A TEST OF THE EXISTENCE OF THE CONDUCTING LAYER

By G. Breit and M. A. Tuve

Abstract

A method previously proposed for a test of the existence of ionization in the upper atmosphere has been developed, and a definite proof of the *existence of echoes from the upper regions* has been obtained. The echoes are present for 70-meter waves with an 8-mile base near Washington, D. C. The effective height of the layer is between 50 and 130 miles. At times multiple reflections are present. *Radio fading* is shown to be not only an effect of interference between the ground and the reflected waves, but also to a large extent an effect of the presence or absence of reflected waves. A *seasonal variation* in the effective height between summer and fall seems to exist. A smaller *diurnal effect* is also suspected. The height seems greater in the fall than in the summer and greater in the afternoon than in the morning. *Effects of wave-length and of location* have been studied. A quantitative discussion of the results enables one to eliminate too gradual distributions of electron density. The measured retardation is shown to correspond to a height greater than the actual by amounts differing for various polarizations of the refracted waves.

With the development of the sciences of radio and of terrestrial magnetism it has become probable that the upper atmosphere is ionized sufficiently to reflect electromagnetic waves. However, the evidence obtained has not been quite direct until recently, when Appleton and Barnett have completed their work. For this reason we have undertaken an oscillographic study of radio signals with the purpose of observing the echo from the layer. We have described the method previously,[1] but for purposes of completeness it is here described again. A transmitting station is operated so as to send out what is commonly called I.C.W.; it is a set of interrupted trains of waves. The duration of each train is made to be about 1/1000 second. At the receiving end the signal is detected, amplified, and oscillographed. The oscillogram may either show a single set of humps corresponding to a single path transmission, or else it may show two or more sets of humps corresponding to the existence of echoes. From the displacement of the echo with respect to its origin, the retardation between the reflected and the directly received wave is ascertained.

Experimental Arrangements

(a) *Transmission from Bellevue.* Arrangements for transmission have been made with the Naval Research Laboratory (station *NKF*, Bellevue,

[1] M. A. Tuve and G. Breit, Terr. Mag. **30**, 15–16 (1925); G. Breit and M. A. Tuve, Nature **116**, 357 (1925).

Anacostia, D.C.), the Westinghouse Electric and Manufacturing Company (station *KDKA*, Pittsburgh, Pa.), the Radio Corporation of America (station *WSC*, Tuckerton, N. J.), the Bureau of Standards (station *WWV*, Washington, D. C.), and several of the enthusiastic amateurs residing in Washington. The most definite results have been obtained from the Naval Research Laboratory owing to the fortunate relative location of the two laboratories and to the high constancy of the frequency emitted by the *NKF* transmitter. This is achieved by the use of crystal control and makes it superior to any of the other stations we tried for the purpose in question. The interruptions in the wave trains were obtained by supplying the amplifier tubes of the transmitter with alternating current while the master oscillator was fed on direct current. This gave a constant frequency and the required type of modulation. The frequency of alternating current used was 500, and the "on" time of the wave trains has been varied to some extent (1/3 to 1/5) of a cycle) by changing the biasing grid voltages. These arrangements have been kindly made for us by Dr. A. H. Taylor and his assistants, Messrs. L. A. Gebhardt and L. C. Young. After the first definite indications of the reflections have been obtained on 70 meters, the wave form of the transmitter was investigated by means of an oscillograph quite similar to the one used in the reception experiments. A single detector tube was first of all coupled to the antenna of the transmitter by means of a coil with connecting leads shielded in a lead tube, the shield being grounded. The output of the detector was applied to the input of a power amplifier containing four tubes of type 202 (5 watts each) used in parallel. The connections of the amplifier will be described in detail in connection with the receiving apparatus. The output of the amplifier was fed through the oscillograph. Visual observations made by means of a rotating mirror showed that the wave form consisted of a single set of humps. The observations taken by coupling directly to the antenna were not very reliable because they had to be taken directly in the gallery containing the 5 k.w. transmitter, and consequently had to be carried through in a hurry under unfavorable conditions of vibration. The apparatus was consequently transferred into another building of the Naval Research Laboratory, and there the signals were received by means of a small antenna as well as a loop on the single-tube detector as before. The wave form appeared to correspond closely to a single set of humps. However, a slight presence of radiation in the "off" time was detected. The effect could not be due to a reflection, the directly received wave being too strong in comparison. The difficulty was eliminated by using a little additional grid bias in the transmitter. The exact cause of this radiation in the "off" time is unknown, though according to Dr. A. H. Taylor it may be due to certain transient effects in the transmitter circuit. Since care was taken to eliminate the transient effect in all of the transmitters operated by Bellevue, it is safe to assume that the wave form sent out was accurately single-humped with the exception of the first two tests. However, even in these the transient effect was about 1/10 of the reflections observed.

(b) *Receiving and oscillographic equipment.* The signals were received in most cases by means of an open antenna connected to ground through the primary of a loose coupler, the secondary of which was connected to the input terminals of a superheterodyne set. The connections were as shown in Fig. 1. Here the tubes are represented in the usual manner. The first tube (1) is the first detector. Its input terminals I_1, I_2 are connected to the secondary of the loose coupler or else to a loop (coil aerial)

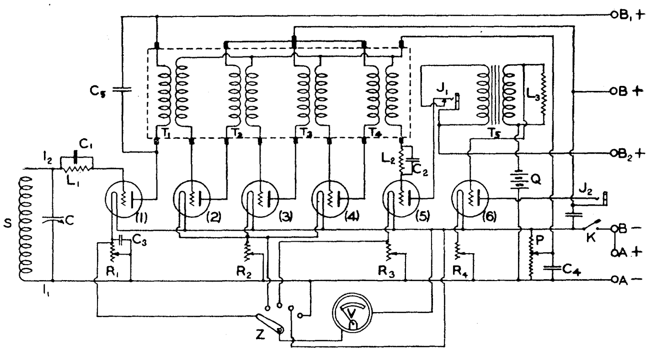


Fig. 1. Wiring diagram of superheterodyne set.

shown as S. S is also coupled to an oscillator giving an adjustable frequency differing from the frequency of the received wave by about 50 K.C. The detection takes place by means of the grid-leak condenser L_1C_1, with $L_1 = 2$ m.Ω, $C_1 = .00025$ microfarad. The tube (1) was entirely enclosed in a brass box. This eliminated to some extent complications arising from the presence of the original frequency in the other tubes. The output of (1) passes through the primary of the transformer T_1 which as well as T_2, T_3, T_4 is tuned to 50 K.C. The condenser C_5 serves to filter out the high frequency from the remaining tubes. Condenser C_3 served the same purpose and had the value .005 microfarad. Tubes (2), (3), (4) amplify the intermediate frequency 50 K.C. which is then detected in (5) by means of leak condenser L_2C_2, with $L_2 = 1$ m.Ω, $C_2 = .00025$ microfarad. The plate voltage for (1) is supplied through

B_1^+, to (2), (3), (4), (6) through B^+, and to (5) through B_2^+. The output of the set was connected to the power amplifier by means of the jack J_1 which, when plugged, disconnected (6) from the circuit. The transformer T_5 is an audio-frequency transformer, and the stray coupling to it was sufficient to hear the signals if the power amplifier was connected through J_1 and phones were connected to J_2. The battery Q kept the grid of (6) at the proper potential. It had a value of 6 volts. The potentiometer P by-passed by condenser C_4 (=.006 microfarad) controlled the regeneration in (2), (3), (4). The voltmeter V could be connected to either of the tubes or to the battery by means of a voltmeter switch with contact arm Z. The transformers T_1, T_2, T_3, T_4 were bought in one unit called the Precise Multiformer and manufactured by the Precise Manufacturing Corporation, Rochester, New York. The description of the auxiliary oscillator is unnecessary in this connection. The tubes used were type 201*A* of the Radio Corporation.

