CONTINUOUS WAVES IN LONG-DISTANCE RADIO-TELEGRAPHY

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ABSTRACT OF PAPER

Ability to predetermine the probable normal daylight sending radius of high-powered radiotelegraphic stations is of prime importance in their design.

The theoretical transmission equations for both continuous and damped waves are discussed and the empirical formulas for the latter are given.

Experiments with continuous waves over a period of six months between San Francisco and Honolulu, a distance of 2100 nautical miles (3880 km.), are described, and an empirical formula for the calculation of probable sending radius with such waves is proposed. This is checked by experiments between Tuckerton, N. J., and Honolulu, 4330 nautical miles (8000 km.).

Curves giving the energy received at Honolulu from San Francisco under both day and night conditions are shown, and the effects of changes in wave length upon transmission efficiency are discussed. Evidence strengthening theories of the reflection, refraction and interference of Hertzian waves in long-distance transmissions, and experimental data showing interference bands not over 18 miles in width, are given. The great value of easy and rapid changes in wave length, especially at night, is apparent from the curves.

Final conclusions drawn from a comparison of the empirical transmission formulas for continuous and for damped waves are that the transmission efficiency of continuous waves is somewhat higher than that of damped waves on wave lengths of approximately 3000 m. or above, and that this advantage increases with the wave length.

THEORETICAL FEATURES

THE comparative transmission efficiency of continuous and damped waves has been the subject of much discussion. Most experimental attempts to study the question have been over moderate distances and no difference has been observed until recently. Austin^{1*} states that experiments of the United States Navy Department from the Arlington station, using a Poulsen arc for the generation of continuous waves and a 500-cycle spark transmitter for the production of damped waves, have shown that at distances of the order of 2000 nautical miles (3700 km.), or above, continuous waves are on an average superior.

*Reference numbers refer to the bibliography at end of paper.

A theoretical analysis of the transmission of electromagnetic waves, either continuous or damped, over a perfectly conducting plane, was given by Sommerfeld² in 1909. Further treatment of the subject has been given by Poincaré³, Nicholson⁴, March⁵, von Rybczynski⁶ and Zenneck⁷. Certain experimental data over short distances have also been given by Duddell⁸, Taylor⁸ and Tissot⁹.

In 1912, Eccles¹⁰ gave a theoretical discussion of the propagation of electromagnetic waves in long-distance transmission around the curvature of the earth. His conclusions are strengthened by the United States Navy Department's tests of 1910 and 1913, recorded by Austin¹¹, and by the Federal Telegraph Co. Poulsen arc, San Francisco-Honolulu tests of 1914, to be described herein.

The results of the Sommerfeld theoretical treatment of the transmission problem may be stated as follows for continuous waves:

$$E = 120 \pi \frac{h_1 I_s}{\lambda d} \sqrt{\frac{\theta}{\sin \theta}} e^{-\frac{0.0019 d}{\lambda^{1/3}}} \quad (1)$$

where E = effective electric amplitude in volts per km. of the electric field at a distance (d) from the sending antenna.

h_1 = effective height¹² of sending antenna in km.

I_s = current in amperes at base of sending antenna.

λ = wave length in km.

d = distance in km.

θ = angle at center of earth subtended by distance d .

It is assumed that the earth is perfectly conducting and that d is several wave lengths.

If the waves are damped, then on account of the wave train form of the oscillations,

$$E = 120 \pi \frac{h_1 I_s}{\lambda d} \frac{\sqrt{\frac{\theta}{\sin \theta}}}{\sqrt{1 + \frac{\delta_1}{\delta_2}}} e^{-\frac{0.0019 d}{\lambda^{1/3}}} \quad (2)$$

where δ_1 and δ_2 are the decrements of the transmitter and receiver respectively.

Solving equation (1) for I_R the current in amperes at the base

of the receiving antenna of effective height h_2 km. and of resistance R ohms, we obtain for continuous waves:

$$I_R = \frac{E h_2}{R} = 120 \pi \frac{h_1 h_2 I_s}{\lambda d R} \sqrt{\frac{\theta}{\sin \theta}} e^{-\frac{0.0019 d}{\lambda^{1/3}}} \quad (3)$$

and from equation (2) for damped waves:

$$I_R = \frac{E h_2}{R} = 120 \pi \frac{h_1 h_2 I_s}{\lambda d R} \frac{\sqrt{\frac{\theta}{\sin \theta}}}{\sqrt{1 + \frac{\delta_1}{\delta_2}}} e^{-\frac{0.0019 d}{\lambda^{1/3}}} \quad (4)$$

This may be divided into four terms:

$$(1) \quad 120 \pi \frac{h_1 h_2 I_s}{\lambda d R}$$

which is the Hertzian expression for the effective value of the current flowing through a resistance at a point in the equatorial plane of an equivalent oscillator of length $2h$ at a distance d .

$$(2) \quad \sqrt{\frac{\theta}{\sin \theta}}$$

takes account of the curvature of the earth.

$$(3) \quad \sqrt{1 + \frac{\delta_1}{\delta_2}}$$

takes account of the damping at both transmitter and receiver and is therefore unity for continuous waves.

$$(4) \quad e^{-\frac{0.0019 d}{\lambda^{1/3}}}$$

corrects for the divergence of energy into the upper strata of the atmosphere due to the waves not following perfectly the curvature of the earth, and might be termed a "divergence factor."

All these theoretical equations are for a perfectly conducting

earth surface. Von Rybczynski states that a slight decrease in conductivity will result in a slight increase in received energy, apparently due to a reduction in the divergence factor. A considerable reduction in earth surface conductivity, however, will result in severe loss, and an absorption factor¹³ must be introduced. This is the case in most overland transmissions.

It is obvious, therefore, that theoretical transmission formulas must vary with the type of earth surface over which transmission is effected, and that empirical formulas derived from experimental data will likewise vary, the only certain uniformity possible in earth surface conductivity being over sea water. Atmospheric conditions affecting electromagnetic waves are so variable during the hours of darkness that it is only under normal day conditions that uniformity can exist. Hence, the only relatively uniform basis upon which theoretical and empirical formulas may be compared is for transmission over sea water under normal day conditions.

In 1911 Austin¹¹ gave the results of quantitative experiments up to 1000 nautical miles (1850 km.) from a spark transmitter at Brant Rock, Mass., and again¹⁴ in 1914 with a spark transmitter from the United States naval radiotelegraphic station at Arlington, Va., up to 2000 nautical miles (3700 km.). These experiments with the damped wave may, according to Austin (*loc. cit.*), be expressed by the following semi-empirical formula:

$$I_R = 120 \pi \frac{h_1 h_2 I_s}{\lambda d R} \sqrt{\frac{\theta}{\sin \theta}} \cdot e^{-\frac{0.0015 d}{\sqrt{\lambda}}} \quad (5)$$

The term $\sqrt{\frac{\theta}{\sin \theta}}$ may be considered as unity for distances of 2000 nautical miles (3800 km.).

The main point of difference between this and the theoretical Sommerfeld formula for the damped wave is in the last term, the divergence factor, $e^{-\frac{0.0015 d}{\sqrt{\lambda}}}$ instead of $e^{-\frac{0.0019 d}{\lambda^{1/3}}}$.

