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Further Results of a Study of Ultra-Short-Wave Transmission Phenomena *

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Earlier published work has shown that, while the chief features of ultra-short-wave transmission over "air line" ranges are calculable from optical theory, there are deviations from this theory at the greater distances where a bending around the earth occurs. In this paper the results of a further study of these phenomena are given. It is shown that transmission to regions beyond the optical range is determined by conditions which are not constant and which, in fact, can produce great signal strength changes. The variable percentage of water vapor normally present in the atmosphere is suggested as a possible cause. The explanation seems, therefore, to involve a combination of diffraction and refraction, this latter variable with time, and at times predominant.

IN a recently published paper [1] results obtained at the Holmdel Laboratory during a survey of ultra-short-wave transmission phenomena have been given. In this report it was shown that, while the chief features of ultra-short-wave transmission over "air line" ranges are calculable from optical theory, there are deviations from this theory at the greater distances where a diffraction around the earth occurs. The results of a further study of these diffraction phenomena form the data of this paper.

It is probable that a diffraction around the earth will be distorted by major topographical irregularities, at or near the area of grazing incidence for the waves, and hence that the ocean surface is preferable for a study of this kind. It hardly seems likely that the ocean contour can be rough enough to give results differing markedly from those for a smooth water surface.

An obvious experimental setup, therefore, is to locate a transmitter at or very near the ocean shore and to record the transmitter field as a mobile receiver is carried towards or away from this transmitter, on paths that go well below the horizon. The receiver can be carried

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[1] *Proc. I. R. E.* **21**, 464, 1933.

either by boat or airplane. It is probable that the wave structure of the ocean surface would produce irregularities in reception if the receiving antenna be too near this surface, as on a boat, and for this type of receiver transport the time occupied by an experiment is rather long. Naturally the slow motion makes a fine grained record possible. In an airplane the time of transit is very much reduced but the vibration and unsteadiness are not favorable for accurate recording and the electrical noise level is high. There is also an increase in range necessary to get the same angular distance below the horizon as with a boat. This range extension, however, is relatively not as great as might appear since the falling away below the horizon is proportional to the square of the distance. For example, a line tangent to the earth is 100 feet up at 14 miles and 1000 feet up at 45 miles from the tangent point.[2] If these be boat and airplane antenna altitudes respectively, the airplane must always travel 31 miles farther to get the same angle of refraction below the horizon as the boat does. Since it is necessary to travel about 92 miles to get one degree below the former horizon (angle between the two earth radii) and the transmitting antenna height will further increase the range for a given diffraction geometry, it is evident that the difference in antenna altitude as between a boat and an airplane, is not of serious effect either in space covered or in accompanying signal attenuation.

We were fortunate in being located so that a land plane could be used to give us an over-water transmission. As a glance at the map (Fig. 1) will show, it is possible so to locate a transmitter on the New Jersey shore that there is an over-water path for an airplane flying along the Long Island shore. Owing to the curvature of the Long Island beach, an over-water path for the entire distance to Montauk Point requires a location of the transmitter at or south of Long Branch, New Jersey, and such a location makes the minimum path length possible (Long Branch to Rockaway Beach) about 20 miles. This was too great a distance to be satisfactory to us and we elected to locate north of Long Branch. Although the curvature of the Long Island shore then interposed land between Montauk Point and the transmitter, this land lay well below the horizon, as viewed from the transmitter, and it was thought, therefore, that its effect might be small or negligible.

North of Long Branch the favorable shore transmitter sites are restricted to the Sandy Hook region and the stretch between Sea

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[2] Air refraction is included by increasing the apparent radius of the earth to 5260 miles. See Schelleng, Burrows and Ferrell, *Proc. I. R. E.* **21**, 427, 1933; *Bell Sys. Tech. Jour.*, XII, 125, 1933.

Bright and Long Branch. Between these two regions the narrow sand strip is almost entirely occupied by breakwater, railroad, and highway with a number of pole-carried transmission lines. Sandy Hook has several splendid locations, but housing and 60-cycle power would have had to be supplied, and we elected, therefore, to transmit from the Calef estate in North Sea Bright. This house, the last one along the beach north of Long Branch, was within 50 feet of the ocean and already had electric power connections.

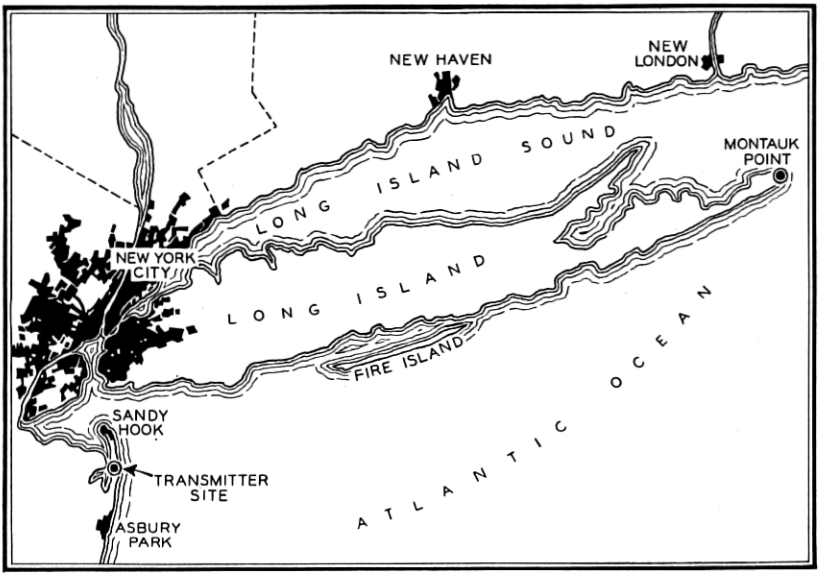

Fig. 1—Map showing transmitter location. Airplane flights were made along the south shore of Long Island.