The connections of the power amplifier were as shown in Fig. 2. The output of tube (5) is passed through a resistance of 25,000 ohms. The

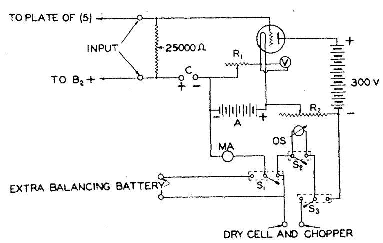


Fig. 2. Wiring diagram of power amplifier.

fluctuations of the potential across this resistance are applied to the grid of the amplifier. The oscillograph element *Os* is protected by the short circuiting switch S_2. With switches S_1, S_3 closed to the right on the figure, the plate current through the milliammeter *MA* is balanced out by a connection from the *A* battery through R_2. R_2 had a range of 0–800 ohms (two 400-ohm potentiometers). By means of S_1 an extra balancing voltage could be applied to *Os*, and by means of S_3 tests for distortion in the oscillograph element itself could be made by connecting it to a chopper and dry cell and thus passing through it a rectangular current wave.

In the power amplifier of Fig. 2, four or five tubes of 5 watts each (type 202 of Radio Corporation) were used in parallel. The 300-volt plate potential was applied by means of storage batteries for the photographs here published. However, satisfactory results could be also obtained by means of dry cells.

Various tests of the performance of the apparatus were carried through and tests for distortion were made with the following results.

The oscillograph element used was of the usual oil-immersed General Electric type. It was supplied with the standard and the high-sensitivity elements and with the usual silver-strip type of suspension. It was found that, while the silver-strip suspension was fairly satisfactory, tungsten wire was more so. The use of this was kindly suggested to us by Dr. Eckhardt, formerly of the Bureau of Standards. Best results for the purpose of oscillographing at high frequency were obtained with the SV element remodeled by soldering the tungsten wire to a heavy copper wire somewhat above the higher bridge. This eliminates the vibrational effect due to the rigidity of the *W* wire. The wire should not be too thick and rigid because then bad distortion is apt to set in. We find 6/10 mil to be the proper thickness, though we also find that different samples of *W* are likely to vary considerably. The wire used gave a period of about 1/12000 second for a tension corresponding to about $1\frac{1}{2}$ scale marks on the spring of the element and to a sensitivity of about 14 m.a./cm at 1 meter distance. This suspension is difficult to use only on account of the inconvenience of soldering tungsten. Ordinary solder was found proper. The wire is likely to be pulled out of the solder, in which it is held mechanically, at about 2 or 3 scale-divisions tension. The damping was effected by castor oil at room temperature. The magnet of the oscillograph was kept cool by circulating water around it in a rubber tube.

Different values of input resistance were tried for the power amplifier. The dependence of the sensitivity on the value of this was found to be not critical, and 25,000 ohms was found convenient. Two 50,000-ohm grid leaks were used for this in parallel.

A current voltage characteristic of the power amplifier was secured using four tubes. This is drawn in Fig. 3. The good range begins at $E_g = -7$ volts. Connecting the power amplifier in the circuit, it was found that $I_p = 60$ m.a. (i.e., $E_g = -7$ volts) if the grid bias is $+12$ volts. Actually for safety somewhat higher values were used.

Having thus adjusted the power amplifier and oscillograph for no distortion, the voltages on B^+, $B_1{}^+$, $B_2{}^+$ were varied using laboratory sources of signals and coupling these to the antenna. Two types of sources were used. One consisted of an oscillating receiving tube fed on alternating current in series with some direct voltage and with proper grid bias. By this means short and sharp trains of waves could be obtained. The other was obtained by using a chopper in the plate circuit of the same oscillator fed on direct current. It was found that B_2^+ at 90 volts or at 67.5 volts is considerably better than at 45 volts, giving better amplification and less distortion. B_1^+ was not very critical, though 22.5 volts was better than O. B^+ was 90 volts. It was found necessary to keep the potentiometer P within safe limits from the oscillation point (1 division on the dial was enough). A badly distorted wave form results otherwise.

In each experiment the deflection at which distortion begins to appear was noted for the particular scale distance used, and the tuning on the oscillator was controlled so as not to exceed such a deflection. The test was usually repeated also during reception by means of visual observations made with a rotating mirror.

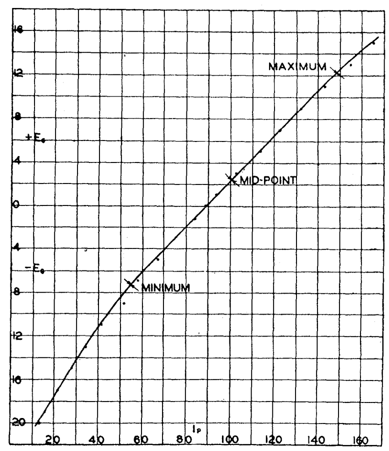


Fig. 3. Current voltage characteristic of power amplifier.

The camera used for recording the wave form was kindly loaned to us by the Sound Section of the Bureau of Standards. The circumference of the drum was about 4 feet and 8 inches. By means of proper relays the drum could be made to spiral on a worm while the picture was taken, thus giving a total length of the record equivalent to three or four revolutions. In the later stages of the work we found it more useful, however, to obtain exposures having a duration of about 1/30 second and corresponding to about one sixth of a revolution. For this purpose an exposure timing commutator was mounted on the shaft of the drum, and the electromagnetic clutch imparting to the drum its translational motion was discarded. The commutator breaks contact when the insulated portion of the commutator drum passes the brush. This corresponds to a definite azimuth of the camera drum. A second commutator is geared to the main one in the ratio of 8 : 1. The two are connected in parallel, and so the circuit is broken only if the brushes of the two are simultaneously insulated. The commutators are shown as C_1, C_2 on Fig. 4. A short circuiting switch S and a resistance R_1 are also connected as shown. The battery B and the resistance R_2 maintain a difference of potential between P_1 and P_2 which can be varied by adjusting R_1, R_2. With P_1, P_2 as terminals the whole combination is put in series with the grid bias of the power amplifier. With S closed the commutators have no influence. With S open and S' open the oscillograph spot is jerked at every revolution of C_1. The camera is placed so that when C_1 is open the spot is in its range, the adjustment being made with S' open. Next S' is closed. The spot hits the shutter only once in every revolution of C_2. When the brush on C_2 approaches the segment, the shutter is opened,

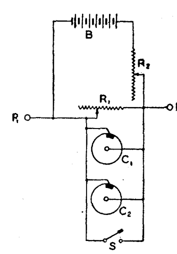


Fig. 4. Connections of exposure timing commutator.

the spot is watched and after it entered the opening, the shutter is closed exposing about one sixth of the film in a particular and known azimuth. The brush on C_1 is then moved into the next position and the last procedure is repeated. Two brushes are provided on C_2 so as to enable all segments to take complete pictures.