This makes long-distance radiotelegraphy much easier than theory would indicate and is probably due to a return of energy from the upper atmosphere by reflection or refraction, or both. Presumably, therefore, a convergence factor might be added to the theoretical formula. From many data available, especially those to be presented herein on the San Francisco-Honolulu sus-

tained-wave experiments of 1914, it is probable that such convergence is considerably greater with continuous than with damped waves. No experimental data are available from any source on the effects of changes in decrement on transmission efficiency and divergence factor over long distances.

The foregoing covers briefly the theoretical equations of long-distance radio transmission for both continuous and damped waves and the empirical formula of Austin for damped waves. This formula (5) proves quite satisfactory for the ordinary calculations of practical work, and would indicate that a change should be made in the theoretical equations to account for the considerable increase in received energy noted, seemingly due to convergence; *i.e.*, a return to the earth's surface, near the receiver, of energy radiated into the upper atmosphere after leaving the transmitting station.

GENERAL DESCRIPTION

The following description of the San Francisco-Honolulu sustained wave tests of 1914 may be divided into two parts.

1. That dealing with the effects of wave length upon the strength of received signals. This has an accuracy which is satisfactory for comparative results, and probably averages within 10 per cent.

2. That part covering the derivation of a proposed empirical formula for sustained wave transmission. This has an accuracy below that which could have been obtained had the two stations involved not been handling commercial work, which necessitated the taking of experimental data at irregular intervals, and caused frequent interruptions. It is probably accurate within 20 per cent.

Thus all deductions based upon the relative value of received energy readings may be regarded as being considerably more reliable than those based upon actual received energy values.

It is believed, however, that all data are of sufficient accuracy for practical purposes and that the transmission formula for continuous waves may be satisfactorily used in commercial design.

DESCRIPTION OF PLANTS

The data presented herein were taken during the period of six months extending from January to June, 1914, inclusive. The range of wave lengths was from 3000 to 11,800 meters, and the distance of transmission 2100 nautical miles (3880 km.).

The stations were the San Francisco and Honolulu plants of the Federal Telegraph Co. Both were equipped with 100-kw. Poulsen-Federal arc transmitters rated on continuous d-c. input, although 40-50 kw. is the usual power employed.

Each had three guyed wooden towers, two 440 ft., and one 608 ft. in height, giving triangular flat top antennas of 0.010 mf. capacity.

At San Francisco the 440-ft. towers were 600 ft. between centers. The 608-ft. tower was 900 ft. from one, 1095 ft. from the other 440-ft. tower.

At Honolulu all towers were on 600-ft. centers, forming an equilateral triangle, and there was in addition the arc of approximately 135 degrees of an umbrella antenna, strung from the back side of the 608-ft. tower over shallow tide water. This accounts for the capacity of this antenna with the close tower spacing being the same as that at San Francisco.

The center of capacity at Honolulu was very close to 394 ft. (120 m.), while at San Francisco, due to greater sags, it was approximately 380 ft. (116 m.).

METHODS OF TAKING DATA

Antenna Currents were measured by hot-wire ammeters calibrated from a 100-ampere Hartmann-Braun unshunted hot band instrument used as a standard.

Wave Lengths were measured by a standard wave meter¹⁵ employing a tikker and phones to indicate resonance.

Centers of Capacity were determined by mapping the triangular network of the antennas giving the height above the earth for various areas, and assuming a low capacity for the down leads.

Received Watts were determined by the shunted telephone method. The general procedure was identical with that used in the U. S. Navy Department tests of 1910 and 1913 described by Austin^{11, 1} and was briefly as follows:

If the receiving telephones be shunted by a variable resistance, the incoming signal has an audibility of one when the shunting resistance is so adjusted that the dots and dashes can just be differentiated. The following relation then exists:

$$A_f = \frac{R + S}{S} \quad (6)$$

where A_f = audibility factor or number of times audibility.

R = impedance of telephones in ohms.

and S = impedance of resistance shunting telephones in ohms.

[FULLER]

EIGHT HUNDRED AND TWENTY FIVE-
FT. STEEL TOWER AT TUCKERTON, N.J.

[FULLER]

SIX HUNDRED AND EIGHT-FT.
TOWER AT SAN FRANCISCO

[FULLER]

TYPE OF RECEIVING APPARATUS USED AT HONOLULU AND SAN FRAN-
CISCO DURING TESTS

[FULLER]
FRONT VIEW 100-KW. POULSEN-FEDERAL ARC TRANSMITTER USED
AT SAN FRANCISCO AND HONOLULU DURING TESTS

[FULLER']
BACK VIEW 100-KW. POULSEN-FEDERAL ARC TRANSMITTER

THIRTY-KW. POULSEN-FEDERAL ARC TRANSMITTER

[FULLER]

For the purpose of determining the received watts for a given value of resistance shunting the phones, or for a given audibility factor, another Poulsen-Federal arc station near by was used as a transmitter, and a thermo-couple and galvanometer were inserted in the antenna of the receiving station. These had previously been calibrated on direct current and indicated the received antenna current.

Measurements of the resistance of the antenna circuit, with the secondary of the receiver adjusted to resonance, were made throughout a range of wave lengths extending from 3000 to 10,000 meters, and the received watts for a known audibility factor were calculated by RI^2 . These values of received energy were reduced to received watts for unit audibility. Using a rotary tikker and sensitive telephone receivers these results gave the relation

$$P = 3.2 \times 10^{-10} A_f \quad (7)$$

where P = received energy in watts and

A_f = audibility factor as defined above.

GENERAL NOTES

Reference to the tabulated data shows the general average of signal strength obtained with the antenna current at the transmitter reduced to 35 amperes.

It was kept below 50 amperes in order that a minimum error might be introduced in correcting received current for a constant transmitting antenna current for all wave lengths. Preliminary investigation of this point showed that for transmitting antenna currents somewhat above 50 amperes the received current did not vary directly as the transmitting current¹⁶ but fell off somewhat.

In order to eliminate as far as possible factors tending to cause questionable results, the antenna current in all tests was kept at such a value as to make it possible to correct received current with certainty to the values which would have been obtained had it been convenient to hold the transmitting antenna current constant for all wave lengths.

All data are for transmission with daylight over the entire path, except on a certain few night tests. With the exception of ten miles of bare hills approximately 1200 ft. in height at the San Francisco end, the path of transmission lies entirely over sea.

DISCUSSION OF CURVES

Figs. 1, 2, 3, and 4 show received energy as a straight-line function of the wave length. It is possible that during these tests the waves were subjected to refraction only and that the amount of energy received by reflection from the upper atmosphere was small, probably indicating stable day conditions.¹⁷

The data in Fig. 5 show a constant gain in received energy up to 7000 meters, with a second peak at 10,000 meters.

Fig. 6 is somewhat similar; again showing a maximum at 7000

FIG. 1—HONOLULU TO SAN FRANCISCO, JAN. 25, 1914—SAN FRANCISCO TIME 1:05 P.M.-2:55 P.M. $I_s = 35$ AMPERES.

FIG. 2—SAN FRANCISCO TO HONOLULU, JAN. 25, 1914—SAN FRANCISCO TIME 9 A.M.-12 M. $I_s = 35$ AMPERES.

meters, a minimum between 8000 and 9000 and a rise again at 10,000 meters.

Fig. 7 is also of this same general type. All three indicate a combination of day and night conditions with possibly partial interference on certain wave lengths, and addition on others, due to a combination of reflection and refraction phenomena.

Fig. 8 is a typical night curve showing a marked reduction in signal strength on certain wave lengths, probably due to reflection phenomena. When compared with Fig. 13, however, it will

FIG. 3—HONOLULU TO SAN FRANCISCO, MARCH 1, 1914—SAN FRANCISCO TIME 10 A.M.-12 M. $I_s = 35$ AMPERES.