EXPERIMENTAL

Our experimental setup was as follows: In the Bell Laboratories' tri-motor Ford plane, placed at our disposal by Mr. F. M. Ryan and his staff, two receivers operating at 1.58 and 4.6 meters respectively, and equipped with manual recorders as described in the earlier cited paper, were installed. The insulated mast antenna support in the tail of the plane was used as the 4.6 meter receiving antenna and connected as an approximately ½ wave, end tapped, conductor. The 1.58 meter antenna was a tubular half wave antenna, cut in the center and connected to an internal two-wire transmission line. It was unbalanced but apparently not seriously so. Its mounting socket was up forward between the wings. These receivers were double detection sets with 100 decibels or more gain at the intermediate frequency and the spring operated recording mechanism recorded the set gain as the operator varied it manually, to hold the set output constant.

At Sea Bright two transmitters were installed in separate rooms on the top floor of the house and the high-frequency power was fed to the antennas by transmission lines. These antennas were center-driven vertical half-wave units mounted on wood beams which were erected in the gables of the house and extended above the roof. The antenna centers were about 8 feet above the roof peak and some 60 feet above mean sea level. Both sets were simple " push-pull " oscillators, the 4.6 meter one using two UX852 tubes and generating something like 80 watts, the 1.58 meter set using two 149Y tubes and generating 12 watts. Meters were arranged so as to maintain a check on the constancy of the antenna currents. Modulating equipment and a 3–5 megacycle receiver were provided so that contact with the plane

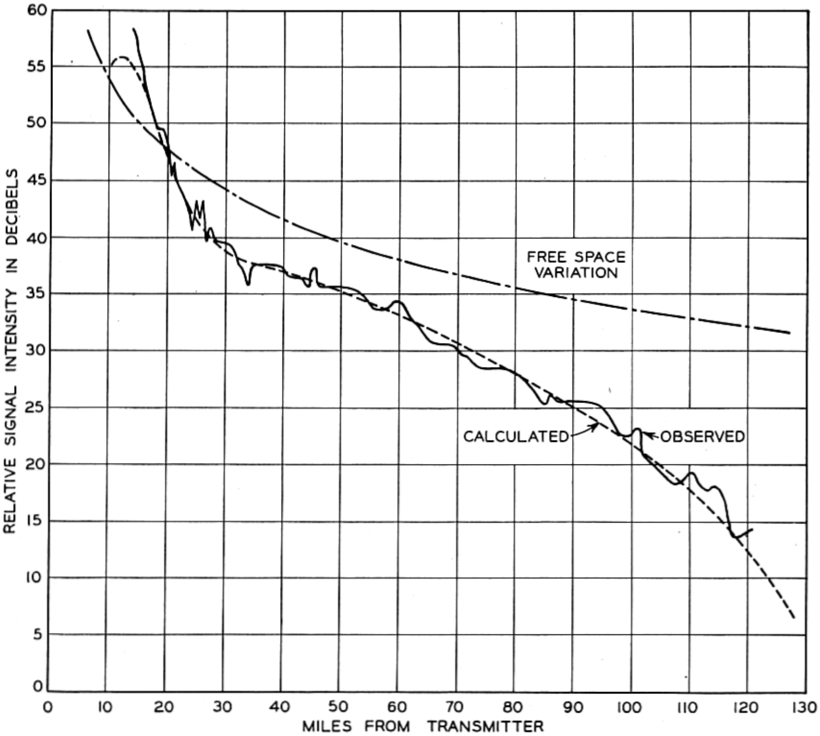

Fig. 2—Flight toward transmitter. Wave-length—4.6 meters; Altitude—8000 feet; September 27, 1933; 11:30 a.m. to 1:00 p.m.

could be maintained at all times, transmitting from Sea Bright on 4.6 or 1.58 meters and receiving on the plane's regular service wave. Contact of this kind is well nigh indispensable.

From September 25, 1933 to November 20, 1933, inclusive, fourteen airplane runs were made, ten of which were recording trips. Measurements were made both " go " and " return," and of the twenty observations resulting, three were made at 8000 feet, four at 2500 feet, two at 2000 feet, and the remainder, or eleven, at 1000 feet. No observations at 2000 feet had been scheduled but on September 28, when a 2500-foot run was begun, clouds forced a drop to 2000 feet. Each round trip lasted from two to five hours and due to the exigencies of airplane operation was completed between 9 a.m. and 5 p.m. In Figs. 2 to 12 inclusive, a set of typical observations is plotted. Superposed on the observational curves are theoretical curves cal-

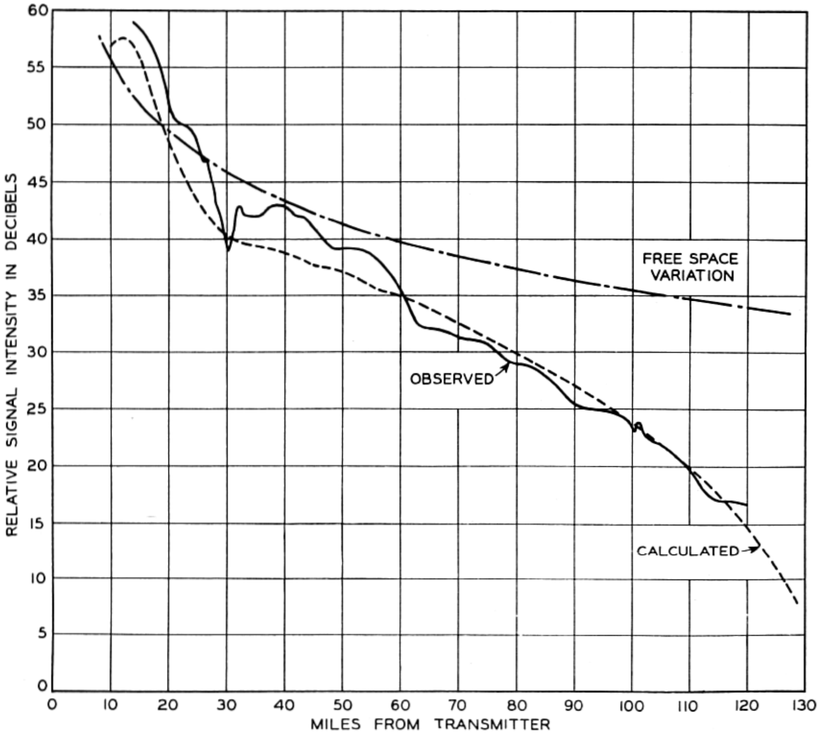

Fig. 3—Flight from transmitter. Wave-length—4.6 meters; Altitude—8000 feet; October 3, 1933; 10:20 a.m. to 11:35 a.m.

culated from the height and distance data and the constants[3] of the sea water, assuming ordinary optical reflection from an earth of 5260 miles radius. These theoretical curves are adjusted best to fit with the observations, the ordinates for all the curves being the decibels left in the receiver attenuator.[4] These results can be summarized briefly as follows:

At 8000 feet the fit with theory is excellent at both wave-lengths. The grazing distance for this altitude is 137 miles and the entire reception is, as it should be, optical. The " out " curves for the 1.58 meter reception show a middle distance roughness which characterizes all the " out " curves for this wave-length. This roughness is due to a minimum in the polar characteristic of the plane which was, unfortunately, directed at the transmitter for the first part of the outward flights.