The whole drum could be moved also by means of proper stops giving another set of six exposures on another band of the film.

We found it useful for best definition of the pictures to add a second cylindrical lens to the customary optical system. The axis of this was vertical, and it was inserted between the oscillograph mirror and the camera.

The films used were of the Eastman high speed NC type.

Results of Transmission Experiments

(a) *WSC, Tuckerton, N. J.*, Radio Corporation of America. These experiments were of a preliminary nature. In the first tests the Western Electric cathode ray oscillograph was employed. It is provided with two sets of deflecting plates. One of them was connected directly to the output of the second detector of the superheterodyne set, no further amplification proving necessary. The other set of plates was connected to an alternating potential of adjustable frequency. The cathode beam was also subjected to the action of a magnetic field of the same adjustable frequency, the arrangement being such as to spread the image on the screen into an ellipse, the deflection due to the signal being applied perpendicularly to the major axis. This gave a uniform time scale in the central portion. The source of the adjustable frequency was a shunt-wound motor provided with collector rings which collected, therefore, an approximately sinusoidal current. This was passed through a transformer serving partly as a filter, and the output of the transformer was applied to two coils, one serving as a primary and the other as a secondary of a second transformer. The potential difference across the second secondary was applied to the deflecting plates and the magnetic field of the combination produced a deflection in a perpendicular direction. A rheostat in the field of the motor served to adjust its frequency to synchronism with a submultiple of the frequency of the signal modulation. The figure on the fluorescent screen could thus be kept stationary and inspected.

The modulation at *WSC* was produced by means of a chopper in the grid circuit of the master oscillator with a frequency of about 600 in these as well as later tests, this being one of the commercial methods of transmission used by *WSC*. The frequency of the auxiliary adjustable displacement was about 60, thus giving about 5 humps on each of the two sides of the ellipse. The tests took place at about 9 A.M. in the spring of 1925, the transmission being on 600, 650, or 675 meters with 5 k.w. No definite indication of reflection was obtained in these.

The cathode ray oscillograph was later replaced by the power amplifier and the General Electric oscillograph, so as to obtain photographic records. The apparatus was essentially that described in the first part of the paper except that the modifications in the oscillograph element had not been made at the time, the standard silver suspension and the ordinary method of attaching this being used.

In some cases effects similar to those which would result from reflections were observed. However, they were not very consistent. Samples of various wave forms are shown in Fig. 5.

In order to decide on the conclusiveness of these experiments, a trip to Tuckerton was made and the wave form of the signals was observed by coupling a detector tube to the power amplifier of the transmitter, the output being connected to the power amplifier. These tests showed that the wave form emitted depended to a large extent on the operation of the chopper and that all the effects observed in Washington could be explained as due to the defective operation of the chopper. (This operation is, of course, quite satisfactory for commercial purposes.) On account of the uncertainty of the emitted wave form, we do not regard these tests as conclusive.

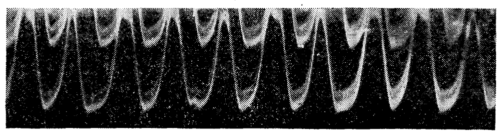


Fig. 5. Wave forms of WSC, Tuckerton, N. J.; $\lambda = 600$ meters; modulation frequency, 600; type of modulation, chopper.

(b) *KDKA*, *Pittsburgh*, *Pa.*, Westinghouse Electric and Manufacturing Company. The tests took place in July, 1925, on 309 meters with 10 k.w. The modulation was made by means of 60-cycle plate voltage supply. The interest of these lies in the fact that the transmission took place at night under conditions showing very pronounced fading. Some photographed wave forms are given in Fig. 6. We should like to call attention to the general distortion in the wave form which may be described as fading of very high frequency and also to the small consistent hump which appeared in one instance. This may be due to two-

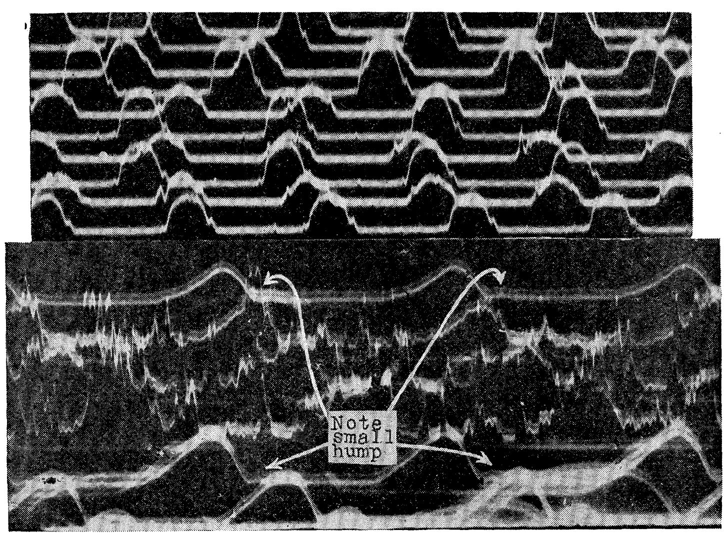


Fig. 6. Wave forms of KDKA, Pittsburgh, Pa.; $\lambda = 309$ meters; modulation frequency, 60; type of modulation, A.C. on plate.

path transmission. However, the fading of *KDKA* is so pronounced and the intensity during the day is so low that we are inclined to look at the main hump as also a reflected one.

