INVESTIGATION OF ANTENNAE AND OF RADIO TRANSMISSION BY MEANS OF MODELS

J. TYKOCINSKI-TYKOCINER, UNIVERSITY OF ILLINOIS

I. ANTENNAE.

The most essential parts of a radio station are the transmitting and receiving antennae. The radiation of antennae as well as the propagation of electromagnetic waves over the surface of our globe constitute the fundamental phenomena underlying the art of radio communication. In this domain the phenomena to be studied take place in the space surrounding our planet. The waves reach the highest layers of the atmosphere and they penetrate even the surface layers of the earth to a considerable depth.

Every antenna consists of a system of wires supported on masts or towers and extending above the surface of the earth. During the process of radio transmission electromagnetic waves are detached from the antennae and forced to radiate into the surrounding space.

Besides its geometrical dimensions every antenna possesses physical properties characterized by a number of constants which can be determined by measurements. The principal constants of an antenna are the following: fundamental wave length, static capacity, dynamic capacity, inductance, ohmic resistance and radiation resistance.

Full size antennae are expensive, their principal dimensions cannot be easily varied so as to maintain others constant, and they are not always available for carrying on experiments. Investigations were therefore carried out at the Engineering Experiment Station of the University of Illinois to find out whether workable antennae models could be made, and if satisfactory, whether they can be used for the determination of constants of typical antennae. M. Abraham gave us the theory of a long, rod-shaped Hertzian oscillator, which represents an idealized simple antenna, and G. W. Pierce in this country extended this theory to a flat-top antenna. In his dissertation on *Electric oscillations around a rod-shaped conductor, treated according to Maxwell's theory*, Abraham deducted mathematically about 12 fundamental properties of oscillators of this ideal type. Two of those theorems which concern directly our problem may be mentioned:

I. "The natural periods of geometrically similar oscillators are related to each other as the lengths of respective segments."

II. "The natural periods of geometrically similar oscillators possess an equal logarithmic decrement."

The first of the two theorems means that given two oscillators, one having its geometric dimension m times smaller than the other, it will emit a wavelength also m times smaller. The other theorem means that the logarithmic decrement of both oscillators, the larger as well as the one which is m times smaller, will be exactly equal. In his theory, Abraham assumed the ohmic resistance of the oscillator to be zero, so that the decrement of the oscillator is due exclusively to radiation. It follows that the radiations of geometrically similar oscillators having negligible ohmic resistance are equal, no matter how large or small they are made.

These two theorems could be raised to a general principle of similitude for all antennae. However, we must gather sufficient evidence to prove that it applies to all oscillators, including antennae of all types.

Before the experimental investigation of models was started, it was clear that even in case a simple relation is not discovered between the model and the original antenna, the study of models promises nevertheless to disclose sufficiently interesting material in connection with properties of radiating systems. To gain a basis for the work, known formulae having any relation with the processes going on in antennae were examined. A rigorous proof was not obtained that from the behavior of a model it will be possible to make conclusions about all properties of a full size antenna. Nevertheless, sufficient evidence was collected to encourage the investigation.

Antenna models may be used either for teaching or for research purposes, especially for predicting those data the knowledge of which is necessary for proper designing of radiating systems adapted for radio communication. Considering the small size of a model, the use of very high frequencies becomes necessary. Apparatus for the production and measurement of currents of very high frequencies by means of thermionic tubes were developed, ranging from 50 to 100 million cycles per second and corresponding to wavelengths of 6 to 3 meters.

Fig 1 shows such a short wave transmitter coupled with the simplest form of an antenna—a Hertzian oscillator.

To demonstrate the origin and the chief properties of antennae all that is necessary to do is to replace one-half of the Hertzian oscillator (Fig. 2) by a mesh held rigidly in a frame clamped to a table and to substitute a rod in place of the other sphere. Thus a simple model of a T-antenna is readily built. By drawing the upper rod out of the connecting T-piece the same antenna is transformed into the inverted L type.