FIG. 4—HONOLULU TO SAN FRANCISCO, MARCH 8, 1914—SAN FRANCISCO TIME 11:44 A.M. - 12:03 P.M. $I_s = 35$ AMPERES.

FIG. 5—HONOLULU TO SAN FRANCISCO, MARCH 8, 1914—SAN FRANCISCO TIME 3:08 P.M.-3:54 P.M.— $I_s = 35$ AMPERES.

FIG 6—HONOLULU TO SAN FRANCISCO, MARCH 15, 1914—SAN FRANCISCO TIME 10:30 A.M.-12 M.— $I_s = 35$ AMPERES.

FIG. 7—HONOLULU TO SAN FRANCISCO, MARCH 15, 1914—SAN FRANCISCO TIME 3 P.M.-4 P.M. $I_s = 35$ AMPERES

FIG. 9—HONOLULU TO SAN FRANCISCO, MAY 3, 1914—SAN FRANCISCO TIME 10 A.M.-12 M. $I_s = 35$ AMPERES.

FIG. 8—HONOLULU TO SAN FRANCISCO, APRIL 1, 1914—SAN FRANCISCO TIME 3 A.M.-4 A.M. $I_s = 35$ AMPERES.

Typical night curve showing a marked reduction in signal strength on certain waves.

FIG. 10—HONOLULU TO SAN FRANCISCO, MAY 17, 1914—SAN FRANCISCO TIME 11:30 A.M.-12 M. $I_s = 35$ AMPERES.

be noted that the efficiency of transmission on the night of April 1st must have been considerably lower than on the night of June 13th, since no reduction in received energy following the radiation resistance curve is noted in the former case. This shows that the reduced losses in transmission on the long waves more than counterbalanced the reduction in radiation resistance. The great difference in observed audibilities on these two nights also indicates this fact.

Fig. 9 again shows a constant daylight condition, the received energy being a straight-line function of the wave length, probably indicating consistent refraction and no reflection.

FIG. 11—HONOLULU TO SAN FRANCISCO, MAY 24, 1914—SAN FRANCISCO TIME 10:25 A.M.-11:25 A.M. $I_s = 35$ AMPERES.

Fig. 10 is interesting in again showing a maximum near 7000 meters; but the 8000- and 9000-meter waves show a decrease. Judging from the last two points on this curve, and from the behavior of curves in Figs. 11, 12, 14 and 15, it is probable that this curve, if continued, would show an increase in received energy.

Figs. 11 and 12 show a maximum at 8000 and 7000 meters respectively, a minimum at 9000 meters, and a decided rise at 10,000 meters. It is thought quite probable that at 14,000 and 16,000 meters, the double of 7000 and 8000 meters, other maximums might be noted. These are shown by dotted extensions.

FIG. 12—HONOLULU TO SAN FRANCISCO, MAY 24, 1914—SAN FRANCISCO TIME 11:25 A.M.-12:05 P.M.— $I_s = 35$ AMPERES.

FIG. 13—HONOLULU TO SAN FRANCISCO, JUNE 13, 1914—SAN FRANCISCO TIME 2:45 A.M.-3:30 A.M.— $I_s = 35$ AMPERES.

Typical night curve showing marked reduction in signal strength on certain waves.

FIG. 14—HONOLULU TO SAN FRANCISCO, JUNE 22, 1914—SAN FRANCISCO TIME 10:30 A.M.-11:15 A.M. $I_s = 35$ AMPERES.

FIG. 15—HONOLULU TO SAN FRANCISCO, JUNE 28, 1914—SAN FRANCISCO TIME 10:45 A.M.-10:30 A.M. $I_s = 35$ AMPERES.

Fig. 13 is another typical night curve, similar to Fig. 8, showing a marked reduction in signal strength on certain waves. It is interesting to note that the average of these points gives a curve which follows the radiation resistance curve of the transmitting station, showing a falling off of the received energy in proportion to the reduction in the radiation resistance at the transmitter. For reasons given in the discussion of Fig. 8, the efficiency of transmission must have been very high and reflection phenomenon marked at the time Fig. 13 was taken.

Figs. 14 and 15 are typical examples of the unstable daylight class, probably indicating refraction, and in addition, reflection and a resulting interference upon certain wave lengths.

From a half-hour to two hours time elapsed during the taking of each set of observations. During this period the conditions of absorption for various wave lengths could have changed materially. However, many sets of observations are the results of two sets of readings, giving identical curves although separated by one-half to three-quarters of an hour. It may be assumed with reasonable accuracy therefore, that as a whole, the observations for any given date recorded herein present conditions existing simultaneously on all the wave lengths. This is undoubtedly true of the data showing stable day conditions and these are the only data from which deductions and calculations have been made.

It is probably not true, however, of the pure night curves, Figs. 8 and 13. At night, conditions of apparent absorption may vary by several hundred per cent within a few minutes. The fact that the mean values of Fig. 13 follow the radiation resistance curve, however, would tend to show that conditions were fairly uniform throughout the period during which its observations were made.

AN EMPIRICAL TRANSMISSION FORMULA FOR CONTINUOUS WAVES

The observed data are presented in the accompanying tables and from these the curves of the fifteen plates are drawn.

Calculations have been made from data taken from the curves *as drawn*. Only curves or parts of curves which show stable daylight conditions have been used. These are:

Fig 1.	All waves
" 2.	" "
" 3.	" "
" 4.	" "

OBSERVED DATA
CORRECTED TO $I_s = 35$ AMPERES

Fig. No.	Wave Length Meters λ	Received En- ergy Watts $\times 10^{-10}$ P	Fig. No.	Wave Length Meters λ	Received En- ergy Watts $\times 10^{-10}$ P
1.	5000	145.	8. N i g h t	6000	1120.0
	7000	190.		7000	1340.0
	9000	259.		8000	788.0
	10000	301		9000	1100.0
	11000	336.		10000	1100.0
	11800	368.			
2.	5000	157.	9.	6000	40.7
	6000	217.		7000	124.0
	7000	288.		8000	127.0
3.	3000	496.		9000	170.0
	4000	531.		10000	210.0
	5000	371.	10.	6000	52.5
	6000	557.		7000	118.5
	7000	905.		8000	113.8
	8000	829.		9000	68.4
	9000	919.		10000	72.2
	10000	1170.			
4.	4000	255.0	11.	5000	26.0
	5000	312.0		6000	110.8
	6000	480.0		7000	130.0
	7000	454.0		8000	168.0
	8000	660.0		9000	75.0
	9000	778.0		10000	82.0
5.	5000	429.0	12.	5000	32.0
	6000	707.0		6000	89.6
	7000	911.0		7000	186.0
	8000	830.0		8000	114.5
	9000	886.0		9000	79.4
	10000	919.0		10000	92.5
	10500	886.0	13. N i g h t	3000	2540.0
6.	4000	7.8		4000	1295.0
	5000	14.6		5000	668.0
	6000	53.6		6000	2720.0
	7000	142.0		7000	576.0
	8000	73.3		8000	1610.0
	9000	75.2		9000	743.0
	10000	135.0		10000	320.0
7.	4000	7.8		10500	842.0
	5000	27.2	14.	6000	179.0
	6000	142.0		7000	310.0
	7000	255.0		8000	292.0
	8000	215.0		9000	127.0
	9000	237.0		10000	111.0
	10500	214.0		10500	151.0
			15.	6000	107.5
				7000	156.0
				8000	179.0
				9000	126.0
				10000	167.0
				10500	178.0

- Fig. 5. 5000-7000 meters
 " 6. 6000-7000 meters
 " 7. 6000-7000 meters
 " 9. All waves

If in formula (3) the last term, the divergence factor $e^{-\frac{0.0019 d}{\lambda}}$ be written e^{-Ad} and the whole formula be solved for A , we obtain

$$A = \frac{1}{d} \log e 120 \pi \frac{h_1 h_2 I_s}{\lambda d R I_R} \sqrt{\frac{\theta}{\sin \theta}} \quad (8)$$

Twenty-five separate calculations of A by the above formula have been made from data taken from the curves on wave lengths ranging from 3000 to 11,800 meters. From these it may be said that for continuous waves

$$A = \frac{\beta}{\lambda \sqrt{2}} \quad (9)$$

within the limits of error of these observations.