(c) *NKF, Bellevue, Anacostia, D. C.*, United States Navy, located 8 miles southeast of the laboratory of the Department of Terrestrial Magnetism. Tests were made on 71.3 meters, 41.7 meters, and unsuccessful ones on shorter waves. These were begun on 71.3 meters on July 28, 1925. The first test ($10^h\ 30^m$ to $10^h\ 50^m$ A.M.) showed double humps with very pronounced fading of one of them. At times a third hump could be seen. The photograph showed only one reflection (two humps). The test was repeated in the afternoon ($3^h\ 15^m$ P.M.). Three humps were observed in a rotating mirror and also photographed. Shortly afterwards a thunderstorm followed. The appearance of double reflections from Bellevue in several instances which followed was also accompanied by a thunderstorm. In the first two tests the wave form of the transmitter was not perfect, showing a very slight second hump at the transmitter as previously mentioned. Through the kind cooperation of Dr. A. H. Taylor and his assistants this hump was removed by proper biasing of the tubes. On August 6 simultaneous observations were made at Bellevue and at the receiving station of the Department of Terrestrial Magnetism in the intervals from $10^h\ 30^m$ to $10^h\ 50^m$ A.M. and $1^h\ 45^m$ to 2^h P.M. The wave form of the transmitter was perfect all the time, while the wave form at the Department showed a varying second hump in the first period and a constant one in the second.

Fading and Polarization Effects on Bellevue

Since according to the hypothesis one of the humps is due to the direct overground transmission and the others are due to reflections, we should expect that all the humps will be received with different relative effectiveness on different aerials. This proved to be the case. The hump which showed a constant amplitude was received best on a nearly vertical antenna, while the others were received best on antennas with horizontal portions. A number of antennas were put up for the purpose. They were connected to switches so as to be able to shift conveniently from one to the other or to a combination used in parallel. Invariably changing antennas produced changes in relative intensities. At the same time no effect on the wave form due to tuning on the superheterodyne oscillator could be observed, thus showing that the effect was not due to detuning of the circuits resulting from different circuit constants of the antennas (such effects have been observed with other transmitters to be described presently). These observations confirm our interpretation of the hump with a constant amplitude as a direct transmission effect. Other quite direct evidence of this interpretation will be given in a later section.

Since the reflected wave must be coming down to the ground, we should expect it to form an *interference pattern* at the surface. If the wave should be coming directly down and if the ground should behave as a perfect conductor, we should expect a node of the electric intensity at the ground and a loop at a height equal to a quarter of a wave-length. We have some indications to that effect. Three antennas stretched east with horizontal portions at about 6, 30, and 50 feet above ground, respectively, indicated that the reflection is received strongest by the antenna of medium height. The two others show the reflection weaker to about the same extent. We can perhaps take 30 feet to be approximately the position of the loop of the interference pattern. The wave-length being 71.3 meters, one quarter of it is 17.8 meters = 58 feet. Hence the angle which the wave would appear to make with the vertical would be $\cos^{-1}30/58 = 60°$. It is hardly correct to attach any significance to this estimate except as a purely qualitative one on account of the interaction of the antennas, the effect of the buildings, the small number of antennas used, etc.

We have also observed the wave form by means of a loop inside the building. The relative intensity of the two waves changed markedly on turning the loop. We do not feel justified in making any interpretation of the actual relations on account of the effects of surrounding objects.

In most of the experiments, with few exceptions, the hump showing variations showed them very markedly. At times these were very rapid (1 or 2 seconds), at others slower (10 to 15 seconds), and in others quite slow (steady for several minutes). The variations in amplitude were very marked, making the reflected wave change from practically zero to the amplitude of the ground wave and sometimes higher. This shows that fading can exist quite apart from interference between ground and reflected waves and that a considerable part of it is due to the different effectiveness of reflection. The great variability of the intensity of reflection suggests either that the reflection itself is governed by interference phenomena or that it is caused by sudden changes in the layer more or less as the flickering of a light on a wavy surface of water. We have no evidence to decide between these points of view. The existence of multiple reflections can perhaps be seen more easily on the hypothesis of a wavy surface in the layer.

Identification of the Waves

Although the intensity of the reflected wave varied considerably, there have been many cases in which it remained definitely below the intensity of the ground wave. In these cases photographs showing the beginning or the end of a dot or dash enabled us to identify the waves because the first hump must be always received along the shortest path and the last along the longest. Some such photographs are reproduced among the others of Fig. 7. They confirmed our previous opinion as to the identity

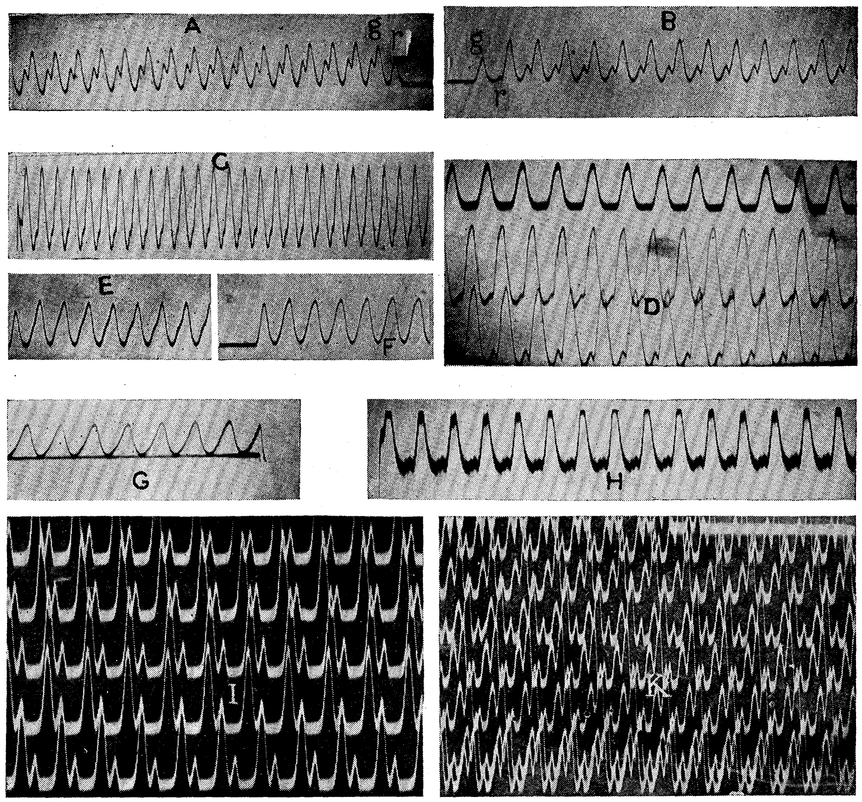


Fig. 7. Wave forms of NKF, Bellevue, Anacostia, D.C.; $\lambda = 71.3$ meters; modulation frequency, 424; type of modulation, A.C. on plate.

(A) Identification of ground and reflected waves at end of transmission, September 25, 1925, 3:30 P.M.
(B) Identification of ground and reflected waves at beginning of transmission, September 25, 1925, 3:30 P.M.
(C) September 25, 1925, 1:30 P.M.
(D) September 25, 1925, 1:30 P.M.
(E) Superposed and interfering waves, September 25, 1925, 3:30 P.M.
(F) Another stage of superposition and interference resulting in approximately sinusoidal wave form, September 25, 1925, 3:30 P.M.
(G) Third stage of distortion due to superposition and interference.
(H) "Multiple reflections," September 21, 1925, 3:30 P.M.
(I) Single reflection with low position of layer, July 28, 1925, 10:35 A.M.
(K) Double reflection, July 28, 1925, 3:15 P.M.

of the humps. It must be noted that in pictures with good focusing such as (A) the shape of the reflected hump is the same as that of the ground hump except for a scale factor representing the intensities.