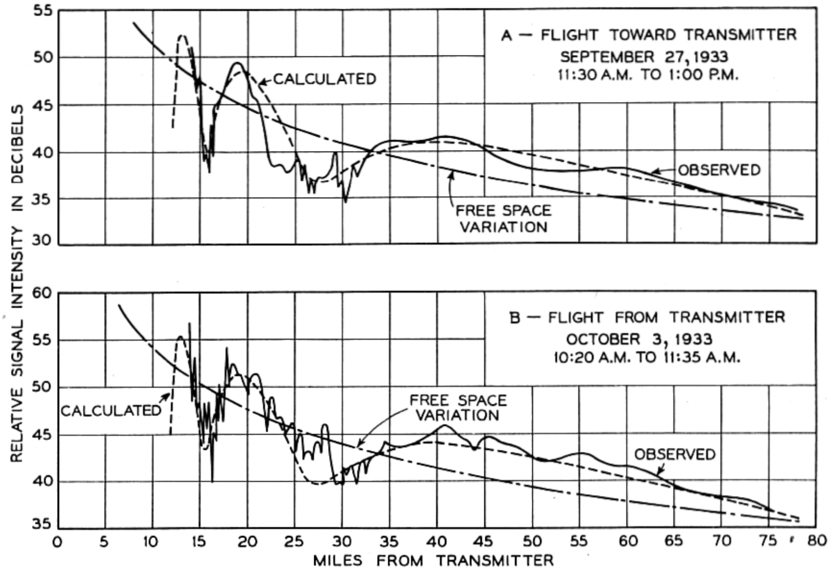

Fig. 4—Wave-length—1.58 meters; Altitude—8000 feet.

At 2500 feet the fit with theory is good for the greater part of the optical range for the 4.6 meter wave transmission. Both curves (5 and 6) show a definite diffraction effect.

[3] Dielectric constant = 80.
Ohms per cm. cube = 20.

[4] The set gain was determined together with the average transmitter ammeter readings for each run. With these and the experimentally determined polar characteristics of the plane antennas, the curves are corrected to set gains of 100 and 110 db respectively for the 4.6 and 1.58 meter receivers and for specified transmitter currents.

The 1.58 meter observations at 2500 feet fall off with distance in fair agreement with theory (Fig. 7). The " out " curve is rough at the shorter distances, as explained above.

Observations at an altitude of 1000 feet occupied most of our flying time. This was the lowest altitude which we cared to try, since the plane had to remain within gliding distance of the shore. The grazing distance for this altitude is 56 miles and, as the Montauk end of Long Island is a little over 120 miles out, a considerable distance where the transmission is below the earth's horizon was available. At 1000 feet, at Montauk, the plane was 5000 feet, or 0.71 degree, below the ocean grazing line from the transmitter.

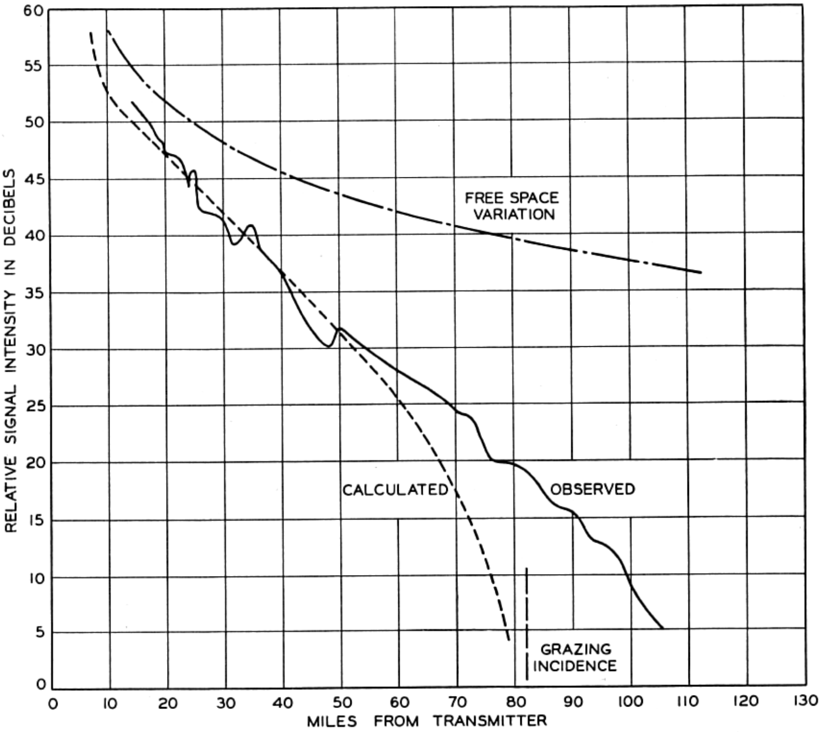

Fig. 5—Flight from transmitter. Wave-length—4.6 meters; Altitude—2500 feet; October 11, 1933; 10:35 a.m. to 11:30 a.m.

At 4.6 meters the first run (the flight of September 27), Fig. 8, carried all the way out to Montauk. Subsequent runs (as Fig. 9) carried barely half way, before the plane noise drowned out the signal.