In the above equation the average of twenty-five values of β is 45×10^{-4} .

The exponent of λ shown in equation (9) holds consistently through all data, while β varies from day to day. The value given above was the average observed during these tests. The maximum noted occurred on March 15th on 6000 meters when β reached a value of 77×10^{-4} . The minimum noted was on March 8th on a 9000-meter wave when β dropped to 20×10^{-4} .

Substituting equation (9) and the above average value of β in formula (3), we obtain the following daylight transmission formula for continuous waves over sea water:

$$I_R = 377 \frac{h_1 h_2 I_s}{\lambda d R} \sqrt{\frac{\theta}{\sin \theta}} \cdot e^{-\frac{0.0045 d}{\lambda \sqrt{2}}} \quad (10)$$

where all factors are expressed as in formula (3).

No attempt has been made to give an average value of β for night work, since it may vary by many hundred per cent within a few minutes and a few hundred meters change in wave length may make a variation of the same order of magnitude. Figs. 8 and 13 illustrate these points. It is also obviously useless to attempt the approximation of β for day work during periods when

partial night conditions exist. All such conditions usually tend to reduce the apparent absorption upon certain waves and increase it upon others. Hence in using formula (10) for the calculation of *average* sending radius and received signal strength, it may be considered safe to use the average value of β given above, provided the transmitting station has several waves at its disposal. If its available wave lengths are limited, however, it is liable, at times during which unstable day conditions exist, to be forced to transmit on a wave having poor transmission efficiency. With such stations it is obviously safer to use a value of β more nearly the maximum noted above for the calculation of *average* sending radius. The value to be used is naturally controlled to a great extent by the importance of the station, the quality of service required, and the geographical location.

During November and December, 1914, tests were carried on by the United States Navy Department from the Goldschmidt high-powered radiotelegraphic station at Tuckerton, N. J., to the Honolulu plant of the Federal Telegraph Company. Signals were transmitted in daylight the entire distance of approximately 4330 nautical miles (8000 km.), using a rotary tikker detector in receiving at Honolulu.

The antenna at Tuckerton consists of 36 wires attached to the top of a steel tower 825 ft. (250 m.) in height. The outer ends of these wires are attached to poles 40 ft. (12 m.) high arranged in a circle of 1500 ft. (450 m.) radius with the steel tower at the center. The wave lengths used by Tuckerton were 7400 and 10,000 meters. The shorter wave was never heard in Honolulu in daylight, but the longer was received consistently during the tests with daylight over the entire path of transmission. On the 7400-meter wave, both a Goldschmidt alternator and a Poulsen-Federal arc were used, but on the 10,000-meter wave only the arc was available.

Certain further checks on formula (10) are possible from these tests. These are as follows:

At San Francisco, approximately 2000 nautical miles from Tuckerton, the ratio of received currents for the 10,000- and 7400-meter waves was

$$\frac{I_{R \ 10000 \ m}}{I_{R \ 7400 \ m}} = 1.56 \text{ observed and } 1.67 \text{ calculated.}$$

This is primarily a check upon the $\sqrt{2}$ exponent of wave length and the constant β of 45×10^{-4} in the divergence factor.

At Honolulu a received current of 5.5×10^{-6} amperes on 10,000 meters was observed. The calculated value from formula (10) is 6.12×10^{-6} amperes.

On the 7400-meter wave from Tuckerton, formula (10) gives a value of received current below audibility and this is roughly checked by the fact that this wave was never heard until noon, Honolulu time, which was 5:30 p. m. at Tuckerton. This late in the day, normal conditions no longer exist and night conditions are beginning. The calculations are made from the following data:

$$\begin{aligned}
 I_s &= 122 \text{ amperes on 10,000 meters and 100} \\
 &\quad \text{amperes on 7400 meters} \\
 h_1 &= 300 \text{ ft.} = 91.5 \times 10^{-3} \text{ km.} \\
 h_2 &= 197 \text{ ft.} = 60 \times 10^{-3} \text{ km.} \\
 \lambda &= 10 \text{ km. and 7.4 km.} \\
 d &= 4330 \text{ nautical miles} = 8000 \text{ km.} \\
 \text{At Honolulu } \left\{ \begin{array}{l} R_{10000} = 150 \text{ ohms. High resistance due to} \\ \quad \text{close coupling, mediocre ground, and} \\ \quad \text{series receiving circuit.} \\ R_{7400} = 135 \text{ ohms.} \\ \theta = 72.5 \text{ degrees.} \\ A_f = 14.25 \text{ times audibility at Honolulu on} \\ \quad \text{10,000-meter wave and zero on 7400-} \\ \quad \text{meter wave.} \\ P_R = 3.2 \times 10^{-10} \text{ watts for unit audibility.} \end{array} \right.
 \end{aligned}$$

No consistent difference was noted at San Francisco or Honolulu in the energy received from the alternator as compared with the arc when both were transmitting upon the same wave length and delivering the same antenna current.

The general conclusions to be drawn from the San Francisco-Honolulu and Tuckerton-Honolulu tests of 1914 are as follows:

(1) Under normal day conditions the comparative transmission efficiency of continuous waves is somewhat higher than that of damped waves on wave lengths above 3000 meters. The last term, the divergence factor of formula (10), compared with that of formula (5) shows this.

(2) The transmission efficiency of continuous waves generated either by a Goldschmidt reflection alternator or a Poulsen-Federal arc would seem to be the same.

(3) In transmissions over distances in the order of 4000 nautical miles, intervening land appears to be the equivalent of sea

water, at least during the winter months. This may be due to the greater part of the received energy traversing the upper strata of the atmosphere.

(4) In the 15 curves shown in the figures, much evidence is found adding weight to the theories of refraction, reflection and interference upon certain wave lengths. These are further borne out by observations made at the Beach station of the Federal Telegraph Company, nine miles from the high-power plant described herein. Very frequently a wave length used by Honolulu, which is excellent at one, is useless at the other, and as atmospheric conditions change, conditions are reversed. This plainly shows interference bands not over 18 miles in width. Such phenomena are most apparent at night when reflection is pronounced.

(5) Ability to change wave lengths rapidly is of the greatest value in long-distance radiotelegraphy. Fig. 13 shows this to good advantage.