Effect of Wave-Length, Time of Day, and Location of Receiver

Signals on 71.3 meters showed reflections when received at the laboratory of the Department of Terrestrial Magnetism in a great majority of cases. On 41.7 meters at $10^h\ 30^m$ A.M. a number of tests in August and September failed to show reflections. However, in the afternoon at $3^h\ 30^m$ P.M. a marked change in the wave form was found (Fig. 8). It is more irregular than that on 71.3 meters. On the whole, reflections on 71.3 meters are more marked in the afternoon than in the morning.

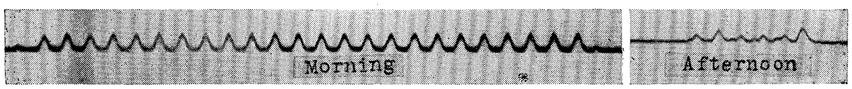


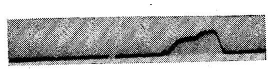
Fig. 8. (A) Wave form of NKF; $\lambda = 41.7$ meters; modulation frequency $\cong 500$; shows original wave form, September 29, 1925, 10:30 A.M.
(B) Wave form of NKF; $\lambda = 41.7$ meters; modulation frequency $\cong 500$; wave form badly broken and visual observations showed rapid and irregular changes, September 29, 1925, 3:30 P.M.

Special arrangements for transmission were made for December 11, 12, 13, 1925, in connection with the annual exhibit of the Carnegie Institution of Washington. The receiving apparatus was moved about 3 miles towards the transmitter (Sixteenth and P Streets, Northwest), the distance being about 5 miles from *NKF* and 2.5 miles from *WWV*. Here also reflections were observed, though weaker than at the laboratory. No specially marked effect of reception in the evening was observed ($9^h\ 30^m$ to $9^h\ 45^m$ P.M.).

No reflections were observed on 20 meters or shorter wave-lengths.

(d) *WWV*, *Bureau of Standards*, Washington, D. C. The two laboratories being very close together (1.2 miles), only a weak reflection could be expected. Transmission took place on 75 meters and 50 meters with 500 cycles as well as 60-cycle modulation. The modulation was effected by means of the usual alternating-current method. However, the set was not crystal controlled, and therefore it did not show a constant frequency during a modulation cycle. This led at first to absurd results giving an apparent change of wave form due to the sharp tuning of the superheterodyne. This change of wave form can be at times confused with a reflection. We made sure that it was not a reflection by oscillographing *WWV* in its own building using the same superheterodyne set and power amplifier. In such a way it was made sure that the effect of Fig. 9 is a detuning effect. However, it appears that with 500-cycle modulation the effect of detuning is not so important, and apparently a real reflection has been observed (Fig. 10). The height of the layer from this film agrees with that obtained from Bellevue.

Effects like the one shown in Fig. 9 have been observed by Bown, Martin, and Potter.[2]



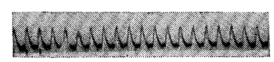


Fig. 9. Wave form of WWV; $\lambda = 50$ meters; modulation frequency $= 60$; type of modulation, A. C. on plate; wave form badly distorted due to frequency change in transmitter, November 10, 1925, 3:30 P.M.

Fig. 10. Wave form of WWV; $\lambda = 50$ meters; modulation frequency $= 780$; November 10, 1925, 3:30 P.M.

Discussion of Results

Measurements of the films obtained on Bellevue give values of the height which seem to vary with the time of year and with the time of day. The latter variation is not certain. The speed of the 500-cycle machine used in the transmitter was measured by means of a revolution counter and was found to be 26.4 revolutions per second. The machine had 32 inductors and two poles giving a frequency $= 424 \ \frac{\text{cycles}}{\text{sec.}}$. This was also checked by means of a whistle borrowed from Mr. Mirick of the Naval Research Laboratory and calibrated by him against standard tuning forks. A mean of 12 observations gave for the frequency $425 \ \frac{\text{cycles}}{\text{sec.}}$ If we should deal with a case of pure reflection taking place in the zenith, we must have

$$\frac{2h}{c} = \Delta t$$

where h is the height of the layer, c the velocity of light, and Δt the time elapsed. If a is the ratio of the distance of the peak of the reflected wave from its parent ground wave to the distance between two ground waves on the oscillogram, we have $\Delta t = \frac{a}{435}$ and with $c = 186{,}000 \ \frac{\text{miles}}{\text{sec.}}$

$$h = 196 \ a \text{ miles}$$

In such a way we calculate from measurements on our photographs for h the results shown in Table I.

[2] Ralph Bown, De Loss K. Martin, and Ralph K. Potter, Bell System Tech. J. 5, 143–213 (1926).

TABLE I

Height of the reflecting layer

Date	75th meridian time	Resulting height, h	Remarks
1925	*h m*	*miles*	
July 28	10:35 A.M.	55	
	3:45 P.M.	55	For strong reflection.
		141	For weaker reflection.
Sep. 21	10:30 A.M.	118	
	11:30 A.M.	117 (80?)	Identification of ground and reflected waves not quite certain.
	1:30 P.M.	125	
	3:30 P.M.	91	For weaker reflection.
		125	For stronger reflection.
		125	When reflection became single.
Sep. 23	10:30 A.M.	106	
	1:30 P.M.	116	
	3:30 P.M.	132	
Sep. 25	10:30 A.M.	79	
	11:30 A.M.	106	
	1:30 P.M.	120	
	3:30 P.M.	125	

These values are recorded more accurately than they can be relied upon. The accuracy of measuring the films is probably 5 percent and in bad cases 10 percent. The speed of the generator could also vary on account of fluctuations in the line voltage by perhaps 2 percent. However, it seems that in the afternoon the layer is higher than in the morning, and with more certainty that in the fall it is higher than in the summer.

From the Bureau of Standards the only film available for measurement gave 80 miles in an afternoon in November. However, we do not rely on this as much as on the results from Bellevue.

It must be pointed out that the "height" which we have tabulated is in reality only a retardation and that we cannot compare it directly with the results of Taylor and Hulburt.[3] In all probability the mechanism involved in producing the "reflected" hump is more similar to refraction than reflection. We must therefore take into account the change of velocity of the waves in the refracting medium. We consider in this connection the group velocity of the waves. If $V(\nu)$ should be the phase velocity for a frequency ν, the group velocity is

$$V' = \frac{d\nu}{d\left(\frac{\nu}{V}\right)} = \frac{V}{1 - \frac{\nu}{V}\frac{dV}{d\nu}} \tag{1}$$

[3] A. H. Taylor and E. O. Hulburt, Phys. Rev. **27**, 189(1926).