By going over the electrical system of the plane, tightening old bonds and loose metal pieces, and adding new bonds and shielding, the noise was reduced to such an extent that the results shown in Fig. 8 for the flight of November 1 were obtained, where Montauk Point was almost reached. Both of these curves fit theory well in the optical range; beyond this the second curve lies 10 decibels below the first one. Evidently the plane noise troubles were due simply to the lower signal level which had to be received. This level fell lower as the cold weather came on, and additional work on the plane electrical system had to be done. The 4.6 meter receiving set was also overhauled and realigned. Finally, on November 20, we obtained the bottom curve of Fig. 8, which appeared to be the best we could hope for, and the

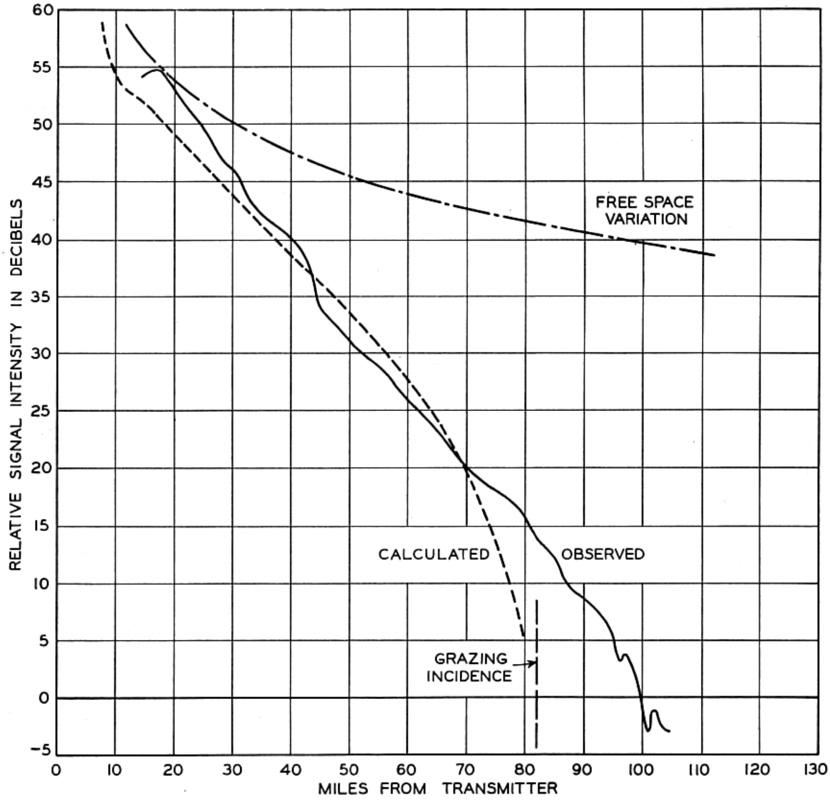

Fig. 6—Flight toward transmitter. Wave-length—4.6 meters; Altitude—2500 feet; November 16, 1933; 12:10 p.m. to 1:05 p.m.

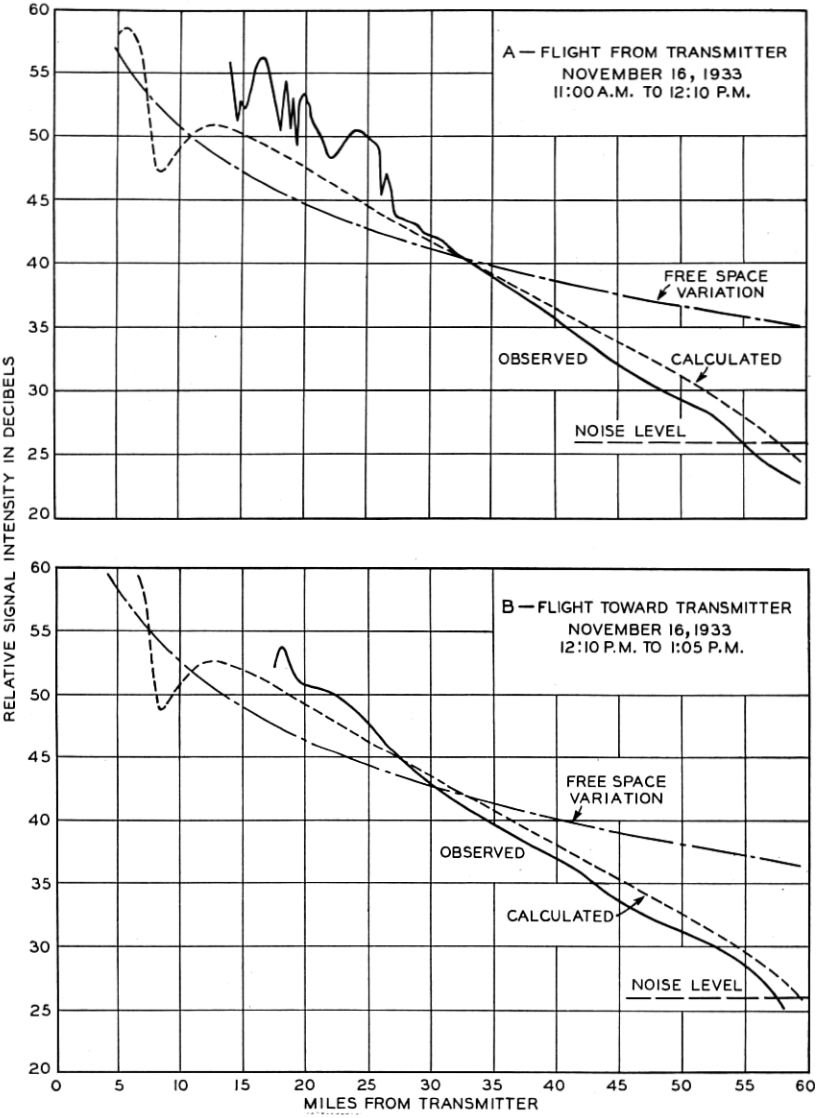

Fig. 7—Wave-length—1.58 meters; Altitude—2500 feet.

work was accordingly discontinued. For this flight, the signal strength at 80 miles was ten decibels below that observed on November 1, and twenty-one decibels below that recorded September 27. The conclusion is inescapable that transmission to regions beyond the optical range is determined by conditions which are not constant and which in fact can produce great signal strength changes.