Formula (10) was derived from a distance of approximately 2000 nautical miles (3700 km.) and has been checked by the data presented herein for a distance of approximately 4330 nautical miles (8000 km.). It is believed that it is of sufficient accuracy for ordinary practical purposes and it is hoped it may be satisfactorily used in commercial design. It must always be borne in mind, however, that variations of 100 per cent or more may occur from day to day under seemingly identical conditions at both transmitter and receiver, and also that the formula was derived from data obtained from waves traveling over the waters of the North Pacific Ocean, which, as a rule, permits of greater transmission efficiency than is found in some other parts of the world.

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DISCUSSION ON "CONTINUOUS WAVES IN LONG-DISTANCE
RADIOTELEGRAPHY" (FULLER), NEW YORK, APRIL 9,
1915.

Alfred N. Goldsmith: As Mr. Fuller has truly said, the paper will be of considerable assistance in enabling us in the future to proportion a transmitting set to the distance to be covered, at least under conditions such as he has mentioned; that is to say, transmission over waters similar in absorbing power to those of the North Pacific.

In my judgment, radio engineering is one of the most interesting branches of electrical engineering imaginable; in fact it is unique in that we are compelled to employ novel units of time and space. The unit of distance for our purposes is logically the distance which an electromagnetic wave travels in a second. We deal with almost incredible velocities, namely, those of the light waves themselves. However, the electromagnetic waves employed differ from the extremely minute light waves in that the wave length ranges from several hundred feet to five or six miles, or more, as indicated by Mr. Fuller.

We deal here with frequencies quite outside of the range normally employed in a-c. engineering. They run from 15,000 to 20,000 per second for our long wave, well up into a million or more cycles per sec. All of these unusual conditions of working lend to radio engineering a certain fascination, which never fails to keep men in that field, once they enter it. There is hardly any possibility of their leaving it thereafter.

To pass to continuous wave transmission, it is extremely interesting to note that sustained wave transmission is practically the meeting ground of ordinary electrical engineering and the radio engineering of the present. We are dealing here with true alternating currents in the antenna, generated by methods which are or should be familiar to every electrical engineer. They may be handled, received, detected, neutralized or manipulated, in general, exactly as are the ordinary alternating currents used in engineering, and the laws which govern 60-cycle currents govern them equally well. That is something which cannot be said, without mental reservation, when we come to the highly damped wave train, used in the older spark radiotelegraphy. Furthermore, the devices employed to produce continuous waves are of a type easily comprehensible to every skilled electrical engineer; for example, a device like the Goldschmidt alternator, which is, as Professor Kennelly has aptly termed it, nothing more than "a nursery for higher harmonics." It is a device in which, instead of eliminating these troublesome visitors of higher frequency, they are nursed and brought to resonance and finally radiated from a properly arranged electrical system.

We have with us this evening a gentleman who has been very prominent in the production of alternators which produce incredibly high frequencies, from 100,000 to 200,000 cycles per

sec. His work in this field has been of a pioneer character, and later on it will be a pleasure to hear what he has to say about sustained waves. Some of the alternators designed by him are provided with a rotor having a rotational speed of 20,000 rev. per min., with 800 to 1200 poles; and to load them, they are directly connected to a capacity and a resistance of proper value so that full energy may be drawn from them. Such alternators are of interest to the electrical engineer, if only to emphasize the fact that not all alternators need to be connected to a water rheostat in order to absorb their output.

In connection with the use of sustained waves, certain new effects have for the first time become of interest and prominence. The first of these is unquestionably that of reflection or interference of the sustained wave. I recall some time ago hearing Dr. de Forest present a lucid description of this phenomenon before the Institute of Radio Engineers. He was at that time with the Federal Telegraph Company. The results he presented were perfectly clear so far as they affected the reflection of waves.

We deal here with a vast out-door laboratory. Imagine waves thousands of meters long, which strike cloud layers, or conducting layers. They are reflected downward and interfere definitely with waves which have pursued a shorter path directly along the surface of the earth. Clearly there will be points at which waves of a certain length are destructively interfered with, and consequently signals will become quite inaudible; and yet at points situated differently, without interfering radiation from the reflecting layer, the same waves may produce powerful effects. We have here a highly novel reflecting effect, one worthy of study, and which may lead to important contributions to our knowledge of the nature of the upper layers of the atmosphere.

The sustained wave methods of radio transmission have also led to the development of new methods of reception. They have led to the introduction of that curiously mysterious device the *tikker*, particularly the rotary *tikker*. This instrument consists of a metal wire resting on a rotating metal wheel. It acts as a commutator which periodically discharges a condenser, this condenser being charged slowly by the incoming energy. The discharge passes through the telephone receiver and produces the received signal. We know that these effects exist; but it is not clear why only certain combinations of metal should be satisfactorily operative. I trust that some light will be shed on these points in the near future.

There is a device known as the tone wheel, used by the Goldschmidt company, which is nothing more nor less than a carefully designed commutator. This interrupts the incoming energy at a frequency slightly different from the incoming frequency, and produces something which is not quite a beat phenomenon, but which fortunately renders the incoming energy

available to deflect the telephone diaphragm at an audible frequency. This would be a device of no great use with damped wave trains. And finally, the use of sustained waves has led to the development of that extremely efficient method of reception known as the heterodyne system of receiving, wherein the incoming energy which, of course, is nothing more nor less than a normal radio-frequency alternating current, is caused to produce beats with the locally generated alternating current. These beats are of audible frequency, and frequently the energy represented by the beat may be, and practically always is, much higher than that of the incoming energy itself. We thus have an extremely efficient device. On a small scale, it is nothing more nor less than the beat effect produced by two alternators which are not quite in step. The synchronizing lamp flickers up and down, and at a frequency less than that of either of the alternators. Similarly, the telephone diaphragm moves to and fro at a frequency which is the difference between that of the incoming energy and that of the locally generated energy, and much lower, therefore, than either. We have, consequently, a device that is efficiently possible only when we are using sustained waves.

The arc as a generator is a device that some time ago seemed to be practically hopeless. No one supposed that so erratic and irregular a device as an arc could be used to produce a steady flow of very high frequency alternating current. Every one knows the arc has the negative characteristic; that a slight increase in voltage will produce an increase in current, and vice versa. It is essentially unstable, and series resistance will be required in general to maintain the stability of an arc, unless a special form of d-c. generator be used with it.

It is, therefore, a scientific *tour de force* that we have been able so to build and control arcs by circuits connected to them that they have now become satisfactory and reliable generators of considerable amounts of sustained energy. Of course, in the radio station, 50 kw. is a large amount of energy.

The arc apparatus is distinguished by unusual simplicity. When looking at the picture of the arc in the paper, one looks at practically all there is of the station except a few switchboards, a key, and a loading antenna inductance. The station is simple, readily worked, and easily accessible in all its parts.

We can imagine the predicament in which Mr. Fuller would have been had he been forced to change his transmitting wave lengths rapidly, using the very high speed radio-frequency alternator. In slowing down or speeding up such an alternator hastily, dangerous strains would have been developed. This brings up a point of interest to those who desire to apply radio apparatus to military purposes; namely, that it is desirable to avoid interference by the enemy's transmitters, or to interfere with them, if desired. It is also valuable from the commercial point of view, in that if a certain wave length is found to be un-

suitable for transmission at a given time, it may be changed; and consequently the possibility of a rapid change of wave length is extremely valuable. Those who are going to work on the production of sustained oscillations should bear in mind that one of the prime desiderata of a generator of this type is the possibility of rapidly changing the wave length.