For an *ordinary* dispersing medium we may take

$$V = c\left[1+\frac{\alpha}{\nu_0^2-\nu^2}\right]^{-\frac{1}{2}} (\alpha>0) \tag{2}$$

This gives

$$V' = c\left[1+\frac{\alpha}{\nu_0^2-\nu^2}\right]^{\frac{1}{2}}\left[1+\frac{\alpha\nu_0^2}{(\nu_0^2-\nu^2)^2}\right]^{-1} \tag{3}$$

In order that $V'<c$ we must have

$$\frac{\alpha}{x} < \frac{2\alpha\nu_0^2}{x^2}+\frac{\alpha^2\nu_0^4}{x^4} \tag{4}$$

where $x=\nu_o^2-\nu^2$.

The most important case for us is that of $\nu>\nu_o$, i.e., $x<0$ and $V>c$. It is also always true for $x>0$ because the maximum value which x may have corresponds to $\nu=0$, i.e., $x=\nu_o^2$. In the case (4) becomes $\alpha<2\alpha+\alpha^2/\nu_0^2$ which is always true. Thus the group velocity is always $<c$, and hence in spite of the greater phase velocity in the upper regions the effective path-difference for our experiment is greater than the geometrical. This tends to make all of our measurements give too large values of h.

The values of h are also likely to be too large on account of a possible oblique direction of the ray. For a real determination of the height, the direction in which the waves come down would have to be measured and one would have to make sure that if the emitted radiation be confined to that direction the reflected wave will exist. Otherwise multiple successive reflections will have to be assumed.

Again, a direct comparison with skip-distance data is not warranted because the skip-distance observations do not give directly the height and are likely to give too high values for the penetration of the waves into the upper regions. Further, in the measurements of skip distances the properties of the layer over a greater range are important, and casual prominences of interest to us may be of no importance in the other case.

The more sudden the transition to the region of strong ionization the less chance there is of error due to the difference between V' and c. Also the greater the angle which the ray makes with the layers of equal refractive index the less is that chance. The reason for this is that formula (3) may be written as

$$V' = \frac{c\mu}{1+\dfrac{\nu_0^2}{\nu_0^2-\nu^2}(\mu^2-1)}$$

which shows that if $\mu = 0$, $V' = 0$, so that if the wave penetrates the region in which $\mu = 0$, there will be a large retardation. If the layers of equal electron density should be horizontal

$$\mu \sin \theta = \text{const.}$$

where μ is the refractive index and θ is the angle which the wave normally makes with the vertical. If the initial value of θ is 0, the highest point in the path is reached when $\mu = 0$.

Quite similarly to the manner in which we have used (2) to derive (3) we may use the various expressions for the refractive index employed by Taylor and Hulburt and given in their expressions (2), (3), (5), (6). Corresponding to them we have for circularly polarized rays propagating along the field

$$V(\nu) = c\left[1 + \frac{\alpha}{\nu(\nu_0 - \nu)}\right]^{-\frac{1}{2}} \tag{5}$$

or

$$V(\nu) = c\left[1 - \frac{\alpha}{\nu(\nu_0 + \nu)}\right]^{-\frac{1}{2}} \tag{6}$$

and if the wave propagates perpendicularly to the magnetic field for polarization parallel and perpendicular to the field respectively

$$V(\nu) = c\left[1 - \frac{\alpha}{\nu^2}\right]^{-\frac{1}{2}} \tag{7}$$

$$V(\nu) = c\left[1 - \frac{\alpha\nu^{-2}}{1 - \frac{\nu_0^2}{\nu^2}(1 - \alpha\nu^{-2})}\right]^{-\frac{1}{2}} \tag{8}$$

Here $\alpha = Cc^2$ where C is the same as that used by Taylor and Hulburt. Corresponding to these expressions we have refractives indice μ given by

$$\mu^2 - 1 = \frac{\alpha}{\nu(\nu_0 - \nu)} \tag{5'}$$

$$\mu^2 - 1 = -\frac{\alpha}{\nu(\nu_0 + \nu)} \tag{6'}$$

$$\mu^2 - 1 = -\frac{\alpha}{\nu^2} \tag{7'}$$

$$\mu^2 - 1 = -\frac{\alpha\nu^{-2}}{1 - \frac{\nu_0^2}{\nu^2}(1 - \alpha\nu^{-2})} \tag{8'}$$

Remembering that $V(\nu) = \frac{c}{\mu\nu}$ we find easily that

$$V'(\nu) = \frac{d\nu}{d\left(\frac{\nu}{V(\nu)}\right)} = \frac{c\mu}{\mu^2 + \frac{\nu}{2}\frac{d\mu^2}{d\nu}} = \frac{c\mu}{1+(\mu^2-1)\left\{1+\frac{\nu}{2}\frac{d\log(\mu^2-1)}{d\nu}\right\}} \tag{9}$$

This gives for the four cases

$$V'(\nu) = \frac{c\mu}{1 + \frac{\nu_0}{2(\nu_0-\nu)}(\mu^2-1)} \tag{5''}$$

$$V'(\nu) = \frac{c\mu}{1 + \frac{\nu_0}{2(\nu_0+\nu)}(\mu^2-1)} \tag{6''}$$

$$V'(\nu) = c\mu \tag{7''}$$

$$V'(\nu) = \frac{c\mu}{1 - \frac{\mu^2+(\mu^2-1)\left(1-\frac{\nu_0^2}{\nu^2}\right)}{\frac{\nu^2}{\nu_0^2}-1}(\mu^2-1)} \tag{8''}$$

It is seen most clearly in the case (7″) that if $\mu=0$, $V'=0$. We must therefore pay attention to the retardation which the group receives in the highest points of the path because there the velocity of the group is very small. The retardation is given in general by

$$\Delta t = \int \frac{ds}{V'} \tag{10}$$

Here we can write

$$ds = \frac{dx}{\sin\theta}$$

and

$$\mu \sin\theta = K = \sin\theta_0 \tag{10a}$$

where K is constant for a given path. Hence

$$\Delta t = \int \frac{\mu}{V'K}\,dx \tag{11}$$

For (7″) this becomes

$$\Delta t = \frac{\Delta x}{c \sin\theta_0} \tag{12}$$

This shows that the measured retardation for transmission along a curved path ABC (Fig. 11) is the same as that which would take place in vacuo along ADC where AD, CD are tangent to ABC at A and D. In this case, therefore, the result depends on somewhat the same type of extrapolation as in the case of skip-distance determinations of the height. If one should be able to perform the reflection experiment with the base line about equal to the skip distance and if one should determine the direction of the down-coming wave at the skip distance, a close agreement for the reflection corresponding to (7) would be expected.

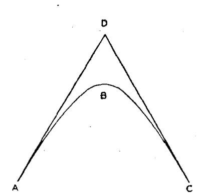


Fig. 11. Relation of actual path to the effective one.