Mushroom form and other types of antennae can be reproduced in the same way by means of a few rods and connecting pieces available in every school laboratory. The vertical rod of the antenna is supported by a board fixed to the table by means of clamps. The general dimensions of the models can be estimated from the illustrations by comparing with the size of the meter stick fixed to the edge of the table. The transmitter is placed in a vertical position so as to enable one to observe the measuring instruments.

For the purpose of experimental research more elaborate constructions of antennae models are required. All those details of antennae systems met in practical construction which may have any influence upon its electrical characteristics have to be considered in the model. So the height and the material of the supporting structure, neighboring dielectric or conductive masses, electric properties of the ground and other details may be taken into consideration.

One of the models used for investigations is illustrated in Fig. 3. It is a model of a flat top antenna supported on three masts. The base of the model consists of a wooden frame supported on four legs. The frame, covered beneath with a copper sheet, forms a tray which can be filled with any material of proper conductivity to approach the properties of the ground. Crosspieces can be shifted and clamped by means of a wooden screw in any convenient position along the frame. Carriages are made to be moved along the crosspieces and to be likewise fixed in any convenient place. These carriages have vertically bored threaded holes into which the bases of standards are screwed, serving to support the antenna wires. The number of cross pieces and carriages to be used depends on the number of masts employed for supporting the antenna wires. In the figure two cross pieces and three carriages are shown with three masts. Hard rubber insulating pieces or rubber bands can be shifted along the masts to set the antenna wires at any desirable height above the ground plate. Two antenna wires are visible in the figure ascending from the ammeter towards the top of one of the masts from which they extend, diverging towards the top of the two other masts. The cross pieces have extensions, reaching 50 cm. beyond the frame, and made to carry a baseboard for the short wave transmitter. By moving this board parallel to the frame the coupling of the transmitter with the antenna can be regulated. Finer adjustment of the coupling is carried out by means of the handle designated to rotate the plane of the transmitter loop.

It is possible to determine the chief characteristics of every type of antenna by preparing a model of the described kind. The natural wavelength, the static as well as the dynamic capacity, the total and the radiation resistance can be determined, and from the values obtained by measurements, the inductance, the losses and the efficiency of a given antenna can then be calculated. The scale of the model is limited on one hand by the space available; on the other hand by the thickness of the wires we may use for the antenna model. If the model is too large, a special building is required to house the structure; if it is too small, thin wires have to be used, possessing too small strength and introducing too large a resistance in the antenna circuit.

For antennae corresponding in size to average ship antennae a model about 1/50 to 1/100 of the original may be used, but for the large antenna of a trans-Atlantic station a scale of 1/250 to 1/500 may be practical.

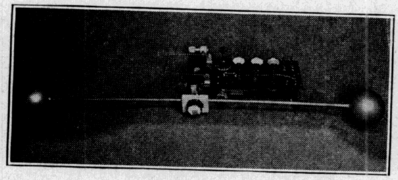

Fig. I. Short Wave Transmitter with Hertzian Oscillator Coupled with it.

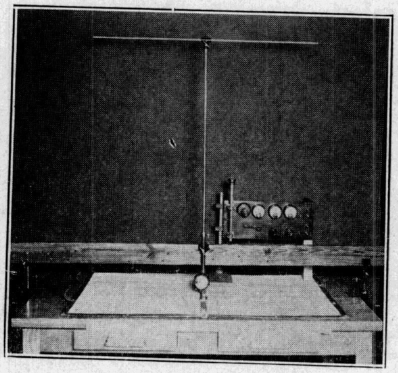

Fig. 2. Model of a T-Antenna for Teaching Purposes.