In this connection, Mr. Fuller has brought out the "sunrise effect", which is of great interest to us. Somewhere between two stations which are widely separated there may be a dividing surface between the light and darkness. In an admirable paper presented to the Institute of Radio Engineers some time ago, Professor Kennelly brought out the fact such a surface of darkness and light would act as a fairly good reflector for waves which strike it. It is a region where there may be considerable ionization of the upper layers of the atmosphere, due to the sunlight falling on one side. In consequence, we may expect to find a sudden diminution of received energy as the sun rises and the ionization boundary layer sweeps along between the stations, and this effect is found to exist. This leads to an interesting speculation of another sort. If the atmosphere, indeed, produces such great changes in transmission, is it not possible that only the earth's atmosphere and ground have properties which make radio transmission over long distances possible? The earth, in effect, is a slightly conducting sphere. A non-conducting layer of air surrounds it, and then above this are upper layers of air which are certainly fairly good conductors, being at approximately the same pressure as exists in a normal Geissler tube. Above this, there is a region of absolute non-conductivity.

The boldness of the early experimenters in this field is to be commended, particularly the experiments at Newfoundland, where Mr. Marconi attempted to receive the S signals sent out from Poldhu, near Cornwall, England, at a distance of several thousand miles. Such boldness was commendable, because there was little reason to expect that energy would follow the curve of the earth. To-night we have experiments described where energy travels along the earth in spite of the fact it might have been radiated off into space. It is obvious that such waves must have their feet attached in some way to the earth, or are reflected from the upper layers of the atmosphere.

Obviously, we have a peculiarly fortunate arrangement of conducting layers on the earth, so proportioned physically that long-distance radiation is possible. The great degree to which radio transmission depends on these physical conditions leads us to wonder whether the earth is not the only planet on which long-distance radio communication is possible.

J. Zenneck: I should like to call your attention to the following points. The formula on which all measurements of Mr. Fuller are based is equation (7):

$$P = R I^2 = 3.2 \times 10^{-10} A_f$$

It indicates that the audibility factor A_f in Mr. Fuller's device was proportional to the received watts. Now the audibility factor is proportional to the current in the unshunted telephone circuit, supposing that the main current in this circuit is not changed by shunting the telephone. Therefore, in Mr. Fuller's arrangement the telephone current must have been proportional to the received watts.

Mr. Fuller used as a detector, a tikker. Therefore we should expect that the telephone current be proportional to the received current I itself, but not to the received watts and therefore not to the square of the current. I should be very much obliged to him if he would kindly give us more details regarding this fundamental point.

Mr. Fuller by comparing his results with those of Dr. Austin comes to the conclusion that the divergence of the continuous waves used by himself is smaller than the divergence of the damped waves used by Dr. Austin.

Now of course two sets of measurements can only be compared if they are made under the same conditions.

Identity of conditions in wireless work in the first place means identity of atmospheric conditions. As the values of Mr. Fuller vary very much from day to day (see Figs. 4, 6 and 9 of his papers) it would be a little embarrassing to say at what time the atmospheric conditions over the Pacific in 1914 have been identical with those over the Atlantic in 1910 and 1913, when Dr. Austin made his experiments. I fully agree with Mr. Fuller that in such cases nothing else can be done than comparing the average values of the measurements. But I think that he will agree with me that this is not what is really wanted.

Further, in all cases where the waves are passing from the surface of the land to the surface of the sea or in the opposite direction, there must be a reflection of the surface waves, because the dielectric constants and the conductivity of solid ground and sea water are quite different. Therefore, two measurements are only comparable, if in both the reflection takes place in the same way. This condition is very troublesome too, as we do not know anything about the laws governing this reflection of surface waves.

Finally, as the divergence factor largely depends on the wave length, only such observations as are made with the same wave length should be compared. Now Dr. Austin made his experiments with wave lengths up to 4000 m., and Mr. Fuller with wave lengths from 3000 to about 10,000 m. Therefore their measurements are only comparable between the limits of 3000 to 4000 m. I have plotted curves, using the wave

lengths as abscissas and the values of the exponent $\frac{\beta}{\lambda^n}$ of the divergence factor as ordinates. In Fig. 1, curve A represents the values based on Dr. Austin's empirical formula and the

curve F those derived from Mr. Fuller's empirical formula (the curve S is that according to the theoretical formula of Professor Sommerfeld). You see that within the limits from 3000 to 4000 m. of wavelength the values derived from Dr. Austin's equation and those corresponding to Mr. Fuller's formula agree excellently.

If we were justified in extending an empirical formula beyond the limits within which it is verified by experiments—for instance, Dr. Austin's formula for wave lengths above 4000 m.—we should get the dotted line A , and we should really come to the conclusion, as Mr. Fuller does, that the divergence factor for his undamped waves is smaller than that for Dr. Austin's

FIG. 1

damped waves. But if we would extend Mr. Fuller's formula on values below 3000 m. (see the dotted curve F), *we should get just the contrary result.*

Under these circumstances it seemed to me more attractive to combine the results of Dr. Austin and Mr. Fuller than to point out any discrepancy between them. This may be done in

various ways: Putting the divergency factor $= e^{\frac{-0.0019}{\lambda^{1/3}} d}$ we get the dash curve Z_1 , or using as divergency factor the simple

term $= e^{\frac{-0.0019}{\lambda} d}$, we get the dash-dotted curve Z_2 . Both curves, especially the first, agree fairly well with the results of Dr. Austin and Mr. Fuller at the same time.

Lee de Forest: Without wishing in any way to violate our neutrality, I might say that this paper tonight should make Americans who are at all interested in the progress of the radio art feel very happy. The work which Dr. Austin and Mr. Fuller have done stands alone to date. There have been no observations of the sort made anywhere else in the world to my knowledge. Of theoretical formulas we have had a plenty, but they lack the interest which an empirical formula based on actual observations of such a thoroughly practical character as this possesses.

It was my good fortune to be with the Federal Telegraph Company at the time this matter of the interference bands and absorption and reflection was first observed, and I believe that you may be interested in a brief account of how it happened to come about. I might say that the chances are it would not have been observed to this day had we been using the alternator instead of the arc.

As you doubtless all know, the system used by the Poulsen company is this—the antenna is connected through an inductance to the arc and thence to earth, with the transmitter key put across a certain relatively small amount of the inductance. The key is normally a back contact key, that is, the contact is broken when the key is depressed. Signaling therefore is by change of wave length, up or down, of relatively 5 per cent. Suppose a station is working with 3000 meters with the key up, it will be radiating at 3300 to 3500 meters with the key down.

We had observed repeatedly, and chiefly in the early hours of the evening, and during the first part of the night generally, that the strength of signals would fall off between San Francisco and Los Angeles, or vice versa; and that at the time when the signals were failing they might within a few minutes change from 40 or 50 times audibility down to zero audibility. At the same time the compensating wave signals, of the wave radiated on the upward stroke of the key, a shorter wave or longer wave, would be heard with undiminished intensity or even increased intensity. In order to hear the compensation wave signals it was merely necessary to change the "tuning" adjustment of the receiver slightly. It was easy to make such observations, and time and time again the operators observed these facts. In such cases they merely told the distant operator to change his wave length, which he did by cutting in a different amount of inductance on the transmitting helix. Or they sent their messages on the commutation wave until the signals came in loud, until such a time as these signals would in their turn begin to fade, when they would then find the compensation wave signals coming in loud, and change back again to the original wave lengths. Such experience became the common talk, although we were quite at a loss to explain the phenomenon. It is simple now to understand it, but at that time it was a tremendous puzzle. As we had a great many fogs at that period, we thought it might be due

to absorption, but could not understand why a wave three thousand meters long should be largely absorbed, while a wave thirty-three hundred meters in length was not, in the same degree. This phenomenon of the huge interference bands in the upper atmosphere forced itself upon us, and all of our observations have established the truth of the explanation more and more.