Formula (11) when applied to the cases marked (5), (6), (8) gives for (5)

$$\Delta t = \frac{\Delta x}{c \sin \theta_0}\left\{1 + \frac{\nu_0}{2(\nu_0 - \nu)}\overline{(\mu^2 - 1)}\right\} \tag{13}$$

for (6)

$$\Delta t = \frac{\Delta x}{c \sin \theta_0}\left\{1 + \frac{\nu_0}{2(\nu_0 + \nu)}\overline{(\mu^2 - 1)}\right\} \tag{14}$$

for (8)

$$\Delta t = \frac{\Delta x}{c \sin \theta_0}\left\{1 - \overline{(\mu^2-1)\left[\mu^2+(\mu^2-1)\left(1-\frac{\nu_0^2}{\nu^2}\right)\right]\left(\frac{\nu^2}{\nu_0^2}-1\right)^{-1}}\right\} \tag{15}$$

where the averaging indicated by the bar is taken over the path assigning equal weights to portions of the path having equal projections along the horizontal (x). Here if $\nu > \nu_o$ which is the case concerning us (13) gives results > those derived from (12) for the same θ_o. On the other hand, (14) gives values which are smaller while the behavior of (15) depends to a large extent on the nature of the electronic distribution. The largest value which $\overline{1-\mu^2}$ may have is 1. For 70-meter waves $\nu_o/(-\nu_o+\nu)$ is about one half and thus the largest discrepancy between the correction-factors in (13) and (12) which we should expect is that given by a factor 5/4, while (14) is not to be expected to give values of the correction-factor smaller than seven-eighths of those given by (12). Such discrepancies are not negligible and may account ultimately for some cases of multiple reflections, especially if it is remembered that $\sin \theta_o$ is different for all the cases so that ADC of Fig. 11 is also different. It may be also that rapid fading of the reflections is due to interference influenced by changes in the group velocity.

We must consider next the question of possible changes in the group velocity within the band of the transmitter. We see by means of (7'') and (7') that

$$\frac{dV'}{d\nu}=\frac{\alpha}{\nu^3\sqrt{1-\dfrac{\alpha}{\nu^2}}} \tag{16}$$

so that if $\mu=0$, $dV'/d\nu=\infty$. The distortion due to changes in the group velocity would be expected to be infinitely great for rays returned from the zenith if the electronic density in horizontal layers is constant. For 70-meter waves, however, we observed a close reproduction of the original wave form in the reflections. We must explain, therefore, why the distortion does not take place. Various explanations may be given. It may be said that the waves are reflected rather than refracted or else it may be supposed that the electron density is not uniform in horizontal layers so that the region of $\mu=0$ is not reached. Before arriving at any such conclusion, however, we must consider the problem in a more exact quantitative manner.

Let us suppose, for instance, that the electron density increases as the square of the height. Then

$$\alpha=by^2$$

where b is a constant. Hence also for (5')

$$\mu^2=1-\alpha(\nu)y^2$$

where

$$\alpha(\nu)=\frac{b}{\nu(\nu_0-\nu)}$$

Calling the range which the ray spans l

$$l=\frac{\pi\sin\theta_0}{\sqrt{a(\nu)}}$$

and since $\overline{1-\mu^2}=a(\nu)\overline{y^2}$ where

$$y=\frac{\cos\theta_0}{\sqrt{a}}\sin\left(\frac{\sqrt{a}}{\sin\theta_0}x\right)$$

we have

$$\overline{y^2}=\frac{\cos^2\theta_0}{2a}\text{ and }\overline{1-\mu^2}=\frac{\cos^2\theta_0}{2}\,.$$

Thus (13) becomes

$$\Delta t=\frac{l}{c\sin\theta_0}\left\{1-\frac{\nu_0}{4(\nu_0-\nu)}\cos^2\theta_0\right\}$$

This is the exact retardation of a group of waves having a very small spectral width. Keeping the range l constant, the initial angle θ_o is determined by

$$\sin\theta_0=\frac{l}{\pi}\sqrt{\frac{b}{\nu(-\nu_0+\nu)}} \tag{17}$$

and the retardation is

$$\Delta t=\frac{\pi}{c}\sqrt{\frac{\nu(-\nu_0+\nu)}{b}}\left\{1+\frac{\nu_0}{4(\nu-\nu_0)}\left[1-\frac{l^2}{\pi^2}\,\frac{b}{\nu(-\nu_0+\nu)}\right]\right\} \tag{18}$$

In the limit if $l=0$,

$$\Delta t=\frac{\pi}{c}\sqrt{\frac{\nu(-\nu_0+\nu)}{b}}\left[1+\frac{\nu_0}{4(\nu-\nu_0)}\right] \tag{18'}$$

We see that neither (18) nor (18′) vary especially rapidly with ν, and hence there is no danger of distortion. In fact it may be shown that the change in the retardation $\delta(\Delta t)$ is of the order of $\Delta t\nu^{-1}\delta\nu$ and is thus very small.

Formula (18) may not be applied if $\nu<\nu_o$ because then $a(\nu)<0$ and its square root is imaginary, nor can it be used if

$$l^2>\frac{\pi^2\nu(-\nu_0+\nu)}{b}$$

because then $\cos^2\theta_o<0$. Formula (18) shows that we should expect a certain variation in the apparent height with the range covered on account of the presence of l. However, in the case of 70-meter waves the variation in retardation is small, amounting to about one eighth of the whole.

With the same electron distribution the circular polarization corresponding to (6′) gives a retardation

$$\Delta t=\frac{\pi}{c}\sqrt{\frac{\nu(\nu+\nu_0)}{b}}\left\{1-\frac{\nu_0}{4(\nu+\nu_0)}\left(1-\frac{l^2}{\pi^2}\,\frac{b}{\nu(\nu+\nu_0)}\right)\right\} \tag{19}$$

It is important to observe that for 70-meter waves (19) is not even approximately the same as (18). Disregarding correction terms in parentheses, their ratio is

$$\sqrt{\frac{\nu_0+\nu}{-\nu_0+\nu}}$$

For 70-meter waves this ratio is approximately 1.4. The fact that in most cases two reflections with such retardation ratios have not been observed speaks for a more sudden increase in the electron density than that given by the $\alpha = by^2$ relation or else for a failure of the simultaneous appearance of the true circular components.

The polarization corresponding to (7′) gives

$$\Delta t = \frac{\pi}{c}\sqrt{\frac{\nu^2}{b}} \qquad (20)$$

a value in between the other two.

It is scarcely necessary to state that the first electron distribution used by Taylor and Hulburt gives possibilities of multiple down-coming rays simply because for every range there are two possible rays for every state of polarization. Unless the hypothesis of a wavy lower surface applies, we may also consider the possibility of a general increase of uniformity in electron distribution as an explanation of multiple reflections.