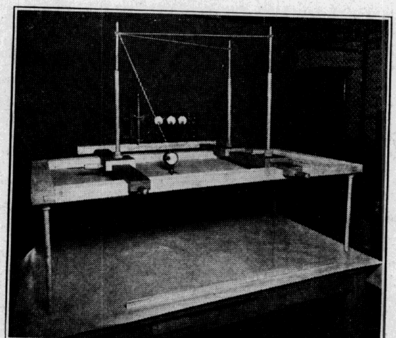

Fig. 3. Model of a Flat-top Antenna Supported on Three Masts.

The methods of measurements employed in connection with the determination of antennae constants are in principle identical with those used on full size antennae, but the technique had to be modified and adapted to the use of short waves and nonquasi stationary circuits.

A special wavemeter had to be constructed for precise determination of short wavelengths. The condenser consists of a pair of circular discs, of which one can be rotated. Both inner surfaces of the discs facing each other are divided into two equal semicircular parallel parts, each of them on a somewhat different level. The step-like discs are mounted in a cylindrical bakelite box. Of these condenser members the stationary one is fixed to the bottom of the box, while the rotating one is set on a circular brass plate of somewhat larger diameter. The latter fits into the opening of the box and is pressed by means of a star like spring and by the bakelite cover against a bronze ring fixed in the box above the stationary condenser member. The inductance consists of one turn of brass strip bent into a narrow rectangular loop. The loop can be rotated around the condenser and brought into every position convenient for performing the measurements, without the danger of changing the constants of the wavemeter. This is possible because of the symmetrical shape of the condenser. It was found convenient not to use any indicator connected directly with the wavemeter. The loop of the wavemeter is directed towards the transmitter, and the calibrated condenser varied until the ammeter in the transmitter circuit indicates minimum of deflection. This takes place when the wavemeter circuit is in resonance, absorbing maximum energy from the 5-watt tube transmitter.

The accuracy of the antenna wavelength measurement depends largely on the damping of the particular circuit. Comparative measurements of a 1/100 scale model of a T-antenna supported on wooden masts, having its two horizontal wires 60 cm. above the ground plates, 75 cm. long and separated 6 cm. from each other, gave 490.5 cm. for the fundamental wavelength, while the original ship antenna represented by the model has a wave length of 510 m. If, however, steel rods with guys were used to support the model antenna its wave length increased to

509.5 cm. This value multiplied by the model coefficient 100 gives a very close agreement with the wave length of the full-size antenna.

The precision with which wave lengths of antennae can be determined by models suggests the use of the described methods for the study of wave length and other constants as affected by the change of the relative position of antenna wires. In a model illustrated in Fig. 3, the length of the wires and the height of the horizontal wires above the ground plate were kept constant while the angle between the top wires was varied. New positions were obtained by separating the masts supporting the ends of the two horizontal wires, when the fundamental wave length of the antenna was determined by measuring that frequency of the oscillating transmitting circuit, which produced maximum current in the antenna. The results obtained show that the wave length increases with the angle enclosed between the two top wires at a rate decreasing as this angle becomes larger. A variation in wave length produced by the relative change of position of wires equal to an angle of only 1° can be detected.

Measurements of the static capacity of the T-antenna model mentioned above gave a value of

$$C_s = 11.95 \text{ cm. e. s.}$$

for the antenna supported on wooden masts. If, however, steel rods 1.2 cm. in diameter placed directly on the ground plate and stayed by insulated guys of copper wire were used to support the antenna, the value

$$C_s = 14.6 \text{ cm. e. s.}$$

was found. The static capacity of the full size ship antenna similar in form to the model but 100 times larger is known to be 1400 cm. The discrepancy of about +4.25% may be due partly to the arrangement of the guys, possibly differing from the actual conditions, partly to the influence of the surrounding walls and objects in the laboratory where the measurements were made.