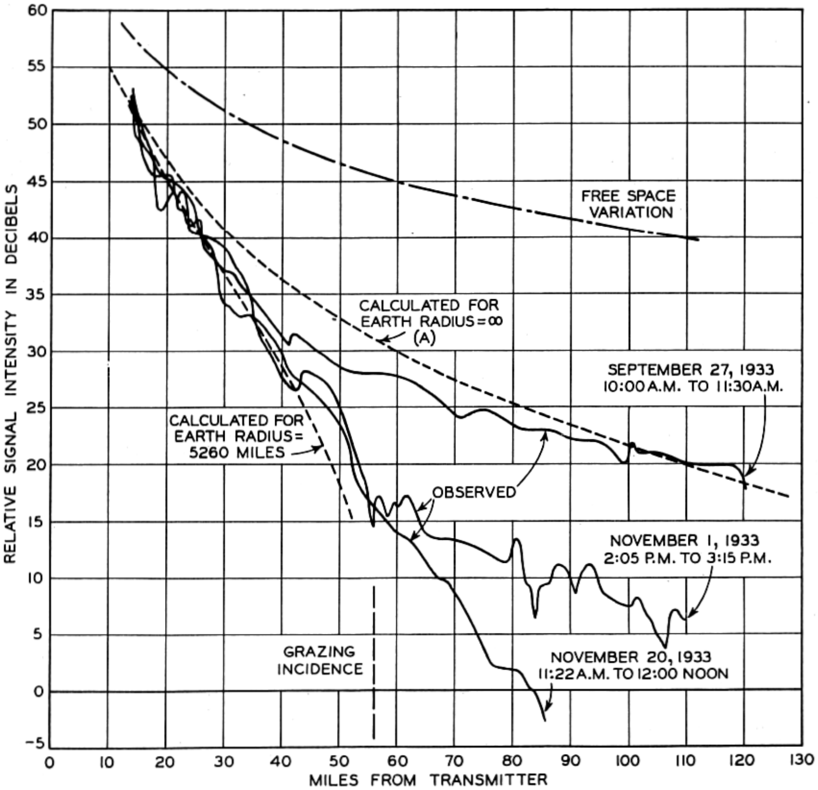

Fig. 8—Flights from transmitter. Wave-length—4.6 meters; Altitude—1000 feet.

The 1.58 meter observations at 1000 feet check the 4.6 meter results fairly well. They follow theory within the optical range. Figure 10, corresponding to Fig. 8 for the 4.6 meter observations, shows some indication of diffraction, and Fig. 11 checks the rapidly falling signal intensity of the bottom curve of Fig. 8. At no time was the half way distance to Montauk reached. There are several reasons for this. The power level available at 1.58 meters was nearly 10 db below that for 4.6 meters, and the plane noise level was higher. It appears, from some rough tests made, that a metal plane is likely to have a peak noise range determined by the natural period of the smaller metal parts, which can vibrate and make variable contact during operation. The " out " curves show the same roughness that was found at the other altitudes. If this effect had been discovered in time, it would certainly have been advisable to move the receiving antenna, so as to shift the polar characteristic minimum to some other angle.

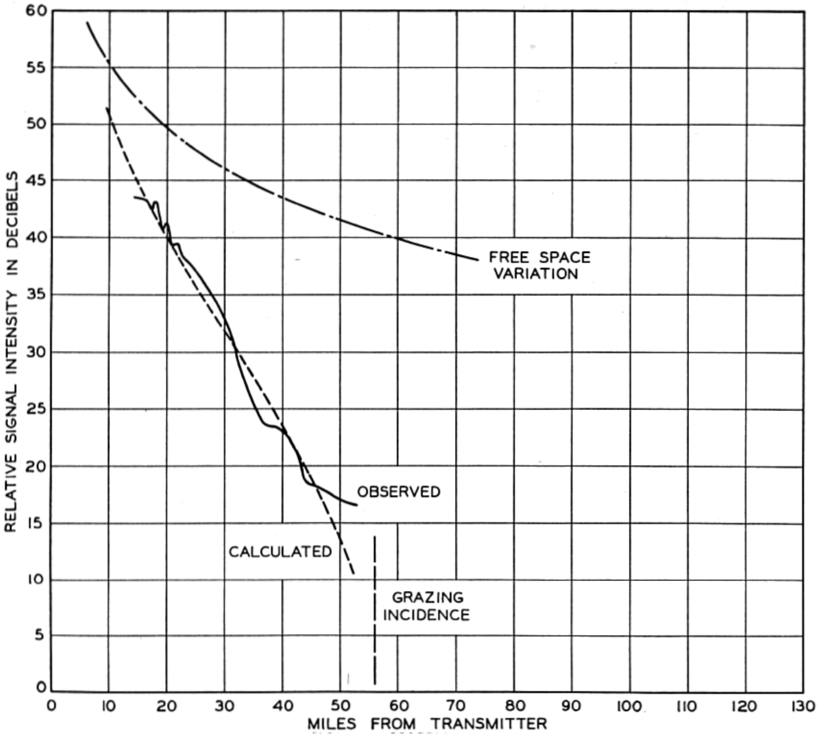

Fig. 9—Flight toward transmitter. Wave-length—4.6 meters; Altitude—1000 feet; October 3, 1933; 11:30 a.m. to 12:35 p.m.