Summary

(1) Groups of radio waves arrive at the receiving station separated from their echoes. This shows that the hypothesis of an ionized upper layer of the atmosphere is correct.

(2) The retardation is such as though the layer were at a height of from 50 to 130 miles. The apparent height is greater in the fall than in the summer for 70-meter waves with an 8-mile base.

(3) Radio fading is present for reflections alone quite independently of interference between the ground and reflected waves.

(4) A quantitative discussion of the possibilities of refraction shows that in most cases the increase of electronic density must be more sudden and discontinuous than that given by a density proportional to the square of the height or else that not all of the possible states of polarization of the waves in the upper atmosphere are present.

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Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
May 19, 1926.

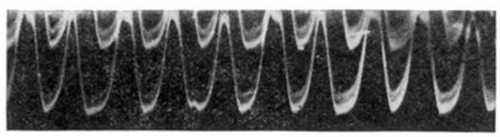

Fig. 5. Wave forms of WSC, Tuckerton, N. J.; $\lambda = 600$ meters; modulation frequency, 600; type of modulation, chopper.

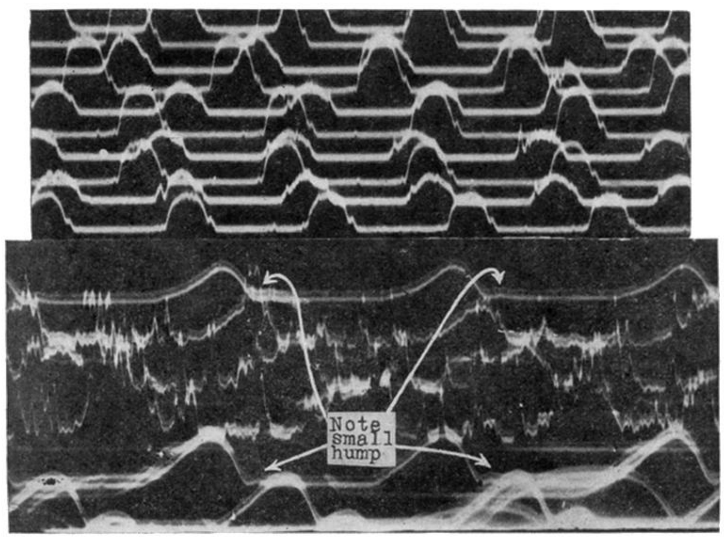

Fig. 6. Wave forms of KDKA, Pittsburgh, Pa.; $\lambda = 309$ meters; modulation frequency, 60; type of modulation, A.C. on plate.

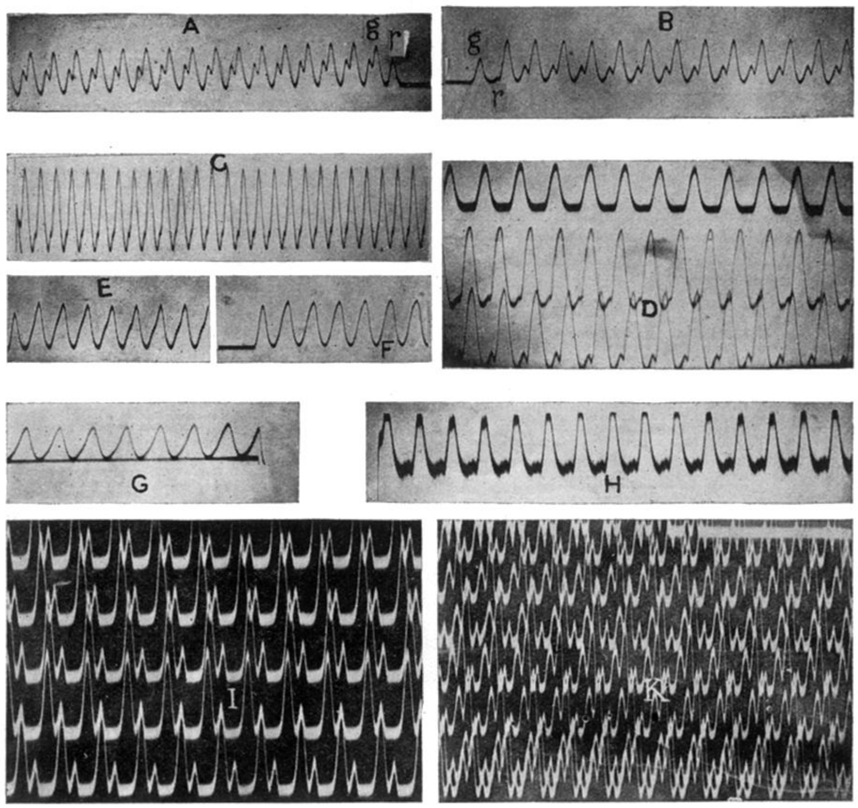

Fig. 7. Wave forms of NKF, Bellevue, Anacostia, D.C.; $\lambda = 71.3$ meters; modulation frequency, 424; type of modulation, A.C. on plate.

(A) Identification of ground and reflected waves at end of transmission, September 25, 1925, 3:30 P.M.

(B) Identification of ground and reflected waves at beginning of transmission, September 25, 1925, 3:30 P.M.

(C) September 25, 1925, 1:30 P.M.

(D) September 25, 1925, 1:30 P.M.

(E) Superposed and interfering waves, September 25, 1925, 3:30 P.M.

(F) Another stage of superposition and interference resulting in approximately sinusoidal wave form, September 25, 1925, 3:30 P.M.

(G) Third stage of distortion due to superposition and interference.

(H) "Multiple reflections," September 21, 1925, 3:30 P.M.

(I) Single reflection with low position of layer, July 28, 1925, 10:35 A.M.

(K) Double reflection, July 28, 1925, 3:15 P.M.

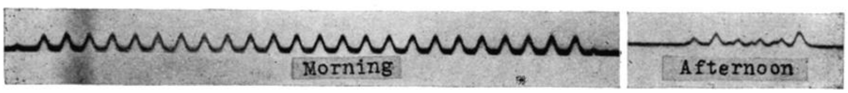

Fig. 8. (A) Wave form of NKF; $\lambda = 41.7$ meters; modulation frequency $\cong 500$; shows original wave form, September 29, 1925, 10:30 A.M.

(B) Wave form of NKF; $\lambda = 41.7$ meters; modulation frequency $\cong 500$; wave form badly broken and visual observations showed rapid and irregular changes, September 29, 1925, 3:30 P.M.

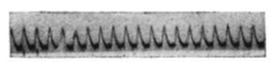

Fig. 9. Wave form of WWV; $\lambda = 50$ meters; modulation frequency $= 60$; type of modulation, A. C. on plate; wave form badly distorted due to frequency change in transmitter, November 10, 1925, 3:30 P.M.

Fig. 10. Wave form of WWV; $\lambda = 50$ meters; modulation frequency $= 780$; November 10, 1925, 3:30 P.M.