For radiation measurements a model of receiving antenna was used, supported on a wooden frame covered with a copper ground plate of exactly the same dimensions as for models of transmitting antennae. This frame carries on a bakelite plate attached to two carriages a telescopic antenna consisting of two brass tubes sliding one into the other. The inner tube, which may be fixed at any definite height by means of a set screw, carries at the top a brass cup with a funnel like channel ending at the lower part with a fine hole. Through this hole a bronze wire slides out of the tube over the cup. The wire carries a counter-weight moving inside the antenna tubes which can be pulled out by means of a cord attached to an elastic insulator fixed to the other end of the wire. The cord leads over pulleys to the place where observations are made and is used to tune the receiving antenna to the frequency of the transmitting antenna by altering the length of its horizontal part formed by the bronze wire. The base of the antenna tube is connected through a thermocouple and resistance element to the ground plate. A pair of leads connects the thermocouple with a sensitive galvanometer.

The earliest method employed for radiation measurements was that suggested by Erskine-Murray for actual antennae which were coupled with quenched spark transmitters. This method was cumbersome and beset with the difficulties encountered with the lowering of antennae without considerably disfiguring their geometrical shape. But it is comparatively easy to use this method of radiation measurements on models of those types of antennae for which the ohmic resistance is small in comparison with radiation resistance. The measurements of radiation on such models must be carried out in a field free from buildings, trees and overhead wires, within a radius of at least 10 wave lengths, in order to avoid reflection, refraction and absorption of the waves.

The first radiation measurements with models were undertaken in Urbana on the grounds extending south of the Electrical Engineering Laboratory under very unfavorable conditions. With the model of a T-antenna described above but with the ground plate set directly on ground the following results were obtained:

Radiation resistance measured	s = 14.8 ohms
Resistance of thermoammeter measured	r = { 4.6 ohms
Ohmic resistance of antenna bronze wires, calculated	3.3 ohms
Balance for the earth resistance	2.5 ohms
Total antenna resistance measured	R = 25.2 ohms
Effective height of antenna calculated	h = 49.8 cm.
Current distribution factor calculated	b = 0.81

The value of s=14.8 ohm is approximately equal to the value of radiation resistance known for actual antennae of this type.

More details on antennae models will be published by the University of Illinois in a bulletin, No. 147, of the Engineering Experiment Station.

II. RADIO TRANSMISSION.

The problem of radio transmission calls for extensive experimental research on wave propagation. By reviewing the great number of investigations made during the last twenty years by prominent mathematicians and physicists (Macdonald, Rayleigh, Henri Poincare, A. Sommerfeld, F. W. Nicholson, H. J. Love, C. N. Watson, L. Austin, W. Eccles, J. Zenneck, etc.), we are forced to admit that our knowledge of the propagation of electromagnetic waves of the kind used for the purpose of radio communication is still in a chaotic state. No general principles have as yet been evolved which correlate the data obtained by years of patient observation. The discrepancies between the values of electric field intensities calculated according to various hypotheses and the actual intensities measured at points a considerable distance of about 3000 to 12000 km. away from the transmitting antennae grew larger and larger in progression with the practical achievements of radio engineering.

L. Austin made a series of very valuable experimental investigations, studying variation of signal strength for distances of 1000-3000 km. He investigated also the influence of day and night and succeeded, in collaboration with Louis Cohen, in finding an empirical formula embracing all his observational data, obtained by measuring the intensities of reception during day time over the surface of the sea. Austin's formula, giving the relation between the current in the receiving antenna and other factors entering into play, whenever radio communication between two points has to be established, marked a conspicuous advance in the art. It was shown by C. N. Watson in 1919 that Austin's empirical results can be deduced theoretically if the conducting layer suggested by Heaviside and Kennelly is placed at a height of 100 km. above the surface of the earth and if the specific resistance of this layer is 0.695 million ohms per cubic centimeter.

It seemed, therefore, that the Austin-Cohen formula represents the true relations of wave propagation at least over the surface of the sea.

However, recent years have added new experience in the transmission of waves over long distances. In fact the largest distances of transmission possible on our tiny globe have already been attained and observations have been made with receivers placed near the antipodes of the transmitting stations. The French navy undertook in 1920 to measure on board the Aldebaran the strength of signals emitted from the long distance stations in Nantes and Lyons. It was found that for distances greater than 3000 km. the signals were much stronger than would be expected from Austin's formula.