The interference effect is easily understood. If we suppose an upper reflecting layer parallel to the earth's surface, and from twenty to one hundred miles above it, then the energy which travels along the earth's surface is, at certain distances from the transmitter, in phase with the energy reflected downwards from some definite zone of this upper layer. Likewise at another point where the difference in the lengths of the two trajectories is one half wave length greater or less than before, the two energies will be in opposite phase.

If we had means of knowing the exact points of reflection, for example, if at the middle of the arc traversed or any point, provided the angle of the reflecting layer there were known, we could, of course, knowing the wave length, compute the elevation of the reflecting layer, which would be of interest. Not knowing anything about the position of the layer or layers, nor the angles involved, we are unable to determine that.

The clause towards the end of Mr. Fuller's paper calling attention to the fact that the interference bands are not over eighteen miles in width is to me one of the most interesting statements in the physics side of the radio art. Imagine an invisible aurora, the bands of the aurora hanging down from the regions of upper atmosphere and wavering as you sometimes see the visible aurora wavering on a winter night. Something akin to that phenomenon is going on, but only the observer who is listening to the undamped wave signals from a distant wireless telegraph station can realize that this really beautiful phenomenon exists. In daylight this phenomenon generally ceases, although I observe these other striking curves of Mr. Fuller's show the same effect, to a certain extent, in daylight. In our work in 1910, '11 and '12 at San Francisco and Los Angeles, using shorter wave lengths over shorter distances, these daylight effects were seldom observed. They are most prominent at night when the altering meteorological conditions of daylight merging into darkness bring down these ionized strata or bodies of conducting air into a great variety of shapes and angles.

Only those who have worked frequently with the undamped wave method of transmission can realize the importance of being able to change the transmitted wave length at an instant's notice, in order to maintain anything like reliable communication.

While we are observing these things and plotting curves of the actual interference phenomena in this country, I have been astonished to see in the foreign papers, notably in the columns of the London *Electrician*, long series of disputes between distinguished solons, on the theoretical possibility of

this reflecting or refracting layer. One says it conceivably might exist, and another says that mathematically it cannot exist, and here it is as well and as indubitably established as is the fact that we can transmit messages through space at all.

A. J. Hepburn: The importance of Mr. Fuller's work embodied in this paper is obvious in view of recent developments in the art and the almost universal recognition of the superiority of the undamped wave for long-distance communication. The experiments described are the most thorough and conclusive that have come to my attention and it seems to me that this paper is the most valuable contribution to the science, as regards the particular phase treated, that has been made since the publication of the Austin formula. In the somewhat hurried consideration I have found it possible to give to this paper, there has appeared to be nothing to criticize as regards conduct of the experiment, analysis or deductions, *provided that one does not go back of the fundamental assumptions.*

The number of radio engineers engaged principally with the problems of long-distance communication, to whom such work as this is of special importance, is but a small proportion of the total number; and the number of those engaged in a purely executive capacity with the technical direction of a large radio system is smaller still. When one of this small number finds himself in a position absolutely unfettered by allegiance to any system, or the necessity of protecting investments in patents and manufacturing plants, and responsible only for producing the most efficient and the most economical results by any means known to the art, it may be conceded that his point of view is likely to be unusual. If the following remarks seem to question some of the most authoritative pronouncements in the matter I trust that the unusual point of view will be taken into consideration.

Briefly, I believe that we need a transmission *theory* more than we need a transmission *formula*. Almost any sort of suggestion as regards possible factors affecting transmission receives a respectful hearing in the present state of variant opinions on that subject, but all efforts to evolve a more accurate formula are made very conservatively, not to say gingerly. This is curious in view of the fact that the formula is but the mathematical statement of the theory. I ascribe it to the restraint imposed by the great weight of authority behind the mathematical work that has been done.

I believe that there is promise of most valuable progress toward the establishment of a complete theory in a course of experimental work such as that which has been contemplated by the Navy Department for several years, but which has been prevented by the pressure of routine work. The plan contemplates the use of the station at the Washington Navy Yard as a transmitting station and the stations at the Bureau of Standards (6 miles distant) and that at Annapolis (23 miles

distant) for measurements of received energy. Starting with the Austin formula as a trial basis each separate factor would be independently investigated, as well as some other possibilities that do not appear in that formula, such as decrement and reflection. For example: The height of the transmitting antenna would be systematically varied while all other factors are kept constant; then the height of the receiving antenna; then the antenna amperes; then the wave length; then the decrement due to added ohmic resistance; then the decrement due to increased radiation resistance, that is, different forms of antennae; and so on. These experiments would of course have to be repeated in a different locality and over greater distances to determine the constants that might appear, but operation at close range where the utmost nicety of measurement is possible would be the first requisite. This is a suggestion rather than an outline of the work planned. If it illustrates sufficiently well the method of attacking the problem, the ramifications of the work will be self-evident.

I cannot but feel that the result of such experimental work would lead to some notable changes in the complexion of the present transmission formulas. In this hasty comment I have no opportunity to submit anything approaching a full statement of the reasons that have led to this point of view, but I would call attention to the few following points, not as presenting any ordered argument but simply as significant in themselves.

(a) The remarkable instances of unusual communication, familiar to every head of a radio station, which do not accord with any known theory. For every instance explainable on the theory of reflection, for example, one may be cited in contradiction; and the same as regards wave length, land or sea effect, etc. A single discrepancy of this nature is sufficient ground for investigation.

(b) On the theory of an upper conducting layer of atmosphere to which the waves are "attached" as to the earth, how conceive reflection from that layer more easily than from the earth itself?

(c) Mr. Fuller's statement that the received energy did not always increase with the antenna current above a certain limit is very significant in view of many observations on this head by others.

(d) The indication of interference bands noted by Mr. Fuller is rather striking, but would not this phenomenon of itself invalidate the quantitative measurements founded on wave length taken at a single fixed station?

(e) I have not had an opportunity to calculate by Mr. Fuller's formula the relative increase of received energy due to sustained oscillations over that given by Austin's formula for the same radiation in the form of wave trains, but my impression is that the consistent results of actual day-to-day work would show the superiority of the undamped wave to be very much greater than indicated by the formula. This, of course, independently of the

more efficient receiving apparatus which is generally used for undamped waves.

(f) We cannot imagine the conductivity of the earth or sea varying to a great extent, certainly not commensurately with the wide variations noted in received energy. Is this factor then of small importance? Every theoretical writer and every practical engineer accords it first place in his consideration of the subject. Whatever its importance, it seems to deserve a place in the transmission formula. It is certainly subject to quantitative measurement.

Considerations of this nature might be added at great length. The point I want to make is that if we limit our efforts in experimental research to refinements of more or less empiric formulas we thereby set a limit to our final knowledge. Of course this work had to come first. Such work as that of Mr. Fuller cannot be too highly commended. Are we not now prepared to go somewhat deeper?

E. F. W. Alexanderson: Mr. Fuller has, as already stated, brought the art of radio engineering very close to the electrical engineer by his paper presented tonight. The matter of the transmission of radio messages has become simply a matter of transmission of alternating current. The formulas for calculating the efficiency of transmission have been given, and what is more important, these formulas have been explored throughout a wide range of practical experience.