The curves of Fig. 12 were taken at 4.6 meters on passing from the 1000- to the 8000-foot level and vice versa. The first one, taken at Montauk Point on September 27, shows very little variation in signal strength in spiraling up from 1000 to 8000 feet. This was the day when our maximum atmospheric refraction was encountered. If we assume a refraction sufficient to bend the radiation into a circle around

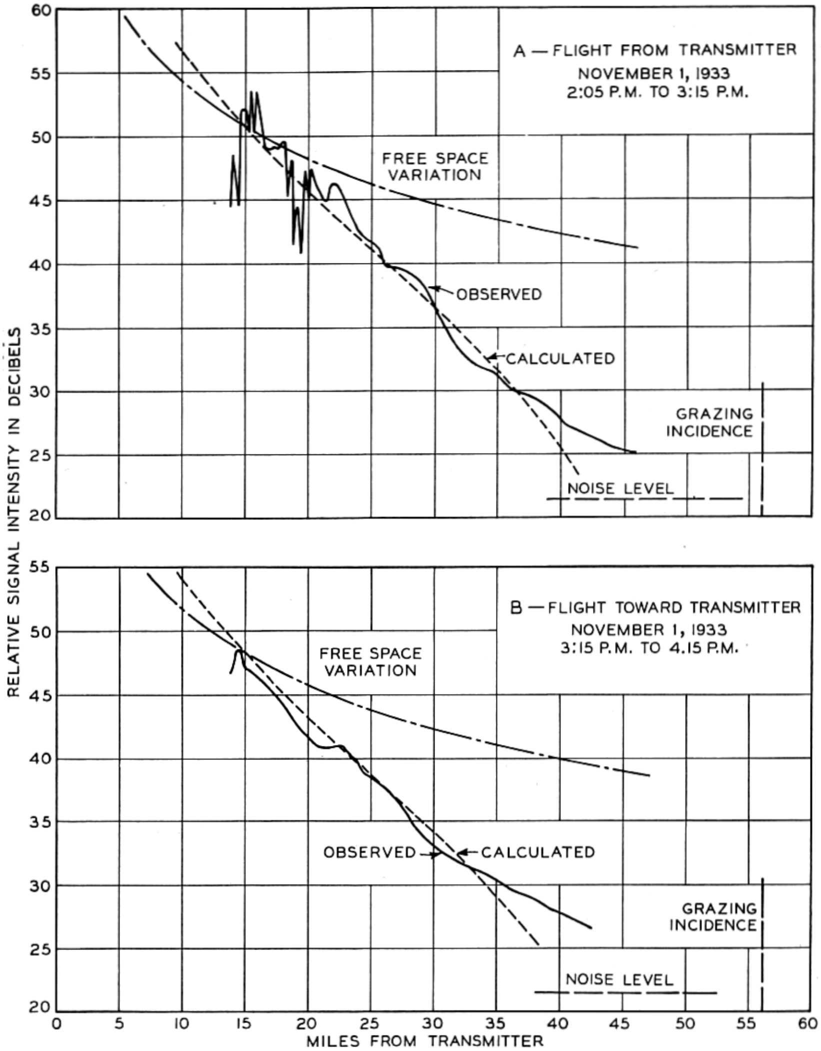

Fig. 10—Wave-length—1.58 meters; Altitude—1000 feet.

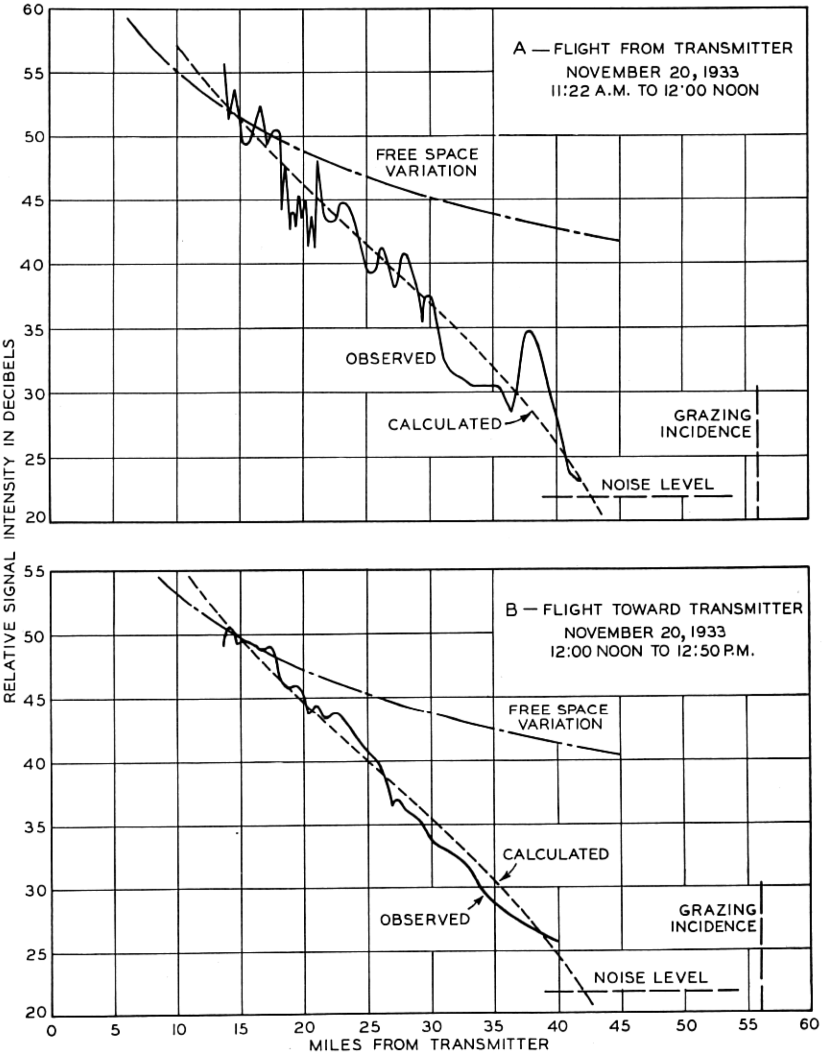

Fig. 11—Wave-length—1.58 meters; Altitude—1000 feet.