In the spring of 1923 a new long distance radio station was completed in Karachi, India. This occasion was used to measure the field strength of British, French and Italian stations at a distance of about 6000 km. The values obtained were 60-300% larger than the values calculated from Austin's formula. The discrepancy is even larger, if we consider that the largest circles connecting Karachi with the respective transmitting stations passes over land, while Austin's formula was deduced from experiments over sea.

The advance made during the last year (1924) by demonstrating the effectiveness of short wave lengths lying between 35 and 100 meters revealed the astounding fact that the application of Austin's empirical formula for a wave length of 100 m. at a distance of 12000 km. gives values of field intensities 10^{24} times smaller than those obtained by measurements. Investigators must be aroused to consider the chaotic state of knowledge in this very important domain and to devise means of discovering the fundamental causes of disagreement. Mathematicians will hardly be in a position to master the problems without an adequate supply of reliable facts which can be gained only by constructive experiments. Not much can be expected from a passive observation of diurnal, seasonal and other variations of signal strength due to erratic meterologic and cosmic causes. Results obtained from occasional expeditions organized by the Navies, in this country and abroad, are not sufficient for a systematic study of the role which a great variety of physical conditions our globe's atmosphere and its surface layers exert on the propagation of waves. More extensive experimental researches are required to be carried out under conditions variable at will by the investigator.

It may be asked, however, whether it is at all possible to accomplish anything in this respect in a laboratory. Indeed, not much can be done in a physical laboratory of the usual kind. Special observational stations or a laboratory of an unusual type will have to be developed. However, the enormous expenditures involved in the creation of such a laboratory makes its realization impossible at the present time.

Nevertheless, it may be useful to consider the conditions under which an experimental study of fundamental problems of wave propagation could be accomplished. An Earth Globe Model, as illustrated in Fig. 4, represents an ideal laboratory as may be suggested for the purpose of investigating radio transmission.

Imagine a spherical cave (c) about 15 m. beneath the surface of the earth and extending 300 m. deep. In the center of the cavity a spherical airship 260 m. in diameter is held floating. In the vertical axis of this floating sphere is placed a supporting structure (column s) having dimensions similar to those of a modern airship. This column (s) carries inside bags (b) filled with Helium sufficient in quantity to keep the whole structure floating. The same column is used to support about 60 trusses (t) hinged at (h) and forming the skeleton of a globe model. Ropes connect every hinge (h) with a drum placed in the equatorial plane of the supporting column. By releasing

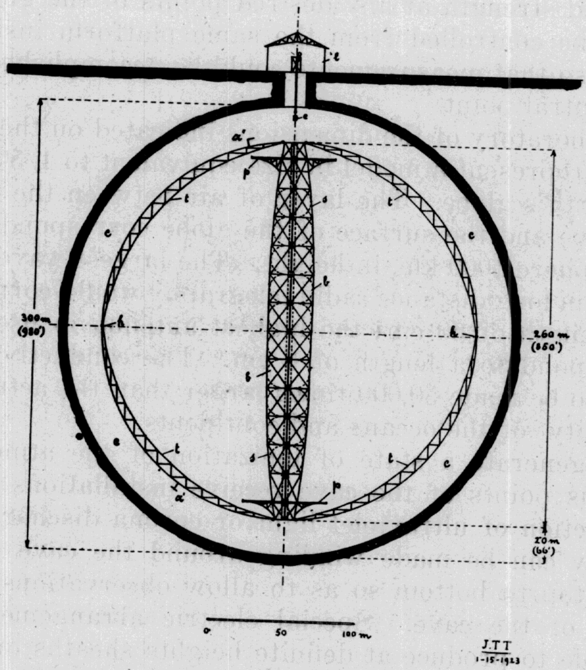

FIG. 4. Earth's Globe Model Suggested for the Study of Propagation of Electromagnetic Waves.

the ropes, the shape of the model can be changed. A radial displacement of the hinges by only 70 cm. will produce a depression making the model identical in shape with the terrestrial spheroid. In order to allow for this kind of form variations, the upper hinges of the trusses (t) are attached to a tube sliding over a cylindrical extension of the supporting structure (s).