If a system for radio transmission is to be designed in view of the knowledge we have now, we will need to determine the frequency or eventually the range of frequency that is most favorable, the power necessary and the voltage for which the aerial must be designed. For instance, if we consult the formula given more generally, we find that in some particular cases it can be figured out that a certain rate of transmission requires 100 amperes in aerial. If we assume to use, as suggested here as a typical example, 0.01 microfarad capacity, we find immediately that 100 amperes flowing through a certain aerial will raise the potential of the overhead wires 30,000 volts in the case of 50,000 cycles, or 60,000 volts in case the frequency is 25,000 cycles. An installation for radio frequency is quite a different matter from such frequencies as electrical engineers ordinarily deal with. The losses from corona are extraordinarily high, and while such corona losses would not be considered to amount to anything ordinarily, they may absorb almost all the energy which is available. Insulators, also, may absorb a great deal of power, and therefore as a whole a condition is easily found where the voltage may be excessive, and consequently the lower limit of frequency may, under certain conditions, be determined by the feasibility of the insulation and the maximum voltage.

If we then further examine the data given on the variations that occur due to refractions and other weather phenomena, it is apparent that a certain range of frequency is much

more favorable. It appears from these curves, as if under the conditions the frequency should at least correspond to something lower than 6000 meters, in other words, lower than 50,000 cycles. It will be very valuable for the design of apparatus for radio frequencies if some practical rule can be given for the range of frequency that is most efficient, in addition to the general formula and theoretical considerations.

The curves given in the paper suggest that possibly for distances of over 2000 miles we might say that the frequencies should range between 15,000 and 25,000 cycles. If that is so, a basis would exist for the design of alternators for generating that power. I must ask indulgence if my mind runs into the channel of alternator designs and what bearing that may have on the problem.

We are just now testing in Schenectady an alternator for long-distance work, which was designed for 50 kw. at 50,000 cycles, and it is particularly gratifying, in view of the information we have tonight, to be able to state that the alternator has proven to give a good deal more than 50 kilowatts throughout the whole range of frequency from 25,000 to 50,000 cycles. The importance of varying the frequencies in order to accommodate the apparatus to the weather conditions prevailing has already been brought out sufficiently by other speakers as well as in the paper.

I want to explain how this particular alternator can be used for varying frequency. The alternator has a speed range from 1800 to 3600 rev. per min., and for these corresponding frequencies no other tuning is needed than the tuning of the antenna itself. The capacity that the alternator needs for bringing out this power in the antenna and the tuning device, is the regular loading coil. Therefore, if the antenna is tuned for any one frequency, it is only necessary to speed up the alternator until it automatically falls in synchronism with the antenna, and then the load is applied by the power flowing from the alternator and the speed is prevented from getting any higher. Test has shown that the speed under these conditions is stable enough for heterodyne receiving. For accurate work additional refinements of speed regulation are, however, needed.

Returning to the question of the frequencies which are really desirable for radio communication, it is, of course, premature to speak about standardization, but the designer must have some definite idea in mind in order to advance the art at all, and the paper presented tonight has brought us a good deal further forward in the knowledge we really need.

G. H. Clark: These days, the formula in connection with wireless seems to have just about as much immunity from attack as the average patent connected with wireless does, and this formula of Dr. Austin's seems to fare pretty badly in this respect. In order to show that even in the field of spark telegraphy there was wide divergence between the absolute results and the results when calculated by the Austin formula, a test

may be referred to which has already been mentioned in Mr. Hepburn's communication. In this test two spark transmitters of widely different efficiencies were coupled to the same antenna and were so adjusted that the same radiations were obtained in each case. On measuring the decrement from the two transmitters it was found that one gave practically twice the damping of the other. The received current was measured, and it was found that the received current was practically twice as great in the case of the transmitter having the smaller damping. There is a case where, according to the Austin formula, it would seem there would be no difference between the two. The conditions were the same, the distance was the same, and yet the decrement had a marked effect in determining the receiving energy. Therefore, that experiment is in line with the wide divergence between the conditions as derived from Austin's formula and the result obtained in connection with Poulsen's experiments.

There is another test I would call attention to, which was carried on recently by the U. S. Navy Department at the stations at Tuckerton and Arlington. The object of the test was to show the results of different wave lengths obtained from a common arc transmitter. The condition in each case was that the power delivered from a 500-volt generator should be a constant. The arc was of the usual type of series arc, directly in the aerial. At various wave lengths the power was adjusted to be exactly the same, and the radiation noted and a curve drawn showing the radiation at different wave lengths. The power was chosen as 30 kw. in each case. It was found in both cases that a very marked maximum was found in the radiation curve. At Tuckerton, where the antenna is of the umbrella type, the natural period of the system was 2500 meters, and the wave length at which the maximum was obtained was 7500 meters, just three times as much. At Arlington, where the antenna is of the flat type, with a natural periodicity of 1900 meters, the best wave length was 5700 meters. It is known that for modern quenched gap transmitters the most efficient wave length for transmission is between 1.75 and 2 times the natural period of the aerial, but in these two cases of arc transmitters it looks as if the best wave length is three times the natural period.

In Mr. Fuller's experiments, he has shown us in his paper that he did not proceed by the method of keeping the energy delivered from the source constant, but, on the other hand, he kept the current in the antenna constant, and in such case it would seem there would be a hump at the transmitting station corresponding to the most effective wave length for that antenna, and it would be only reasonable to expect that the same maximum would be shown in the receiving signals. Almost all the curves Mr. Fuller shows from Honolulu to San Francisco show maxima at 7000 meters, and the object of

all these remarks I have made is nothing more than to ask Mr. Fuller if the natural period of the aerial at Honolulu is not one-third of 7000, or 2300.

L. F. Fuller: Mr. Clark's deductions in regard to the natural period of the Honolulu aerial are quite correct; it is approximately 2300 meters.

Referring to his description of the experiments with two damped wave transmitters, of widely different decrements, it is interesting to note that Dr. Austin's latest published damped wave absorption formula includes a correction factor for the decrements at both transmitter and receiver. The earlier formula did not do so, and I presume it is to this Mr. Clark refers.

Dr. Goldsmith has mentioned the complicated theory of operation of the rotary tikker used in these measurements. This complication may, I think, be seriously considered in connection with the fundamental point raised by Dr. Zenneck (in regard to formula (7) of my paper) that we should expect to find telephone current proportional to the received current itself. Prior to the beginning of these experiments, this point, being fundamental, was thoroughly investigated with the result that, contrary to what might be expected theoretically, the telephone current, with the type of rotary tikker used, is proportional to the received watts. This may be explained at present only by the peculiarities of tikker electrical characteristics.

We have had many theoretical formulas covering radio transmission and but two empirical ones, namely—that of Austin for the damped wave, now corrected for decrements, and that proposed in this paper for continuous waves. I agree heartily with Dr. Zenneck that these empirical formulas can only be compared, even in a general way, over a one-thousand and meter range of wave lengths, since the Austin data do not go above four thousand meters, and our continuous wave data have not been taken below three thousand meters, and further, since the Austin experiments were over the Atlantic, and the continuous wave data were taken over the Pacific many months later, under widely different conditions.

As men familiar with the making of radio measurements realize, the difficulties encountered in taking data of this character are severe, and it will require years of experimenting before the ultimate formulas with proper constants and factors are determined.

The best that can be done at present is to compare the many theoretical and two empirical formulas with a full appreciation of the limiting features of each.