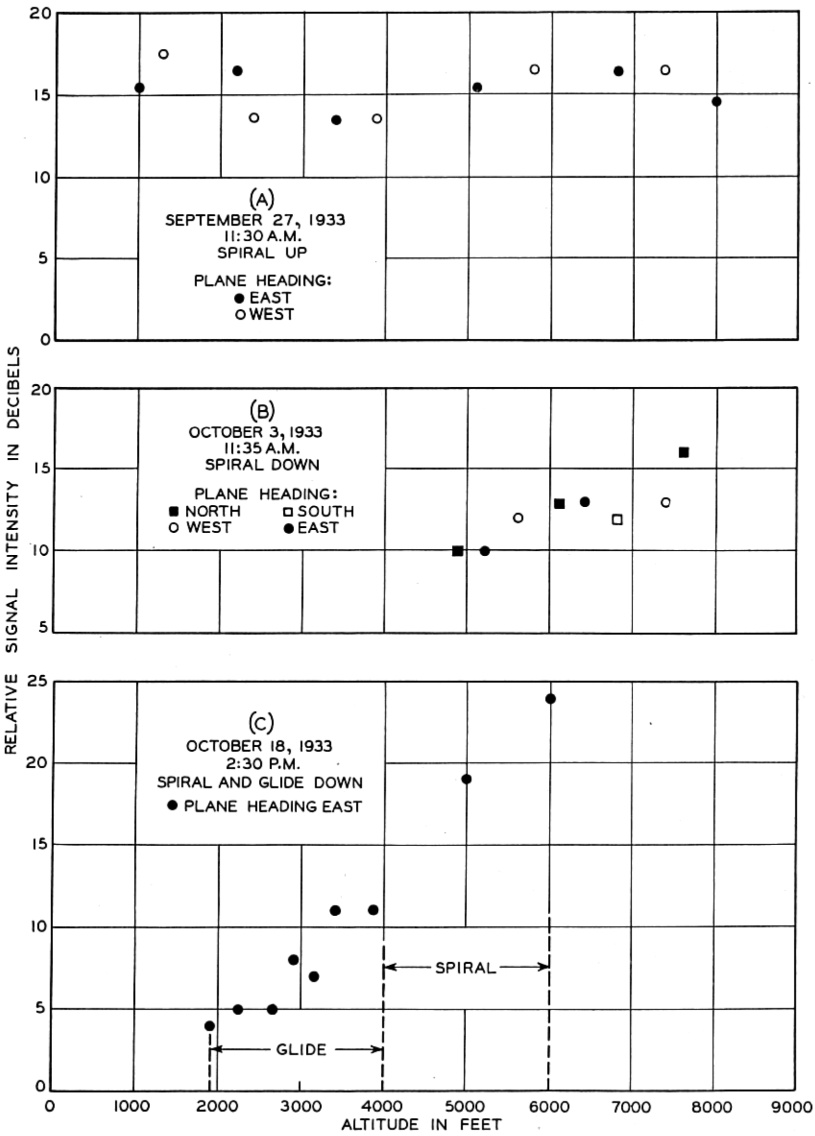

Fig. 12—Signal strength as a function of altitude. Wave-length—4.6 meters. Data for Figs. *A* and *B* obtained at Montauk Point. Data for Fig. *C* obtained 90 miles from transmitter.

the earth, we shall have the theoretical curve " A " of Fig. 8. Evidently the actual refraction was something of this order.

The second curve of Fig. 12, was taken spiraling down at Montauk Point on October 3. The third curve was taken at a distance of 90 miles from the transmitter while spiraling and gliding down, headed " out," on October 18. Unfortunately this was a day of low humidity and the signals were lost before reaching the 1000-foot level and were not picked up again on the return trip. The reduction in plane noise while idling the engines, after the descent had begun, was pronounced, and permitted following the signal almost to 1000 feet.

DISCUSSION

The check with theory for the optical range, though gratifying, was expected from our earlier work. At these low angles of incidence the reflectivity does not vary rapidly with dielectric constant and conductivity changes so that the values assumed by us are adequate. The results for the range beyond grazing incidence are rather unexpected. Diffraction was looked for, and anticipated, but the results themselves seem most readily explicable by a combination of diffraction and refraction, the latter variable with time, and at times predominant. Apparatus variations are ruled out; no effect of ocean roughness has been discernible, and calculations show that the height of the tide is not the explanation. There remain changes in the constants of the air, or in other words, changes in air refraction to consider. Not enough data are available to predict correctly an air refraction effect, but that this is the most plausible explanation is shown by the following.

Because of the change in air density with height, the effect of air refraction is to bend the radio ray into a curved path. This bending is proportional to the gradient of the dielectric constant of the atmosphere, which in turn is proportional to the sum of the gradients of the dry air and water vapor constituting the atmosphere. The dielectric constant of a gas can be written as,

$$\epsilon - 1 = K\frac{p}{T}.$$

In the table below some calculated values of " K " are given. They indicate that water vapor is some 18 times as effective as air, as a refractive medium. They are for wave-lengths greater than 100 meters; no measurements at about 5 meters wave-length have been found, so far, in the scientific literature.

760 MM. BAROMETRIC PRESSURE

Temp.	K Air	 Water Vapor
45° F.	0.000211	0.00381
63° F.	0.000211	0.00366
83° F.	0.000211	0.00356

As is shown in the appendix, the small percentage of water vapor, present normally in the atmosphere, has a very marked effect on the radius of curvature of the radio ray. While the bending, there calculated, does not quantitatively explain our September 27, 1933 results at 1000-foot altitude, it is qualitatively in the right direction. The weather bureau data given us were,

Date	Temp.	Bar.	Per Cent Water Vapor by Vol.
Sept. 27, 1933	83° F.	760	2.46
Nov. 1, 1933	63° F.	763	0.935
Nov. 20, 1933	45° F.	757	0.617

and were taken on top of a New York City building. The humidity and its gradient, at the ocean surface may well have been greater. It is not impossible, either, that water vapor absorption bands occur in the ultra-short-wave region. High and irregular refraction effects would then occur.

It is evident that a slight change in ray curvature under grazing incidence transmission conditions will give a marked increase in range. The fading of weak signals under these conditions, which has been observed in this country by Bell Laboratories engineers at Deal Beach, New Jersey, and by Radio Corporation of America observers, and in Europe by Senatore Marconi and International Telephone and Telegraph Company engineers, may possibly be explained in this manner.

This work is being continued.

APPENDIX

1. From the accepted theory [5] the dielectric constant of a gas is given by

$$\frac{\epsilon - 1}{\epsilon + 2} = \frac{4\pi N}{3}\left(\lambda e^2 + \frac{A\mu}{3RT}\right).$$

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[5] See Debye, "Polar Molecules," Chemical Catalogue Company.