The outer surface of the globe is covered with a light textile material so treated with conductive dyes as to imitate the geographical distribution of the various electric properties of the earth's surface. The relief of the continents and even artificial obstacles could be produced by suitable modeling materials. All points on the surface are accessible in order to attach there model antennae. The lower platform (p) carries electric apparatus and batteries for the production of short wave oscillations, with which the model antennae will have to be excited. The receiving antennae used for measuring the field strength at any desired points of the globe are all to be controlled from the same platform inside the globe, so that measurements could be accomplished from one central point.

A laboratory of the dimensions indicated on the sketch would represent a model in size equivalent to 1/50,000 of the earth's globe. The layer of air between the wall of the cave and the surface of the globe corresponds to an atmosphere 1000 km. in height. The largest wave length in use in long distance radio telegraphy would correspond to a length of 60 cm; the highest antenna in use would correspond to a length of 6 cm. The conductivity will have to be made 50,000 times larger than the actual conductivity of the oceans and continents.

To generate a state of ionization of the atmosphere various points of the cave receive installations for the production of ultraviolet light or corona discharges. A gallery can be made winding around the cave spirally from top to bottom so as to allow observations at any point of the cave. Special electric arrangements are feasible to produce at definite heights sheaths or clouds of ions to act as Kennelly-Heaviside layers. Further developments will make posible the production of variations of humidity, temperature, magnetic field, and also electro-magnetic disturbances.

Near the entrance to the cave an above-ground laboratory (1) and a workshop serves for the auxiliary work to be done in connection with the investigation on the model. The communications with the upper laboratory are performed by means of a suspended elevator cage (d) descending the cave opening and down the inner column. During the experiments the elevator cage is lifted and the entrance to the cave closed, so that the earth's model is floating in the cave entirely insulated from the laboratory.

Investigations of fundamental importance will be made possible on the model by suppressing certain complicating influences, by creating at first ideal conditions of uniformity in the medium of wave propagation, and then only varying and combining the predominating factors, influencing the propagation of energy radiated by different antennae systems. So the influence of wave length, of the geometric shape of the globe, of the conductivity of its surface, the absorption, refraction, and reflection of waves due to ionization, earth's magnetic field, and of other factors can be studied.

There is no reason why, after a period of extensive building of libraries, astronomical observatories, medical research institutes, etc., there may not come a time for a special wave propagation laboratory of the described type.

From the investigations carried out with model antennae the following conclusions may be drawn:

1. The characteristics of full-sized antennae can be predicted by means of miniature models to scale of about one to one hundred excited by proportionately short waves from three to six meters long.

2. The wave length, static capacity, effective capacity and effective height of the model can be determined with sufficient accuracy for the design of full sized antenna installations.

3. The relation of these characteristic constants of full-sized antennae to the corresponding values as determined with accurate models is the simple ratio of linear dimensions, noted as "m" in this paper.

4. The determinations of radiation resistance by means of models approximate measured values of actual antennae. The slight discrepancies are believed to be due chiefly to presence of interfering objects.

5. Special simple forms of adjustable model antennae permit the rapid comparison of variations of form or dimensions as affecting the performance of full-sized antennae. This type of model serves for the purpose of demonstrating the properties of various types of antennae.

6. The results of any suggested alteration in the form or dimension of full-sized antennae are convincingly shown leading rapidly and economically to the production of the most satisfactory structure of any general type.

7. A new type of condenser and of wavemeter have been developed permitting remarkable precision of measurement of the two to ten meter waves.

8. Radio transmission around a spheroid may be experimentally investigated by means of antennae models distributed over the surface of a suggested earth globe model.