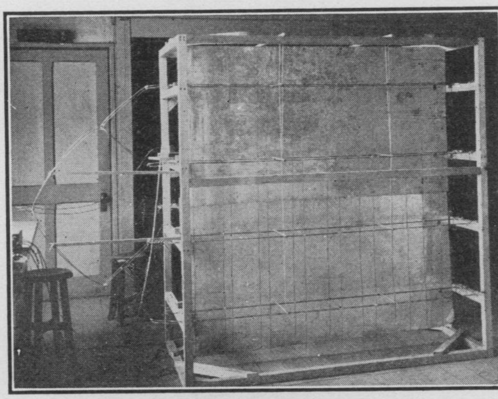


Fig. 32—Antenna System for 40 cm. Wave Transmitter.

The apparatus used in this experiment is shown in Fig. 32 (front view) and Fig. 33 (rear view).

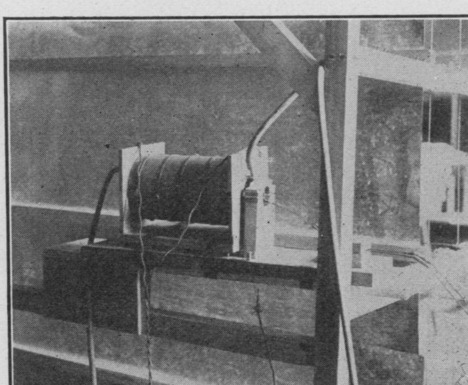


Fig. 33—Magnetron Oscillator for 40 cm. Wave Transmitter.

In order to obtain various directive effects, antenna systems, as shown in Fig. 34, may be used and several of these may be combined, using metal plates as reflectors; or groups of reflectors as shown in Fig. 35 may be used with parabolic reflectors of sheet metal. Fig. 24 shows a radiating system of

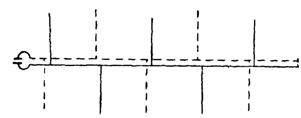


Fig. 34—Directive Antenna, 40 cm.

the type given in Fig. 34. The polar diagrams (Fig. 36) of the antenna system can be calculated from the arrangement of the various elements. The actual measurements showed good

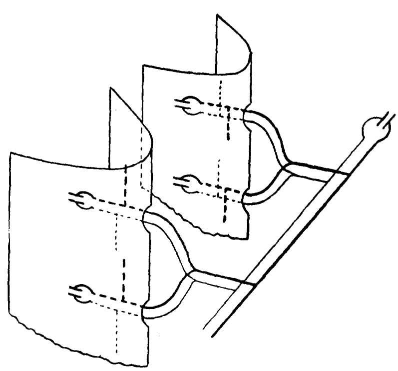


Fig. 35—Directive Antennas.

agreement with the theoretical values and the beam was confined within a small angle in the horizontal and vertical planes.

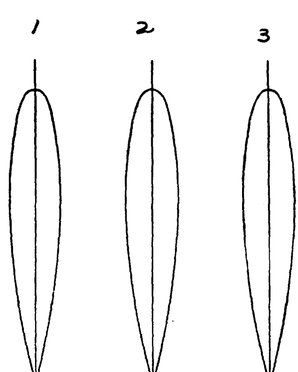


Fig. 36—Polar Curves. 1-Calculation; 2-Horizontal Observed; 3-Vertical Observed.

Reception of Short Waves

For reception a crystal detector or thermocouple attached at the center of a straight antenna can be used. The currents from several such detectors may be combined in parallel or in series, according to the circumstances.

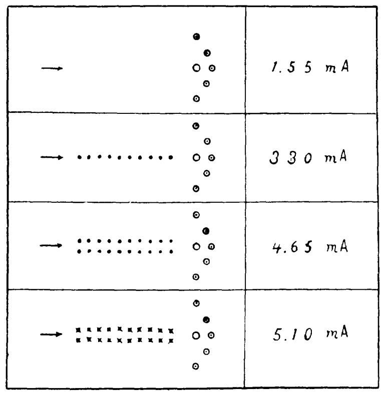


Fig. 37—Reception with a Collector and Wave Canals.

To increase the signal strength a wave collector was built, but its effect was not as remarkable as that of the wave canal. Wave directors on the transmitter proved to be astonishingly advantageous. It was found necessary to use a wave director in order to transmit signals at this short wavelength. The effect of the wave canal at the receiver is shown in Fig. 37.

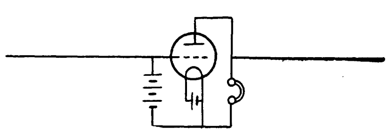


Fig. 38—Receiver (Barkhausen).

The maximum distance covered has so far not exceeded 1 kilometer. In this 1-kilometer experiment the wave was modulated at 900 cycles per second. The exact wavelength was 41 cm. and the anode voltage 1000. A single Hertzian resonator with a crystal detector at the center, a double row of 12-meter director chains and a three-stage amplifier for the modulation frequency were employed. The results are shown in the following table:

1. Single Hertz resonator only	Signal not heard
2. One director chain, no amplifier	Very weak

3. Two director chains, no amplifier	Very weak
4. One chain, with amplifier	Loud and clear
5. Two chains, with amplifier	Loud and clear

The type of receiver suggested by Barkhausen[1] and shown in Fig. 38 was also tried and gave better results than the crystal detector in detecting modulated waves in the neighborhood of $1\frac{1}{2}$ meters.

The experiments described in Part I were made by Mr. S. Uda, and those in Part II by Mr. K. Okabe, to the ingenuity of both of whom the successful development of the beam system is mainly due.

Discussion

J. H. Dellinger:† Professor Yagi's remarkable work stimulates some thought of a radical order. I venture to suggest that before many years radio operations will generally be considered as divided into two classes, broadcasting and directive radio. Radio communication is to a large extent done the wrong way today. And before 1920 radio was all wrong. The only use of radio was for communication between two points, and it was always done by broadcasting in every direction. It was not until 1920 that we had the advent of broadcasting as such, transmission intended for reception by large numbers of receivers. In the eight years since 1920 we have successfully developed broadcasting. At present, therefore, the job of straightening radio out is half done.

It is interesting that 1920 marks not only the rise of broadcasting but also the beginning of directive radio. Ideally, radio transmissions should be broadcast in every direction only when intended for reception in every direction, and should be sent as nearly as possible in one line when intended for reception by one receiver. Since 1920 we have had the gradual and partial evolution of beam systems and other means of confining a communication more or less to the path desired. One instance is the use of a string of relay stations. Now Professor Yagi has shown us that one of the ways to accomplish the directive function is to use a string of absolutely automatic relay stations, viz., the simple devices he calls "directors." Not only in this ingenious suggestion but throughout a wide field of basic possibilities in directive radio,

[1] *Phys. Zeits.* **21**, 1, 1920.
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