For a perfect gas $pv = \frac{R}{M} T$ or $\rho = \frac{1}{v} = \frac{Mp}{RT}$ and since $N = \frac{A\rho}{M}$

$$\frac{\epsilon - 1}{\epsilon + 2} = \frac{4\pi}{3} \cdot \frac{A}{R} \cdot \frac{p}{T} \left(\lambda e^2 + \frac{A\mu}{3RT} \right) \cdot$$

The symbols are:

ϵ = dielectric constant
N = no. of molecules per cm.^{3}
λ = elastic binding constant of optical electrons
e = electron charge (= 4.774×10^{-10} E.S. Units)
μ = electric moment of molecule
R = gas constant (= 8.314×10^7)
A = Avogadro's const. (= 6.064×10^{23} molecules per mole)
T = absolute temperature
p = pressure in dynes per cm.^{2}
v = specific volume (cc. per gm.)
M = mole (molecular wt. in gms.)
ρ = density (gms. per cm.^{3})

For practical purposes this equation can be simplified. For most gases $\epsilon + 2 = 3$, to a high degree of accuracy and, as the material constants "λ" and "μ" are not readily separately measurable, it is convenient to lump them in a single constant. It is also convenient to change to another unit of pressure, the millimeter of mercury. In this unit and with the above simplifications

$$\epsilon - 1 = K \cdot \frac{p}{T} \text{ and the gas equation becomes } \frac{p}{T} = \frac{62370}{M} \rho.$$

2. From the Smithsonian tables we have the value of "K" for air practically constant and equal to

$$K_{\text{air}} = 211 \times 10^{-6}.$$

From the results of Jona, Zahn, Stuart, Sänger and Stranathan,[6] the value of "K" for water vapor is

$$K_{H_2O} = 182 \times 10^{-6} \left(1 + \frac{5582}{T} \right) \cdot$$

From these values the table below is calculated, assuming 760 mm. of mercury pressure. The temperatures chosen are those encountered in our airplane work, on the dates given.

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[6] Jona, *Phys. Zeit.* **20**, 14, 1919. Zahn, *Phys. Rev.* **27**, 329, 1926. Stuart, *Zeit. f. Phys.* **51**, 490, 1928. Sänger, *Phys. Zeit.* **31**, 306, 1930. Stranathan, *Amer. Phys. Soc. Bull.*, **Vol. 9**, No. 2, abstract No. 7.

Temp.	ϵ_{air}	$\epsilon_{\text{water vapor}}$	Date
45° F........	1.000574	1.01033	11–20–33
63° F........	1.000554	1.00965	11– 1–33
83° F........	1.000534	1.00898	9–27–33

3. The velocity of propagation, of electromagnetic waves in a gas, is given by $v = \dfrac{3 \times 10^{10}}{\sqrt{\epsilon}}$, and the radius of curvature of the ray, in the plane of " h," is,

$$R = \frac{v}{\dfrac{\partial v}{\partial h}} = -\frac{2\epsilon}{\dfrac{\partial \epsilon}{\partial h}} = -\frac{2}{\dfrac{\partial\left(K\dfrac{p}{T}\right)}{\partial h}} = -\frac{2M}{62370\dfrac{\partial(K\rho)}{\partial h}}.$$

From the linear addition theorem, the " K " of a composite gas like moist air will be

$$100K = \left[(100 - \alpha)211 + \alpha\left(182\left(1 + \frac{5582}{T}\right)\right)\right] \times 10^{-6}$$

or

$$K = \left[211 + \alpha\left(\frac{10159}{T} - 0.293\right)\right] \times 10^{-6},$$

where " α " is the percentage of water vapor, in the air, by volume. Hence

$$R = -\frac{M \times 10^{6}}{31185} \cdot \frac{1}{\dfrac{\partial}{\partial h}\rho\left[211 + \alpha\left(\dfrac{10159}{T} - 0.293\right)\right]},$$

where " M " is the molecular weight of the gas involved, and " ρ," " α," and " T " are to be determined as functions of " h," the altitude above the earth.

4. From Humphrey's " Physics of the Air " we obtain the following data:

On page 38 average summer and winter temperature versus height curves are given. For the first two kilometers a good fit to the summer curve is given by the equation,

$$T = -6.19h + 288 \quad \text{where " } h \text{ " is in miles.}$$

On page 72, average summer and winter air and water vapor pressure, and total density tables, as a function of the height, are given. For the first two kilometers the density is given by the equation,

$$\rho = -0.000185h + 0.001224$$

and the percentage of water vapor by

$$\alpha = -0.405h + 1.372.$$

The water vapor percentage gradient increases (in absolute value) up to 1.25 kilometers, after which it decreases; the other two curves (" T " and " ρ ") do not have a point of inflection. The curve for " ρ " has a continuously falling slope above 2 kilometers, that for " T " has a rising slope (both in absolute value). Either rising slope curve should show, by itself, a certain converging lens effect.

5. Carrying out the differentiations indicated in paragraph 3 gives

$$\frac{\partial}{\partial h}\rho\left[211+\alpha\left(\frac{10159}{T}-0.293\right)\right]$$
$$=211\frac{\partial\rho}{\partial h}+\left(\frac{10159}{T}-0.293\right)\left(\alpha\frac{\partial\rho}{\partial h}+\rho\frac{\partial\alpha}{\partial h}\right)-\frac{10159\alpha\rho}{T^2}\frac{\partial T}{\partial h}.$$

Three terms result, distinguishable, respectively, as due to the air density gradient, the water vapor density gradient, and the temperature gradient.

As a typical and simple numerical example, we may select the values of " ρ," " T," and " α " for $h = 0$, that is at the earth's surface. We have then

$$\frac{\partial\rho}{\partial h_0} = -1.85\times10^{-4}, \qquad \alpha_0 = 1.372,$$
$$\rho_0 = 1.224\times10^{-3}, \qquad \frac{\partial T}{\partial h_0} = -6.19,$$
$$\frac{\partial\alpha}{\partial h_0} = -0.405, \qquad T_0 = 288,$$
$$M = 28.6,$$

and hence

$$R = \frac{917.5}{390+262-12.6} = 14350 \text{ miles},$$

where the three terms in the denominator are: the air, water vapor, and temperature gradient terms, respectively. It is evident that the existence and distribution of the small amount of water vapor present (1.37 per cent), adds very greatly to the effectiveness of the air itself as a refractive medium.